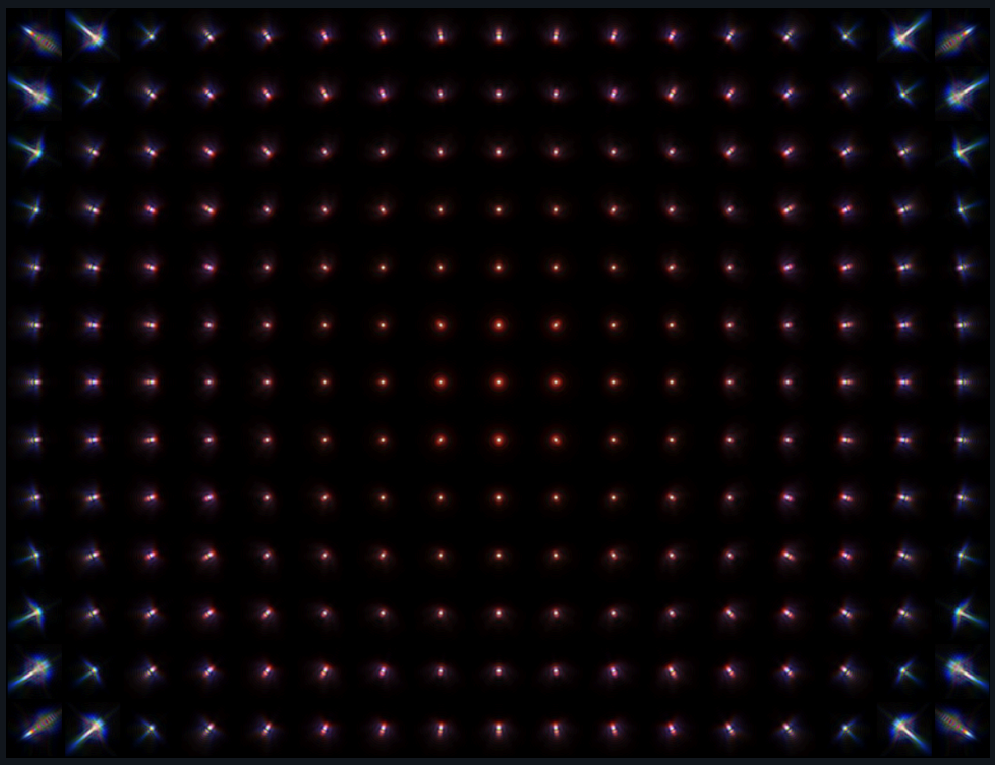
CASE STUDY 1 · SMARTPHONE REAR MAIN CAMERA · 22 OCTOBER 2026

An eight-element phone lens that the factory can build

A flagship phone's main camera squeezes eight molded plastic lenses into less than 1 cm, in front of a 50-megapixel sensor. This study takes a published eight-element design, scales it to a 1/1.28-inch sensor at f/1.78, and asks two questions: how sharp is it, and how many molded copies pass the factory's through-focus MTF test? It then maps the lens's blur across the whole sensor, the input the image processor needs. Every optical number comes from the Paraxial API.



The lens's blur across the whole sensor: 17 × 13 point-spread functions at 650, 555 and 470 nm (red, green, blue), each tile 24 µm wide, all computed by the Paraxial API.

0.54
MTF on axis at 205 lp/mm (half the pixel Nyquist)

99 %
of 1 µm-class builds pass every centre and 0.7-field MTF check

17 %
pass at 3 µm molding tolerances: the factory sets the yield

0.14
corner MTF peak at 102 lp/mm against a 0.20 limit: not met

Paraxial · fea deployment (API 0.9.248) · designed and analysed by Claude through the Paraxial SDK · summary edition

BACKGROUND 01

What this case study is trying to solve

Every flagship phone has three or four rear cameras, and the main (wide) camera does most of the work. It sits behind a lens about 7 mm long made of eight injection-molded plastic elements, each one a strongly aspheric shape that no glass shop could grind, in front of a sensor with pixels just over a micrometre wide. The lens must be sharp across a 84° diagonal field at f/1.8, keep the light hitting the sensor's microlenses at less than about 35°, and still be made by the hundred million.

