DOCUMENT IDENTITY STATEMENT

This document is a technical reference developed by POMEAS based on optical engineering principles, laboratory testing practices and machine vision application experience. It is intended to support optical system specification, testing, comparison and integration. **It is not an official national, international or industry standard.**

POMEAS TECHNICAL REFERENCE SERIES

Machine Vision Optical Imaging Systems — Performance Test Methods

TR-001 · Version 1.0 · 2026-09-16

DOCUMENT NUMBER	VERSION	RELEASE DATE	SCOPE
POMEAS-TR-001	1.0	2026-09-16	16 parameter groups
STRUCTURE	**STATUS**		
Definition → ... → Interpretation	Public — free to cite		

Field	Value
Document number	POMEAS-TR-001
Document type	Technical Reference (test methods and evaluation guidance)
Version	1.0
Release date	2026-09-16
Language	English (original). A Chinese edition is published separately as POMEAS-TR-001-CN.
Prepared by	POMEAS Machine Vision Optics — Applications & Metrology
Applies to	Machine vision optical imaging systems: fixed focal length FA lenses, telecentric lenses, motorized continuous zoom lenses, macro and line-scan lens assemblies, and the cameras, illumination and mechanics they are integrated with.
Status	Public. Free to download, cite and redistribute with attribution.

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Where this document cites an external standard, the standard is identified by number, title and edition. Only the standards listed in Section 3 have been verified against their issuing body's catalogue at the release date of this document. Nothing in this document claims conformance to, or approval by, ISO, IEC, GB, DIN, ANSI, IEEE, EMVA or any other standards body.

1. Scope

This document specifies test methods, calculation methods and interpretation guidance for the performance parameters of machine vision optical imaging systems.

It covers the following parameters:

1. Field of View (FOV)
2. Working Distance (WD)
3. Magnification (β)
4. Optical Resolution and Modulation Transfer Function (MTF)
5. Pixel Resolution and System Resolution
6. TV Distortion
7. Full-field Geometric Distortion
8. Depth of Field (DOF)
9. Telecentricity
10. Numerical Aperture (NA) and Aperture Setting
11. Parfocality (motorized zoom lenses)
12. Zoom Repeatability and Backlash
13. Focus Repeatability
14. Sensor Compatibility and Image Circle
15. Illumination Conditions
16. Calibration and Measurement Uncertainty

The methods are written to be executable with equipment normally available to a machine vision integrator: a rigid bench, a calibrated target, a translation stage, an industrial camera able to output unprocessed images, and a focus/edge evaluation software tool. Where a method needs equipment that is normally found only in a metrology laboratory or a lens manufacturer's facility, this is stated explicitly.

Out of scope. Surface form and surface imperfection of optical elements; environmental and durability testing; chromatic aberration and colour reproduction; stray light and veiling glare; laser and non-imaging optical systems; and the internal design or production tolerances of the lens. This document evaluates *systems as they are used*, not optical designs in isolation.

Application. The results of these methods support three decisions: (a) whether a candidate lens meets a stated requirement before purchase; (b) whether an incoming or in-service lens is fit for a measurement task; (c) whether an existing measurement station is still within its calibration interval. They are not a substitute for a type test performed by the manufacturer against its own specification.

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2. Purpose

Most lens data published by machine vision suppliers answers the question "*what are the numbers?*". This document answers a different question:

> **How do you test it?**

For each parameter, this document provides, in a fixed structure:

Definition → Test Equipment → Test Setup → Test Procedure → Calculation → Result Recording → Common Errors → Engineering Interpretation

The structure is deliberate. A number without a test condition is not a specification: "FOV 100 mm" is meaningless unless the magnification, the working distance, the sensor format and the measurement plane are also stated. Section 12 catalogs the errors that most often make a reported value unreproducible, and Section 11 provides a report template that forces the test conditions to be recorded alongside the result.

Measured values versus theoretical values. Through this document, values are labelled as one of:

- **[T] — Theoretical / calculated** from geometry and the datasheet parameters of the components. Exact within its model, but the model is an approximation of the real system.
- **[M] — Measured** on a specific physical assembly under the stated test conditions. Applies to that assembly only, within the stated uncertainty.
- **[POMEAS LAB TEST DATA REQUIRED]** — A value that this document's method defines, but for which POMEAS does not yet have published laboratory data. Appendix B is the register of

every such value, and the companion deliverable *TR-001 Laboratory Test Data Plan* defines the experiment, the equipment, the photographs and the data records required to fill it in.

No value in this document is presented as a POMEAS product specification unless it appears in a POMEAS datasheet. Engineering examples used for illustration are labelled as such.

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3. Normative references

The following documents were verified against the issuing body's catalogue at the release date of this document. Where a later edition exists, the later edition applies.

Reference	Title (verified)	Edition / status	Relevance in this document
ISO 12233	Digital cameras — Resolution and spatial frequency responses	**ISO 12233:2024**, Edition 5, published 2024-09, ISO/TC 42	Slanted-edge SFR (e-SFR) measurement algorithm and test chart requirements; Section 8.4
ISO 9335	Optics and photonics — Optical transfer function — Principles and procedures of measurement	**ISO 9335:2025**, Edition 3, published 2025-02, ISO/TC 172/SC 1	General rules for OTF/MTF measuring equipment and environmental controls; Sections 6 and 8.4
ISO 9334	Optics and photonics — Optical transfer function — Definitions and mathematical relationships	**ISO 9334:2012**, confirmed	Terminology for OTF, MTF and PTF; Section 4
ISO 9039	Optics and photonics — Quality evaluation of optical systems — Determination of distortion	**ISO 9039:2008**, Edition 2, published 2008-02, ISO/TC 172/SC 1	Reference method for distortion determination; Sections 8.6 and 8.7
ISO 1	Geometrical product specifications (GPS) — Standard reference temperature for the specification of geometrical and dimensional properties	**ISO 1:2022**, Edition 4, published 2022-06-14, ISO/TC 213	Standard reference temperature t_{90} = 20 °C, adopted as the default test temperature; Section 5
ISO/IEC Guide 98-3	Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM)	Guide 98-3, ISO/IEC	Framework for the uncertainty budget; Section 13
ISO/IEC Guide 99	International vocabulary of metrology — Basic and general concepts and associated terms (VIM)	Guide 99	Definitions of measurand, uncertainty, traceability; Section 4
ISO 14253-1	Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for verifying conformity or nonconformity with specifications	**ISO 14253-1:2017**, Edition 3, published 2017-10, confirmed 2023, ISO/TC 213	Decision rules for accepting or rejecting a lens against a specification when the measured value is close to the limit; Section 12.4
ISO 5725-1, ISO 5725-2	Accuracy (trueness and precision) of measurement methods and results	—	Repeatability and reproducibility definitions used in Section 13

Reference	Title (verified)	Edition / status	Relevance in this document
EMVA 1288	Standard for Characterization of Image Sensors and Cameras	**Release 4.0**, effective June 2021 (modules *Linear* and *General*), hosted by the European Machine Vision Association	Camera-side parameters. EMVA 1288 is an industry standard hosted by EMVA — it is **not** an ISO or IEC standard. Where a camera's own characterisation is required, it is referenced from the camera supplier's EMVA 1288 report rather than re-measured here.

Not referenced. This document deliberately does not reference GB, DIN, ANSI or IEEE documents for the parameters it covers, because no verified edition of such a document was identified that is directly applicable to machine vision lens system characterisation. Their absence is a statement about applicability, not a claim about their quality.

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4. Terminology and symbols

4.1 Symbols

Symbol	Quantity	Unit	Definition and notes
β	Magnification (lateral, image/object)	dimensionless	Also written *m* in general optics literature. For a zoom lens, β is defined at a stated zoom position and a stated working distance. $\beta > 1$ means the image is larger than the object.
m	Magnification, alternative symbol	dimensionless	Used identically to β; retained where a formula is conventionally written with *m*.
FOV_O	Object-side field of view	mm	Extent of the object plane imaged onto the active area of the sensor. Reported as width × height, or as the diameter of the inscribed circle for a circular field.
FOV_I	Image-side field of view	mm	Equal to the active sensor dimensions used.
WD	Working distance	mm	Distance from the manufacturer's reference plane (normally the front mechanical face of the lens) to the object plane at best focus. The reference plane **must** be stated; a WD quoted from a different datum is not comparable.
p	Pixel pitch	µm	Centre-to-centre spacing of sensor pixels. Taken from the sensor datasheet, not from the number of pixels divided by the format.
N_H, N_V	Active pixel count	px	Horizontal and vertical *active* pixels. Excludes dummy, optical-black and boundary pixels.
L_obj	Object-space pixel size	µm	$L_{obj} = p / \beta$. The size, on the object, that one sensor pixel covers.
z	Axial position along the optical axis	mm	Positive away from the lens.
F#	f-number (image side)	dimensionless	Ratio of focal length to entrance pupil diameter at the design conjugate, as set on the aperture control.
N_eff	Effective f-number	dimensionless	Image side: $N_{eff} = F\# \times (1 + \beta)$.
NA_obj, NA_img	Numerical aperture	dimensionless	$NA = n \cdot \sin\theta$. Object side and image side. Related by the Abbe sine condition: $NA_{obj} / NA_{img} = \beta$ (in air).
λ	Wavelength	µm	Always state the value used; 0.55 µm (green) is this document's default.
c	Permitted blur, image side	µm	Circle of confusion used in the DOF calculation. **Must always be stated** together with DOF.

Symbol	Quantity	Unit	Definition and notes
c_obj	Permitted blur, object side	µm	c_obj = c / β.
f_img, f_obj	Spatial frequency, image side / object side	lp/mm	Related by f_obj = β × f_img.
f_Nyq	Nyquist frequency	lp/mm	f_Nyq = 1000 / (2 p) with p in µm.
f_cut	Diffraction cutoff frequency	lp/mm	f_cut = 2 NA / λ (incoherent illumination), with λ in mm.
θ	Chief-ray angle in object space	mrad or °	Deviation of the chief ray from the optical axis.
D(x,y)	Local distortion	%	Relative error of the local magnification with respect to the centre magnification.
E	Relative illumination (vignetting)	%	E = irradiance at a field point / irradiance at the field centre.
u_c, U	Standard and expanded uncertainty	µm or %	U = k·u_c; this document uses k = 2 (approximately 95 % coverage) unless stated.

4.2 Key definitions

Active area. The part of the sensor that produces valid image data over the full exposure. Determined from the camera's own documentation, not from the marketing pixel count.

Best focus. The axial position of the object (or of the image plane) at which the chosen focus metric is maximal. Because different metrics peak at slightly different positions, *best focus is only defined together with the focus metric*. This document uses the MTF50 of a slanted edge at the centre of the field unless stated otherwise (Section 6.4).

Measurement plane. The object plane at which the measurement is taken. For a system with a depth of field, the object may be anywhere within the DOF, and the measurement result validly applies to that plane. A measurement is not valid for objects outside the measurement plane unless the system is object-side telecentric (Section 8.9).

Optical resolution. The ability of the *lens* to transfer contrast at a given spatial frequency. A property of the lens, evaluated at the image plane.

Pixel resolution. The spatial frequency limit imposed by the sensor's sampling: the Nyquist frequency. A property of the *camera*.

System resolution. The combined imaging capability of lens + sensor + illumination + relative motion + algorithm. Always lower than either the optical or the pixel resolution taken alone.

Telecentricity (object side). The degree to which the chief rays of the imaging bundle are parallel to the optical axis in object space, expressed as the maximum chief-ray angle over the specified object field.

Parfocality. The property of a zoom lens that the image remains at the same axial position (the object stays in focus at the same WD) as the magnification is changed.

Repeatability. The closeness of agreement between the results of successive measurements of the same measurand carried out under the same conditions (same procedure, same operator, same instrument, same location, over a short period). Reported as a standard deviation and a range.

Distortion. The variation of magnification over the field, i.e. the departure of the image from a geometrically similar mapping of the object. Distortion does not blur an image; it displaces it, which is why it matters for measurement and does not matter for presence/absence inspection (Section 8.7.8).

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5. General test conditions

Unless a procedure states otherwise, all tests are performed under the following conditions. **The actual values must be recorded in the test report (Section 11).** A result without its test conditions is not a result.