The question this study answers: **can an eight-element plastic asphere lens meet a flagship 1/1.28-inch main-camera specification, and what share of molded builds passes a production through-focus MTF test at the centre, 0.7 field and 1.0 field?** It also builds the full-field PSF map an image-signal processor (ISP) uses to undo the lens blur.

This is the first of four studies; the others cover the telephoto and ultra-wide, the front module, and this lens's thermal and mechanical environment.

THE JOB 02

What the lens has to do

All requirements come from public data (sensor datasheets, lens patents, published production MTF specifications and molding literature).

WHAT THE JOB NEEDS	SPECIFICATION
Fill a 50 MP 1/1.28″ sensor	`9.99 × 7.50 mm, 1.22 µm pixels, ImgH 6.245 mm`
24 mm-equivalent view	`EFL ≈ 6.9 mm, 84° diagonal`
Bright	`f/1.78`
Short	`TTL ≤ 8.7 mm`
Match the sensor microlenses	`chief-ray angle ≤ 35°`
Bright corners	`relative illumination ≥ 32 %`
Straight lines	`|distortion| < 2 %`
Production MTF test	`through-focus peak at 102 / 205 lp/mm: centre > 60 / 40 %, 0.7F S > 50 / 30 %, T > 40 / 20 %; 1.0F S > 30 %, T > 20 % at 102`
Focus together	`all 0.7F peak positions within ±2 µm after alignment`
Moldable	`centre thickness ≥ 0.27 mm; decenter 1–3 µm class`

WHY IT IS HARD 03

Four demands that pull against each other

- **Short lens against a wide field.** Fitting an 84° field into a lens shorter than its image diagonal forces the last elements into strongly curved, wavy shapes to flatten the image.
- **Steep light against the sensor.** A short lens sends light into the corner pixels at a steep angle; the microlenses only accept about 35°.
- **Aspheres against tolerances.** The same strong aspheres that make the design work make it sensitive: a micrometre of decenter on one element is a visible loss of contrast.
- **Plastics against colour.** Only a few optical plastics can be molded, with two refractive indices to choose from, so colour correction has little room.

THE DESIGN 04

A published eight-element lens, checked, scaled and re-balanced

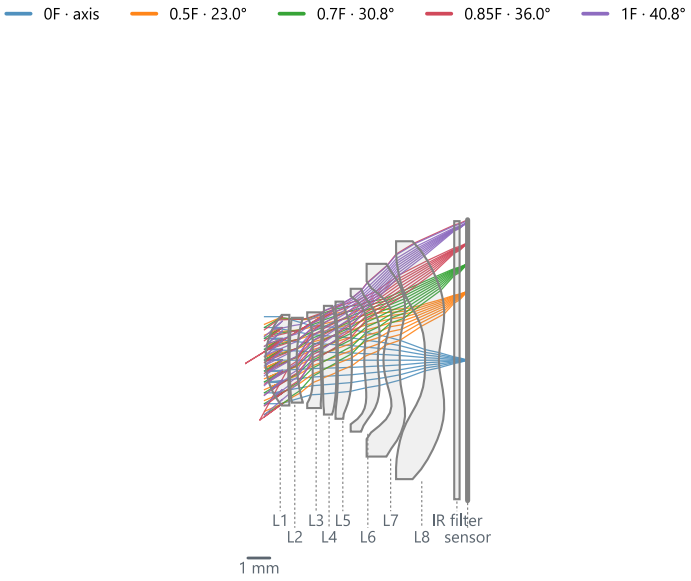


Figure 1. Layout from the Paraxial layout endpoint: element outlines are the API sag of the prescription out to each surface's clear aperture, rays are the endpoint's rays at five field positions (0, 0.5, 0.7, 0.85 and 1.0 of the 6.245 mm image height). The same field colours are used in every figure.

A published eight-element patent lens, checked through the API against the patent (EFL 6.046 mm against 6.05 mm), scaled to the sensor (EFL 7.02 mm, 24.3 mm equivalent, f/1.78) and re-balanced on RMS wavefront.