5.1 Environment

Condition	Requirement	Reason
Ambient temperature	20 ± 2 °C, measured within 1 m of the test bench. The standard reference temperature for dimensional measurement is 20 °C (ISO 1:2022).	Magnification and scale factor depend on the mechanical spacing, which is temperature dependent. A 100 mm aluminium lens barrel expands by ≈2.3 µm per K; a steel structure by ≈1.2 µm per K.
Thermal stability	The lens, camera and illumination must be powered and thermally soaked for ≥30 min before the first measurement.	LED output and camera black level drift for the first 10–30 min of operation.
Ambient temperature drift	≤0.5 K over the duration of one test series.	Drift during a series appears as repeatability error. If drift cannot be avoided, record it and report it as a separate contribution (Section 13).
Vibration and airflow	Rigid optical bench or granite plate; no fan, no air-conditioning outlet directed at the bench; machine tools on the same floor stopped.	Sub-pixel centroiding is sensitive to sub-micrometre motion. Fan-induced airflow over a lens barrel causes focus drift.
Stray light	The test area shielded from direct sunlight and from nearby uncontrolled sources.	Veiling glare lowers measured MTF, particularly in the dark bars of a test target.

5.2 Illumination

Item	Requirement
Type	LED with constant-current drive. If PWM dimming is used, the PWM frequency must be ≥20 kHz, or the exposure must be synchronised to the PWM, otherwise intensity ripple appears as noise.
Spectrum	Record the peak wavelength (monochromatic) or the correlated colour temperature (white). Use a band-pass filtered source (λ = 0.55 µm typical) for MTF measurement, because chromatic aberration in a white-light measurement broadens the edge and depresses the measured MTF.
Geometry	Record whether the illumination is: coaxial (through the lens), ring, bar, dome, backlight (transmitted), or telecentric. Record the working angle and distance.
Telecentricity of illumination	State explicitly. **Non-telecentric illumination introduces the same perspective error as a non-telecentric lens** and will be measured as part of the imaging system (Section 8.15).
Uniformity	For MTF and distortion measurement, the target behind the edge or grid must be uniformly illuminated to within ±5 % over the region of interest. For MTF, non-uniformity changes the effective edge contrast. For distortion, gradient in the illumination does not move centroids, but saturation does — keep the peak signal between 60 % and 80 % of full scale.
Backlight targets	For FOV, magnification and distortion measurements on a chrome-on-glass target, use a diffuse backlight and check that the chrome is fully opaque at the exposure used (measured density ≥ 3).
Stability	Capture a reference frame at the start and at the end of the series. If the mean grey value differs by more than 2 %, the series must be repeated.

5.3 Camera settings

The camera is a measuring instrument in this document's methods. Its processing must be neutralised.

Setting	Required state	Reason
Gamma	1.0 (linear), or a measured gamma curve is applied to linearise before analysis	MTF and centroiding both assume a linear relationship between irradiance and grey value.
Sharpening	**Off**	Sharpening raises apparent MTF and can raise MTF50 by tens of percent. Any MTF or resolution number obtained with sharpening on is invalid.
Noise reduction / temporal filtering	**Off**	Alters the edge profile and the noise statistics.
Digital gain / white balance / colour correction	Off or fixed; record the values	Channel processing alters the edge profile.
Binning	**Off**	Reduces resolution and changes the effective pixel pitch.
Black level / offset	Fixed; record the value. Do not clip at zero	Standard deviation from a clipped distribution is not the standard deviation of the signal.
Exposure and gain	Fixed for the whole series. Determined so that the brightest region of interest is at 70–80 % of saturation	Avoids clipping and uses most of the dynamic range.
Format	Uncompressed: RAW, or 16-bit TIFF/PNG. If only 8-bit is available, record it and expect a lower achievable MTF at low contrast	JPEG compression modifies edges and invalidates MTF.
Averaging	Where noise is a limitation, average ≥16 frames **after** confirming that the illumination is square-wave stable	Frame averaging reduces random noise; it does not correct drift.

5.4 Alignment

Item	Requirement	Verification
Optical axis vs target plane	Perpendicular to within 0.2° for FOV, magnification and distortion tests	Autocollimator, or measure the same target at 0° and 180° rotation: a tilt θ produces a magnification difference between the two orientations of approximately 2θ. If the two values differ, the target is tilted or the lens axis is not normal to it.
Centring	The target centre, the lens axis and the sensor centre shall be coaxial to within 2 % of the FOV	The measured centre magnification and the four 0.7-field magnifications should be symmetric.
Rotation	For distortion tests, the grid axes should be aligned to the sensor axes to within 0.5°	Squareness of the imaged grid.
Focus	Best focus set by the same operator, with the same metric, for the whole series	

5.5 Data handling

- **Repeat count.** Minimum 5 repeats for any reported value. Where the parameter is the subject of an acceptance decision, minimum 10.
- **Report format.** Report the mean, the standard deviation *s*, and the range (max − min). Do not report only the mean.
- **Outliers.** Reject a value only on an identified cause (a bumped bench, a lost frame, an illumination change). Record every rejection and its cause. Never remove a point only because it is far from the mean.
- **Rounding.** Round only the reported value, never an intermediate result. Report to the resolution of the reference standard used: for a typical chrome-on-glass scale with a certificate uncertainty of 1 µm, reporting more than 0.1 µm is not justified.
- **Traceability.** Record the certificate number and the calibration due date of every certified reference used.

6. Required equipment

#	Item	Minimum specification	Used for
E1	Rigid optical bench or granite plate with a vertical or horizontal rail	Flatness ≤20 µm/300 mm; deflection under load ≤10 µm	All tests
E2	Linear translation stage for the target, axial (z)	Resolution ≤1 µm, backlash ≤2 µm, with a digital readout	WD, DOF, parfocality, telecentricity
E3	Two-axis (x, y) or three-axis stage for the target	Resolution ≤10 µm	Feature selection, centring
E4	Calibrated chrome-on-glass scale, length ≥1.2 × the largest expected FOV	Certificate expanded uncertainty ≤2 µm (k = 2); traceable	FOV, magnification, distortion, repeatability
E5	Calibrated dot grid or chessboard target, ≥15 × 15 nodes, covering ≥1.2 × FOV	Node position uncertainty ≤3 µm; nodes on a common flat substrate	Distortion, calibration
E6	Slanted-edge target conforming to ISO 12233 (or a certified Siemens star)	Edge straightness ≤2 µm over the analysed length; edge angle 2°–7° from vertical	Optical resolution / MTF
E7	USAF 1951 or equivalent line-pair target	Certification of the bar widths	Visual/quick resolution check (screening only; not for reported MTF)
E8	Depth-of-field artefact: a tilted plane, a stepped block, or a target of known step heights	Step heights known to ±1 µm	DOF, telecentricity, telecentric illumination
E9	Diffuse backlight with a controllable, DC-driven source	Uniformity ±3 % over the target; stability ±1 % per 10 min	Backlit target measurement
E10	Integrating sphere or opal-diffuser flat-field source	Uniformity ±1 % over the image circle	Vignetting, sensor compatibility
E11	Industrial camera able to output unprocessed images (see Section 5.3)	Sensor format ≥ the largest format the lens is specified for	All tests
E12	Autocollimator (or a rotation fixture that allows the target to be imaged at 0° and	Angular resolution ≤0.05°	Tilt verification

#	Item	Minimum specification	Used for
	180°)		
E13	Thermometer / temperature logger	Resolution ≤0.1 K, accuracy ≤0.3 K	Test conditions
E14	Software: edge-SFR analysis to ISO 12233, sub-pixel centroid and circle fitting, and a fitting routine for the radial distortion polynomial	Validated against a synthetic target with known SFR	Analysis

Equipment that is normally available only to a lens manufacturer or a metrology laboratory — and that this document therefore does not require: an interferometer for transmitted wavefront, a collimator of known focal length for infinite-conjugate measurement, a nodal-slide bench, or a goniometric spectrophotometer. Where a lens must be characterised at an infinite conjugate, the manufacturer's own data should be used.

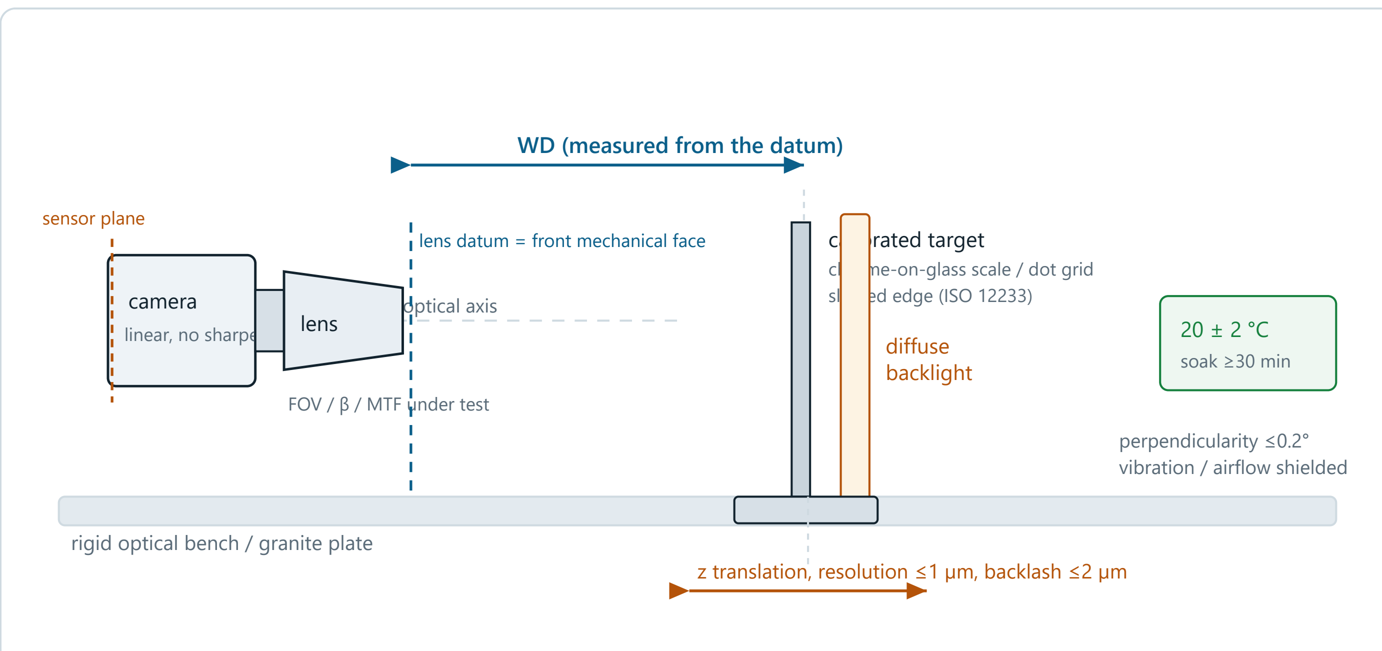

Figure A1. General arrangement of a machine vision optical test bench. WD is measured from the lens datum to the target plane; the target moves in z while camera, lens and illumination stay fixed. Using the frame edge, the total pixel count, or the lens body edge instead of the datum invalidates the result.

7. Performance parameters — master table

#	Parameter	Symbol	Unit	Method section	Primary reported metric	Dominant influence
7.1	Field of view	FOV_O	mm	8.1	FOV width × height at a stated WD and zoom position	β, sensor active area, WD
7.2	Working distance	WD	mm	8.2	Best-focus WD from the stated datum, with the focus band	focus metric, datum definition
7.3	Magnification	β	–	8.3	β at field centre and at field edge, at a stated WD	design, WD, zoom position
7.4	Optical resolution / MTF	MTF50	lp/mm	8.4	MTF50 image side and object side, at ≥5 field points	aberration, aperture, λ, focus
7.5	Pixel resolution	f_Nyq	lp/mm	8.5	Nyquist limit and object-space pixel size	p, β
7.6	System resolution	f_sys	lp/mm	8.5	Combined MTF50 of the lens + sensor	lens + sensor + illumination + motion
7.7	TV distortion	TV	%	8.6	Bowing of the edge line, normalised to image height	design; and the reporting convention
7.8	Geometric distortion	D(x,y)	%	8.7	Max local magnification error over the field, with a distortion map	design, WD, tilt
7.9	Depth of field	DOF	mm	8.8	Object-space DOF for a stated c and criterion	F#, β, c
7.10	Telecentricity	θ_max	mrad / °	8.9	Maximum chief-ray angle over the specified object field	design, WD
7.11	Numerical aperture	NA	–	8.10	NA object side; diffraction cutoff frequency	aperture setting, β
7.12	Parfocality	Δf	mm	8.11	WD shift needed to restore focus after a zoom change	zoom cam design, focus adjustment

#	Parameter	Symbol	Unit	Method section	Primary reported metric	Dominant influence
7.13	Zoom repeatability	σ_z, β_b	µm / ppm	8.12	Position spread and optical spread on returning to a preset	mechanism, encoder, control loop
7.14	Focus repeatability	σ_f	µm	8.13	Spread of the resulting focus position or MTF50	mechanism, autofocus algorithm
7.15	Sensor compatibility	E, IC	% / mm	8.14	Corner relative illumination; image circle diameter	design, sensor size, adapters
7.16	Illumination conditions	–	–	8.15	Type, geometry, telecentricity, uniformity, stability	illumination design
7.17	Calibration status	u_c, U	µm	8.16, 13	Scale factor, distortion map, uncertainty budget	reference standard, procedure

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8. Test methods

Each subsection has the same eight parts. Section 8.1 is written in full as the pattern; later subsections refer back to it rather than repeating general conditions.