> **Decision.** Start from a published production-class design rather than from scratch. An eight-element asphere lens has about 150 free parameters, and a local optimiser starting from a guess finds a poor local minimum; a manufacturer's design is already in a good one.

PERFORMANCE 05

Sharp in the centre and at 0.7 field, soft in the corner

All values are at the stored image plane, polychromatic over five bands from 470 to 650 nm. The MTF is computed with the Huygens method: at chief-ray angles of 30° and more the image-space beam is strongly inclined to the sensor, which a Huygens PSF integrates directly.

FIELD	RMS WFE (WAVES)	MTF T/S @ 100	MTF T/S @ 205	MTF T/S @ 410
0F · 0.0°	0.069	0.76 / 0.76	0.54 / 0.54	0.32 / 0.32
0.5F · 23.0°	–	0.70 / 0.67	0.40 / 0.49	0.20 / 0.27
0.7F · 30.8°	0.146	0.49 / 0.65	0.12 / 0.47	0.07 / 0.22
0.85F · 36.0°	–	0.56 / 0.51	0.31 / 0.34	0.13 / 0.11
1F · 40.8°	0.592	0.06 / 0.40	0.02 / 0.20	0.02 / 0.11

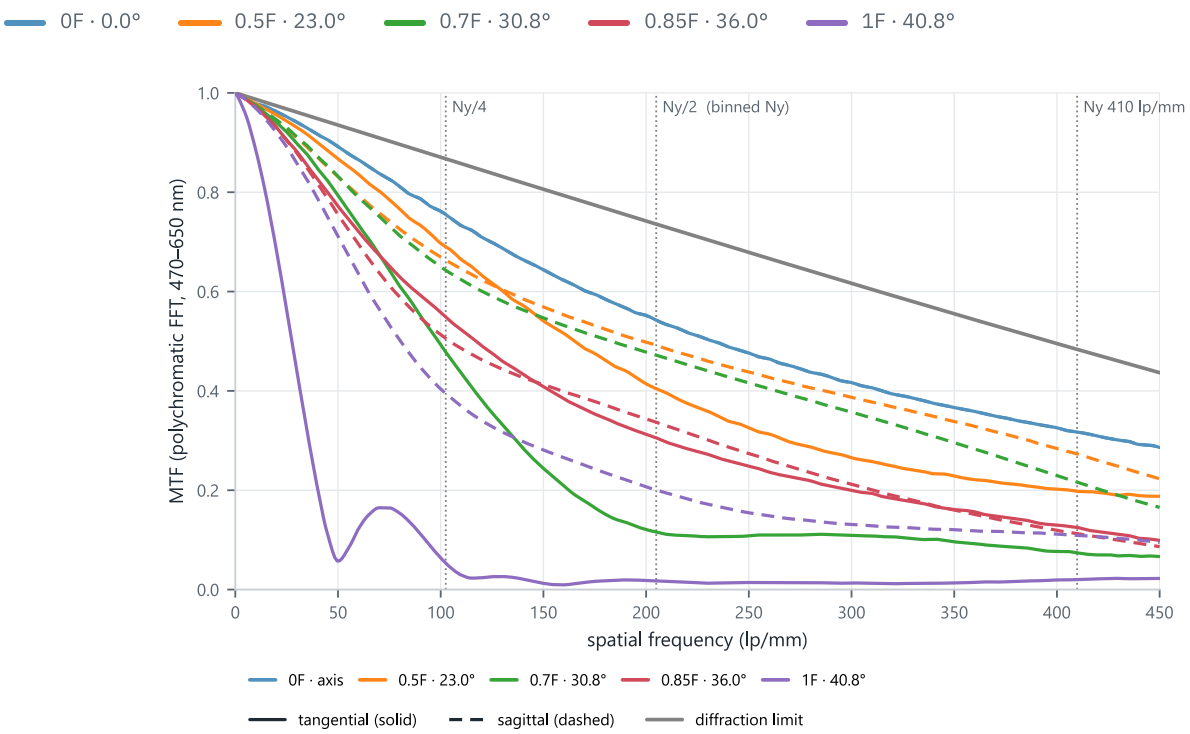


Figure 2. Polychromatic Huygens MTF to 450 lp/mm (1.1 × the 410 lp/mm pixel Nyquist). **Sampling:** 128 pupil samples per axis, 256 grid, 5 lp/mm steps, T/S by polar slicing. A run at half the sampling differs by at most 0.010.