8.1 Field of View (FOV)

8.1.1 Definition. The extent of the object plane that is imaged onto the **active** area of the sensor, at a stated working distance and zoom position.

For a system that is distortion-free and paraxial:

```
FOV_H = (N_H × p) / β        [T]        (8.1a)
FOV_V = (N_V × p) / β        [T]        (8.1b)
```

with N in pixels and p in µm (giving FOV in µm; divide by 1000 for mm).

Two warnings that invalidate most published FOV figures:

- **Use N_H, not the total pixel count.** A 2448 × 2048 sensor with 16 optical-black and 8 dummy columns per line does not have 2448 active columns. The error is typically 0.5–2 %, which is larger than the tolerance on many measurement tasks.
- **Use the diagonal only when the sensor is used diagonally.** The frequently seen formula FOV = sensor diagonal / β is a *field coverage* statement (does the image circle cover the sensor?), not a field-of-view statement. Reporting a diagonal FOV as "the FOV" overstates the usable field by 20–30 % and causes integrators to specify a lens that does not cover the part.

8.1.2 Test equipment. E1, E2, E3, E4, E9, E11, E13, E14.

The scale (E4) must be long enough that the full FOV falls *inside* the certified region, with at least two graduations inside each edge of the frame. A scale that only just covers the FOV forces the operator to use the physical end of the scale, whose position is not certified.

8.1.3 Test setup.

1. Mount the lens and camera on the bench (E1); the camera sensor plane parallel to the lens mounting flange within the mechanical tolerance of the mount.
2. Set the target plane at the nominal WD using the z-stage (E2), referenced to the **stated datum** of the lens.
3. Place the calibrated scale (E4) at the target plane, centred, with its graduations horizontal for the measurement of FOV_H. Backlight it (E9) if it is a negative chrome-on-glass scale.
4. Verify perpendicularity per Section 5.4 before taking data.

8.1.4 Test procedure.

1. Set the lens to the zoom or focus setting under test. If the setting is reached by a motor, always approach it from the same direction (Section 8.12).
2. Adjust the exposure so that the graduations are in the linear part of the sensor response and neither the clear nor the chrome regions are clipped.
3. Identify two graduations whose object coordinates x_1 and x_2 are known from the certificate, separated by at least 60 % of the frame width, and both clearly inside the frame. The lines must be *imaged*, not synthesised, and their pixel positions u_1, u_2 determined by sub-pixel centroid of the line profile (fit the line with a first moment or a Gaussian; a threshold-based measurement introduces a half-pixel bias that depends on the illumination).
4. Compute the local scale factor:

```
s = (x₂ − x₁) / (u₂ − u₁)        [M]        (8.1c)
```

in mm per pixel. Take the reciprocal for the pixel size in object space, in µm: L_obj,meas = 1000 / s.

5. Compute the measured FOV from the **active** pixel count:

```
FOV_H,meas = s × N_H        [M]        (8.1d)
```

6. Repeat at four positions across the field (left, centre, right, and the two diagonals if the target allows), so that the variation of the local scale factor across the field becomes visible. **That variation is the distortion** (Section 8.7) and it is the reason a single scale factor is not sufficient for a measurement system.
7. Repeat the whole procedure 5 times, refocusing between repeats, and report the mean and standard deviation.

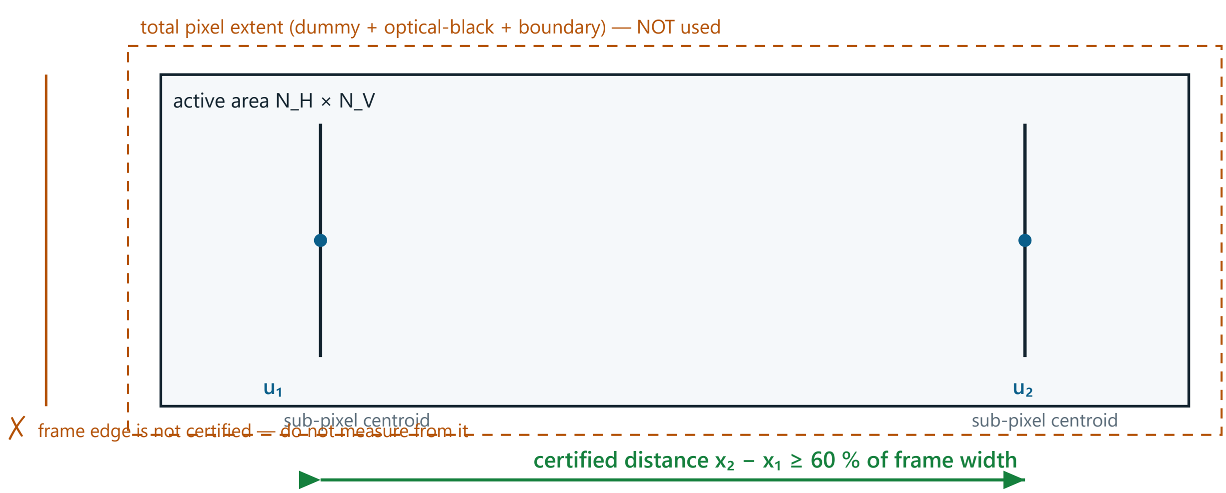

Figure A2. FOV measured from certified graduations inside the frame. **$s = (x_2 - x_1)/(u_2 - u_1)$** gives mm per pixel; **FOV_H = s × N_H** uses the *active* pixel count. Measuring to the frame edge, or using the total pixel count, invalidates the result.