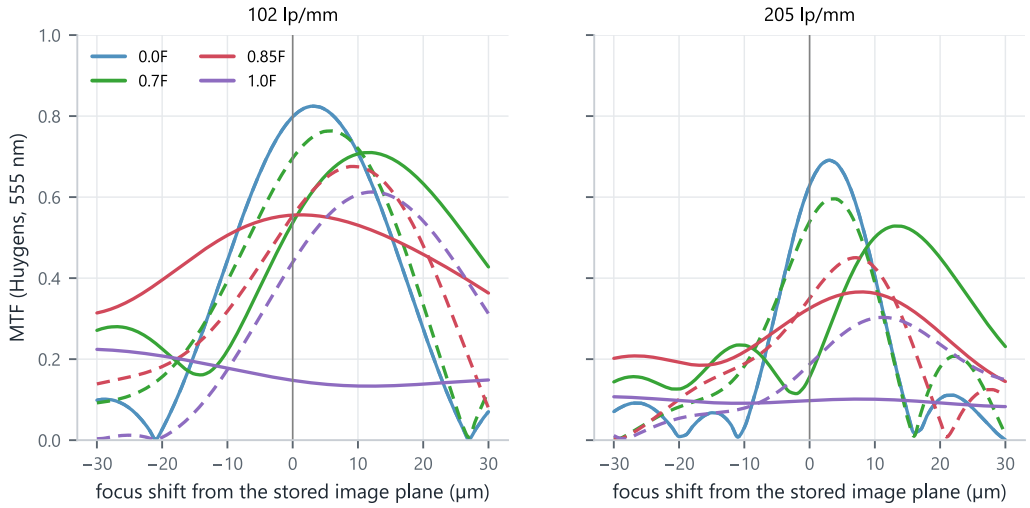


Figure 3. Through-focus MTF at 102 and 205 lp/mm (Huygens, 555 nm, ±30 µm in 1 µm steps) at 0, 0.7, 0.85 and 1.0 field; tangential solid, sagittal dashed. The production test reads the peak of each curve and where it sits.

> **Finding.** At 0.7 field the tangential and sagittal peaks sit 6.5 µm apart in focus, more than the ±2 µm the production test allows, and the corner's tangential peak is 0.14 against 0.20. Both are properties of the nominal design (astigmatism and field curvature at the edge of the field), not of manufacturing.