8.1.5 Calculation.

- Object-space pixel size: L_obj = 1000 / s, in µm.
- FOV for an arbitrary region of interest: FOV = s × N_roi.
- FOV sensitivity to working distance (important for non-telecentric lenses): repeat the measurement at WD_nom ± ΔWD (e.g. ±0.5 mm) and report

```
d(FOV)/d(WD) = ΔFOV / ΔWD        [M]        (8.1e)
```

For an ideal object-side telecentric lens this slope is zero up to the measurement uncertainty. A non-zero slope means the system is not object-side telecentric, and every measurement result carries a FOV error proportional to how well the WD is reproduced.

- Magnification from the scale: $\beta = (u_2 - u_1) \times p / (1000 \times (x_2 - x_1))$, with p in µm and x in mm. This is the same quantity as Section 8.3 and must agree with it within the stated uncertainty.

8.1.6 Result recording.

Record	Value
Zoom position / focus setting	
Working distance, with the datum stated	
Active pixel count used (N_H × N_V)	
Pixel pitch and its source (sensor datasheet)	
Measured scale factor s, at centre and at 4 field positions	
FOV_H, FOV_V (measured), mean ± s, n = 5	
Theoretical FOV from equation 8.1a, and the difference	
d(FOV)/d(WD)	
Ambient temperature	
Reference target certificate number and due date	

8.1.7 Common errors.

Error	Effect	Verification	Correction
Using total instead of active pixels	0.5–2 % FOV error	Compare against the camera's own ROI readout	Use the active count from the camera documentation
Measuring FOV at the wrong WD	FOV error proportional to the WD error, up to 1 %/mm for a typical non-telecentric lens	Run the ±ΔWD test (8.1e)	State the WD and, if it varies, report d(FOV)/d(WD)
Using the sensor diagonal as the FOV	20–30 % overstatement	Compare with FOV_H × FOV_V	Report width × height; use the diagonal only for image-circle checks
Measuring from the printed border of a film target rather than the certified graduations	Film targets stretch; 0.1–0.5 % error	Compare the certified distances	Use chrome-on-glass, or certify the film target
Target not flat (film sag, or a scale lying on a non-flat surface)	Local defocus and a scale error that varies across the field	Check the focus metric at the frame edges	Mount the target on a flat reference surface; vacuum or a glass carrier
Threshold-based line position	Half-pixel bias that changes with illumination	Repeated measurement at two exposure levels	Sub-pixel centroid or Gaussian fit
Reading the FOV from the lens's printed "×0.5" marking	Design value, not the as-built value	Compare with the measured scale factor	Always measure
Saturation at the target	Centroid pulled by the flat-topped profile	Check peak grey value	Keep the peak at 60–80 % of full scale

8.1.8 Engineering interpretation.

- **A FOV specification is only comparable if the sensor format, the active pixel count, the WD and the measurement plane are the same.** Require all four when comparing two suppliers' data.
- Use the **inscribed circle**, not the corners, when specifying the field for a circular part: FOV_circle = min(FOV_H, FOV_V). For a 2/3" sensor at 1× the inscribed circle is 8.4 mm, not 11.0 mm.
- Add a working margin: a part that exactly fills the FOV cannot be measured at its edges, because distortion, vignetting and edge MTF are all worst there. A practical target is that the part occupies ≤80 % of the FOV_H and is fully inside the 0.9-field radius.

- If the required FOV cannot be achieved with an object-side telecentric lens at the required magnification, this is a design conflict, not a lens selection problem: FOV and β are linked by equation 8.1a. The available responses are (i) a larger sensor, (ii) a different β, or (iii) accepting a non-telecentric system with the height-variation error quantified per Section 10.3.
- **[POMEAS LAB TEST DATA REQUIRED — FOV-01]** Measured FOV and d(FOV)/d(WD) for each POMEAS telecentric and motorized zoom model at its specified WD, with the actual active pixel counts of the standard POMEAS test cameras. See Appendix B for the register of all such values, and the companion deliverable *TR-001 Laboratory Test Data Plan* for the experiment design.

8.2 Working Distance (WD)

8.2.1 Definition. The distance from the manufacturer's reference plane to the object plane at which the system is in best focus.

Three different quantities are commonly called "working distance" and must not be confused:

Quantity	Meaning	Typical treatment
WD (nominal)	The design value, quoted in the datasheet	A single number, e.g. 110 mm
WD (best focus, measured)	The value at which *this* assembly actually focuses	Measured per this section
Focus band	The range of WD over which the focus metric stays above the acceptance threshold	Derived from this section; the practical tolerance for the mounting of the station

8.2.2 Test equipment. E1, E2, E4 or E6, E9, E11, E13, E14.

8.2.3 Test setup. Mount a slanted-edge target (E6) or a scale (E4) on the z-stage. Ensure the stage travel covers WD_nom ± (2 × the expected focus band). Align per Section 5.4. Set the illumination and the camera once and do not touch them for the rest of the series.

8.2.4 Test procedure.

1. Approach WD_nom from below (from the lens side) to eliminate backlash.
2. Step the stage in increments of Δz = band_expected / 10 along z. At each step, capture one frame and compute the focus metric M(z) — this document uses MTF50 of the central slanted edge (E14), or, if MTF analysis is unavailable, the normalised gradient energy of a high-contrast region. **Do not change exposure between steps**; a metric computed on differently exposed frames is not comparable.

3. Continue until M(z) has decreased to 50 % of its peak on both sides.
4. Fit a parabola to the 5–7 points around the peak (or a Gaussian, which is often a better model for the through-focus MTF of a real lens):

```
M(z) ≈ M_max − a (z − z₀)²        [M]        (8.2a)
```

and solve for the vertex z_0.

5. Best-focus WD = z_0 (referenced to the datum).
6. **Focus band.** Find the two axial positions at which M(z) falls to the acceptance threshold M_thresh, and report the band as $z_+ - z_-$. The threshold must be tied to the application: a common choice is M_thresh = 0.8 × M_max for a measurement task, and 0.5 × M_max for a detection task.
7. Repeat 5 times, approaching from below each time; report the mean and standard deviation of z_0.

8.2.5 Calculation.

- Object-space focus band from the geometric DOF formula (8.8a), for comparison with the measured band.
- WD error sensitivity: for a non-telecentric lens, the magnification error caused by a WD error Δz is $\Delta\beta/\beta \approx \Delta z \times (d\beta/dz)/\beta$, measured per Section 8.3.5. For a typical 0.5× FA lens, a 1 mm WD error changes β by roughly 0.5–1 %, i.e. a 100 mm measurement changes by 0.5–1 mm. **For an object-side telecentric lens the same WD error changes β by ≈0**, which is exactly what the user is buying.