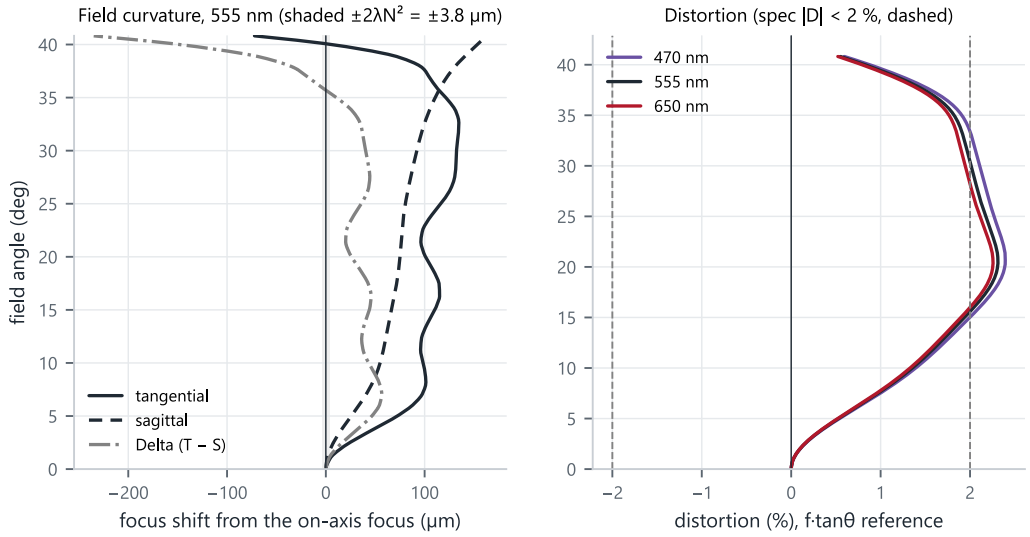


Figure 4. Left: tangential and sagittal focus against field at 555 nm, relative to the on-axis focus, and Delta (their separation); shaded ±2λN² = ±3.5 µm. Right: distortion at 470, 555 and 650 nm (f·tanθ reference).

MANUFACTURING 06

Molding tolerance, not the alignment machine, sets the yield

A molded lens is never built as designed: every element sits a few micrometres off-centre and tilted, and every spacer is a little thick or thin. In production the finished lens is **actively aligned**: a machine moves the whole barrel in focus and tilt against the live sensor until opposite corners focus together, then glues it. It cannot fix errors inside the barrel.

Tolerances

ERROR	LIMIT	DISTRIBUTION	WHY
Element decenter x / y	±3 µm (×k)	uniform	Typical injection-molding decenter 3–5 µm
Element tilt x / y	3 µm TIR over the element (×k)	uniform	Same molding class
Surface decenter x / y (mold halves)	±2 µm (×k)	uniform	A top yield driver in published studies
Centre thickness	±5 µm (×k)	normal, ±2σ	Next air gap absorbs it (lenses stack at flanges)
Spacer (air gap)	±5 µm (×k)	normal, ±2σ	Propagates down the stack

How each build is judged. The API's Monte Carlo sampler draws the errors (seeds 42–46). Each drawn build is rebuilt as its own optic and measured like a lens on a production tester: Huygens through-focus MTF at the centre, at 0.7 field in four directions and at the four sensor corners, scanning ±30 µm about the design focus (±60 µm about the refocused plane for builds whose peaks fell outside that range). The alignment tilt is the plane through the four 0.7-field focus positions, removed before the spread is measured. The rebuild was validated against the API's own trial: with no further error added, the rebuilt optic reproduces the sampler's per-trial wavefront values.

TOLERANCE CLASS	SCALE	BUILDS	CENTRE + 0.7F MTF PASS	CORNER PASS	SPREAD PASS	ALL CHECKS
medium (3 um class)	k = 1.00	115	17 % (11–24 %)	0 %	0 %	0 % (0–3 %)
intermediate	k = 0.50	115	87 % (80–92 %)	0 %	0 %	0 % (0–3 %)
challenging (1 um class)	k = 0.33	500	99 % (97–99 %)	0 %	0 %	0 % (0–1 %)

Intervals are the API's 95 % Wilson intervals (POST /tolerancing/yield-verdict). k scales every limit in the table above.