8.2.6 Result recording. Datum definition; stage readout value at best focus; measured WD; focus band with its threshold; number of repeats with mean and s; temperature; and the target and camera used.

8.2.7 Common errors.

Error	Effect	Correction
Measuring to the front edge of the barrel rather than the front vertex / the manufacturer's datum	Systematic offset, often 2–10 mm	Photograph the datum with a scale; align the datum definition with the datasheet
Measuring to the cover glass of a target that has one	Offset equal to the glass thickness divided by the refractive index	Measure on an uncovered chrome-on-glass target, or subtract n·t
Assuming the z-stage readout is the WD	Readout origin is arbitrary	Establish the origin against the lens datum with a gauge block or a height gauge
Exposure changed between steps	The focus curve is distorted and the peak is displaced	Fix exposure; verify with a reference frame
Backlash in the z-stage	Hysteresis in the focus curve	Always approach from the same direction, or report both directions
Temperature drift during the sweep	Apparent focus shift	Thermal soak; keep the series short; record the temperature at the start and end

8.2.8 Engineering interpretation. The nominal WD is a *design* number; the mounting of the station should reproduce the measured best-focus WD, not the nominal one. The difference between the two is a useful incoming-inspection item: if it exceeds the focus band, the mechanical interface of the station will need adjustment. For a motorized zoom lens, the WD at which focus is set must be the WD at maximum zoom (Section 8.11), because the DOF is smallest there and a focus error is most visible.

8.3 Magnification (β)

8.3.1 Definition. The ratio of image size to object size:

```
β = (n_px × p) / L_obj        [M]        (8.3a)
```

where n_px is the number of pixels between two features, p the pixel pitch in μm and L_obj the corresponding object distance in μm.

Note that for a lens with a specified magnification, β is defined **at the design working distance**. Reporting β without WD is incomplete: for a non-telecentric lens the two are coupled, and for a telecentric lens β is nominally independent of WD — the residual dependence is a direct measure of the telecentricity error (Section 8.9).

8.3.2 Test equipment. E1, E2, E4, E9, E11, E14.

8.3.3 Test setup. Calibrated scale (E4) at the target plane, centred and perpendicular. Prefer a line scale with lines of 3–10 μm width, whose centroid can be determined to better than 0.1 pixel.

8.3.4 Test procedure.

1. Choose two graduations separated by **at least 60 % of FOV_H**. The relative error of β is dominated by the relative error of the measured pixel count; a short baseline wastes the available accuracy. With a 2448-pixel sensor and sub-pixel centroids of 0.05 px, a 60 % baseline gives a relative uncertainty of about 0.007 %; a 10 % baseline gives about 0.04 %.
2. Compute the pixel positions u_1, u_2 by sub-pixel centroid.
3. $\beta_{centre} = (u_2 - u_1) \times p / L_{certified}$.
4. Move the scale so that the same two graduations now straddle a field position at 0.7 × FOV_H/2, and repeat → β_edge.
5. Repeat at 0.7 field in four directions (up, down, left, right).
6. Repeat the whole set 5 times at fixed WD; report the mean and s for each position.
7. **WD dependence.** Repeat steps 3–5 at WD_nom ± 0.5 mm and ±1.0 mm. Fit β(z) and report dβ/dz in %/mm and the corresponding Δβ for a 1 mm WD error.

8.3.5 Calculation.

- Object-space pixel size: $L_{obj} = p / \beta$.
- **Magnification error from a WD error:**

```
Δβ/β = (1/β) × (dβ/dz) × Δz        [M]        (8.3b)
```

- **Field-dependent magnification** (this is the distortion):

```
D(x) = (β(x) − β_centre) / β_centre × 100 %        [M]        (8.3c)
```

- **Perspective magnification for a non-telecentric lens [T]:** for a chief-ray angle θ at the field point, an object at height h above the nominal measurement plane is imaged with an apparent lateral shift of $h \cdot \tan\theta$ and an apparent magnification change of approximately $(h \cdot \tan\theta)/x$, where x is the distance of the feature from the axis. This is the single most common source of gross measurement error in machine vision, and Section 10.3 gives the decision threshold.

8.3.6 Result recording. β at centre and at four 0.7-field positions; the certified distance used and the certificate number; WD; zoom position; dβ/dz; repeat count and s; temperature.

8.3.7 Common errors.

Error	Effect	Correction
Short measurement baseline	Multiplied relative error	Use ≥60 % of FOV
Using the nominal printed length of the target rather than the certified value	0.01–0.1 % systematic error	Use the certificate
Film target that has stretched or been mounted under tension	0.05–0.5 % error, and anisotropic	Use chrome-on-glass
Approaching a motorized zoom position from different directions	β differs by the backlash	Always approach from the same direction (8.12)
Fitting β from the frame edges only	Reports the edge magnification, not the centre value	Measure the centre separately, and report both
Assuming β applies at all working distances	Error equal to dβ/dz × Δz	Measure dβ/dz

8.3.8 Engineering interpretation. For a measurement system, what matters is not β itself but the **measured scale factor** s (mm/pixel) and its stability. β is a useful cross-check against the datasheet and a useful diagnostic: a β that differs from nominal by more than the combined uncertainty indicates that the WD is wrong, the sensor pixel pitch assumption is wrong, or the lens is not the model it is claimed to be. Report β and s together, and state the field position for both.

8.4 Optical Resolution and MTF

8.4.1 Definition. The ability of the lens to transfer contrast from the object to the image as a function of spatial frequency. The modulation transfer function MTF(f) is the modulus of the optical transfer function; it is dimensionless, from 1 at zero frequency to 0 at the cutoff. Three ways of reducing MTF to a single number are in common use:

Metric	Definition	Where it is appropriate
MTF50	The spatial frequency at which MTF = 0.50	The standard comparative metric; correlates well with perceived sharpness and with the smallest reliably detectable feature
MTF at a specified frequency	e.g. MTF at 100 lp/mm	The appropriate metric when the application has a *known* feature frequency. Preferable to MTF50 for a specification, because it is not affected by the shape of the curve far from the working frequency
Limiting resolution	The highest frequency at which MTF exceeds a stated threshold (e.g. 0.05 or 0.10)	Useful for a rough "can it see it" assessment; sensitive to the threshold, so the threshold must always be quoted

The diffraction limit for incoherent illumination is:

```
f_cut = 2 × NA / λ        [T]        (8.4a)
```

with NA on the same side as f_cut and λ in mm. With NA_obj = 0.1 and λ = 0.55 µm, f_cut,object = 364 lp/mm; the image-side cutoff is f_cut,obj / β.