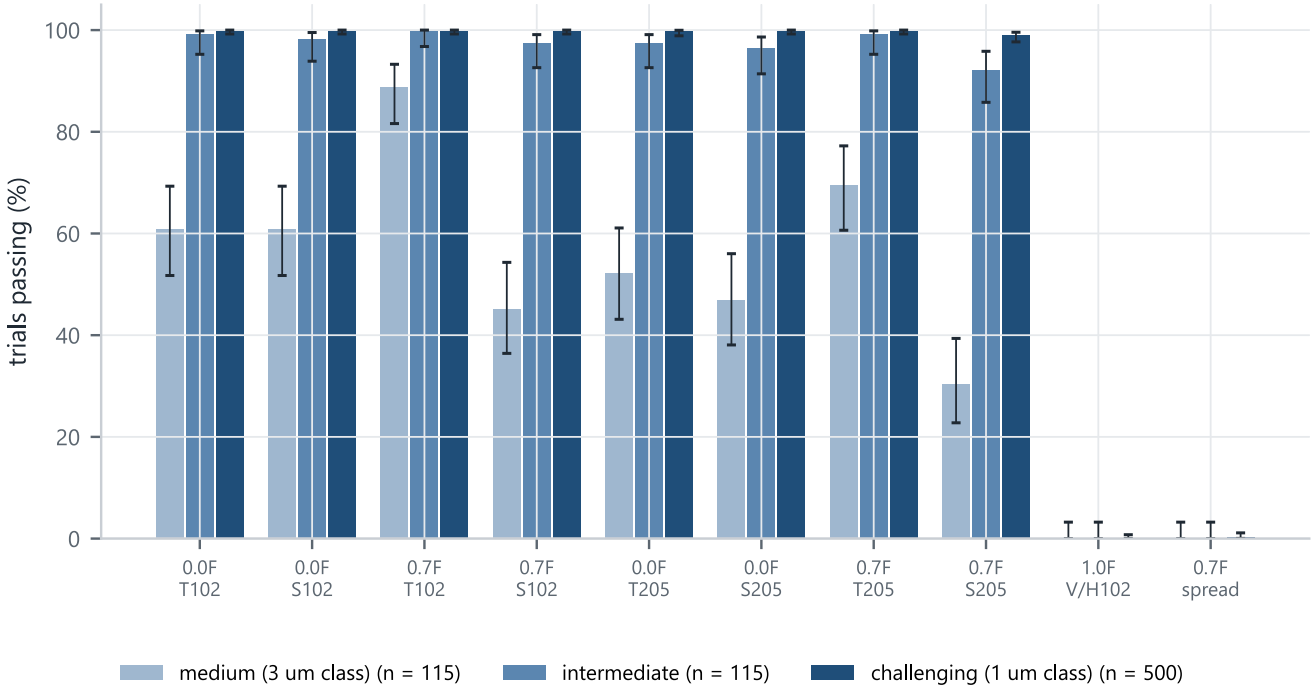


Figure 5. Share of builds passing each production check, for three tolerance classes (error bars: 95 % interval). Darker = tighter tolerances.

> **Finding.** At 1 µm-class tolerances 99 % of builds pass every centre and 0.7-field MTF check; at the 3 µm class only 17 % do. No build in any class passes the corner check or the focus-spread check, because the nominal lens already fails them: those two need a design change, not a better factory.

ISP 07

The PSF map the image processor needs, and what it buys

A phone does not show the lens's raw image. The ISP corrects the corner darkening (lens shading), straightens the distortion and sharpens each region with the inverse of the local blur. It needs a map of that blur across the sensor. The API computed the point-spread function at 63 points of one sensor quadrant (17 × 13 over the full sensor by symmetry) at 470, 555 and 650 nm.

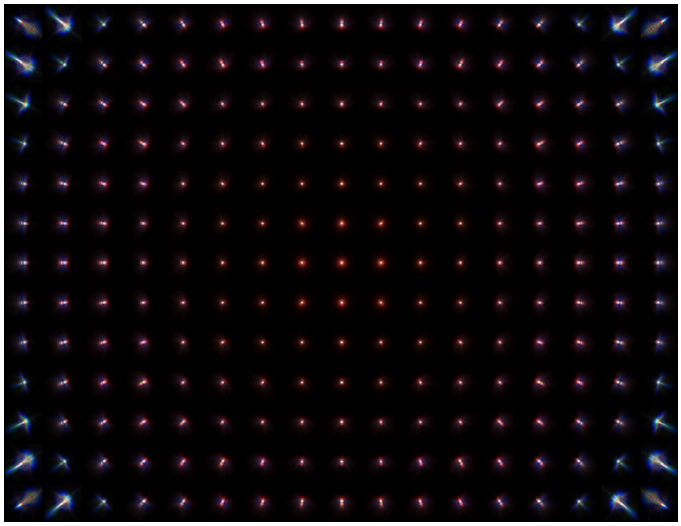


Figure 6. PSF map over the 9.99 × 7.50 mm sensor: 17 × 13 positions, each tile 24 µm wide, R/G/B = 650/555/470 nm, square-root intensity, each tile normalised to its own peak. Field angles were solved through the API's distortion map and checked against the real chief-ray height (largest error 4.2 µm).

A modelled ISP chain (local image processing on the API PSFs, not optics): slanted-edge and Siemens-star tiles are blurred by the local PSF, integrated over the pixel, shaded by the API relative illumination and given shot and read noise; the ISP then divides out the shading and deconvolves with the same PSF (Wiener filter).

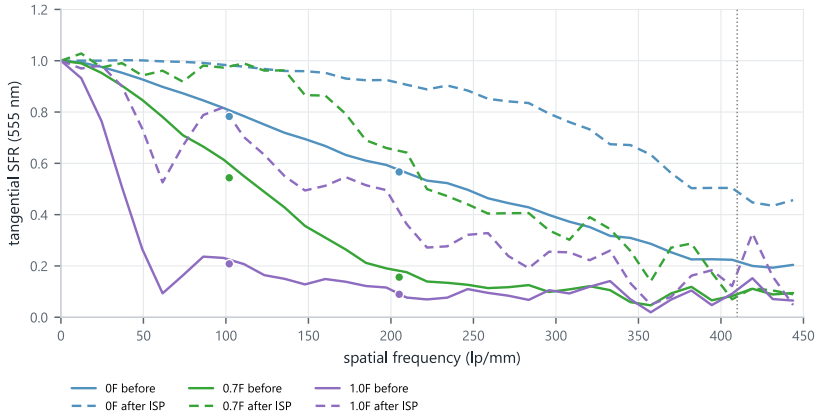


Figure 7. Tangential slanted-edge SFR before (solid) and after (dashed) the ISP. Dots: the API's monochromatic Huygens MTF at the same field times the pixel response, the value the raw SFR should match.

> **Finding.** Deconvolution with the API's own PSFs lifts the 205 lp/mm response at 0.7 field from 0.18 to 0.65 and in the corner from 0.09 to 0.41, at the cost of noise, which is why it needs a PSF map measured or computed per field. The distortion map moves image points by up to 92 µm and its inverse restores them to 0.7 µm.

THE RESULT 08

Where the lens stands

REQUIREMENT	TARGET	RESULT	STATUS
Equivalent focal length	23–24 mm	24.3 mm	◐ Partly
f-number	f/1.78	f/1.78	✓ Met
Total track (L1 to sensor)	≤ 8.7 mm	9.19 mm	◐ Partly
Chief-ray angle	≤ 35°	35.01°	◐ Partly
Relative illumination (corner)	≥ 32 %	31.6 %	◐ Partly
Distortion	< 2 %	2.39 %	◐ Partly
Lateral colour	< 3 px	1.34 px	✓ Met
Centre + 0.7F MTF, nominal	all peaks above limits	all above	✓ Met
Corner MTF peak, nominal	> 0.20 at 102 lp/mm	0.14	✗ Not met
0.7F focus spread, nominal	≤ 4 µm (±2 µm)	6.5 µm	✗ Not met
Centre + 0.7F yield, 1 µm class	≥ 90 %	99 %	✓ Met
Centre + 0.7F yield, 3 µm class	≥ 90 %	17 %	✗ Not met

Next steps

- **Rebalance the edge of the field.** Re-optimise with the 0.7-field astigmatism and the corner tangential focus as explicit targets (the optimiser here balanced RMS wavefront), so the nominal lens passes the corner and focus-spread checks before tolerancing.
- **Desensitise.** Add the leading tolerance drivers to the merit function, or split their power, so the 3 µm molding class yields.
- **Measure the PSF map.** The ISP should be calibrated per module; the computed map shows where it matters (corners, 205 lp/mm).

METHOD 09

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 (470–650 nm; through-focus at 555 nm). Each of the 730 Monte Carlo builds was rebuilt as its own lens and tested like a production lens; yield intervals are the API's 95 % Wilson intervals. The ISP chain is local image processing on the API's PSFs.

The full report adds the prescription, illumination, spot, wavefront and colour figures, build statistics and tolerance drivers, the scripts and run times, and the aspheric coefficients.