8.4.2 Test equipment. E6 (ISO 12233 slanted edge or certified Siemens star), E1, E2, E11, E9, E13, E14.

8.4.3 Test setup.

1. Mount the slanted-edge target at the target plane, at the exact WD, perpendicular to within 0.1° (an edge that is imaged with tilt is imaged at a different magnification across its length, which biases the SFR).
2. Use a **narrow-band** source (λ = 0.55 µm ±20 nm) for the reported measurement. If the application is white light, additionally report a white-light measurement and label it as such; expect a lower MTF50 due to chromatic aberration.
3. Set the edge angle between 2° and 7° from vertical. Outside this range the ISO 12233 algorithm's phase averaging loses accuracy; near 0° the edge aliases.
4. Position the edge so that its analysed length covers at least 10 pixels and it does not run into a corner region where perspective or vignetting changes the local magnification.
5. Focus at the centre of the field using the same slanted edge before moving to other field points. Record the focus position.

8.4.4 Test procedure.

1. Capture the edge. Confirm: no clipping, peak signal 70–80 % of full scale, background above black level but below 10 % of the peak. Confirm the camera settings of Section 5.3 are in force.
2. Apply the ISO 12233 e-SFR algorithm: locate the edge, project the pixels onto the edge normal direction, bin them into the oversampled edge profile, differentiate to obtain the line spread function (LSF), and take the modulus of the Fourier transform of the LSF to obtain the SFR. The phase averaging over the edge length is what makes the method robust to noise.
3. Apply the correction for the finite pixel aperture if the standard's method requires it (the pixel's own integration over its area acts as a low-pass filter with a sinc response). Report whether this correction was applied.
4. Read off MTF50, and MTF at the target working frequency.
5. Repeat at: field centre; the four 0.7-field positions (up, down, left, right); and the four corners. Report a table, not a single number, plus the ratio of the worst field point to the centre.
6. Where the lens is astigmatic, measure MTF50 separately for the sagittal and tangential orientations at each field point and report both.
7. Repeat the centre measurement 5 times, refocusing between repeats. The spread of MTF50 across repeats with refocusing is the *focus-related* reproducibility of the measurement and is normally larger than the within-focus repeatability.
8. **Convert to object space** for the application:

```
f_obj = β × f_img         [T]        (8.4b)
w_obj = 1000 / (2 × f_obj)   µm     [T]        (8.4c)
```

where w_obj is the width of one line pair (line + space) that the lens resolves at that frequency. If the application's smallest feature is w_obj or smaller, the lens is marginal; a factor of 2–3 in hand is normal engineering practice.

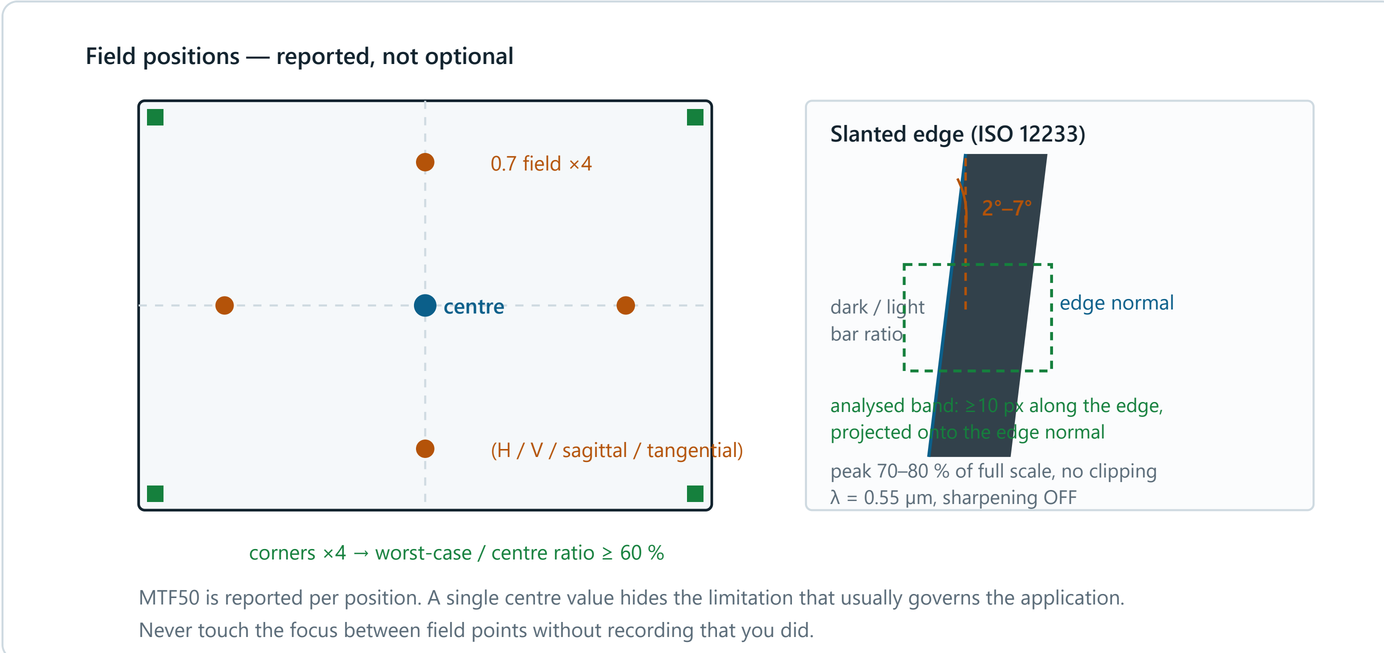

Figure A3. Slanted-edge resolution test. MTF50 is reported at the centre, at 0.7 field in four directions, and at the four corners. The edge angle must stay between 2° and 7° from vertical for the phase-averaging in the ISO 12233 algorithm to remain accurate.

8.4.5 Calculation.

- Object-side MTF50: $f_{50,obj} = \beta \times f_{50,img}$.
- Object-side limiting resolution from equation 8.4a.
- **Consistency check:** $f_{50,obj}$ must not exceed $f_{cut,obj}$. A value above the diffraction limit is a measurement artefact (usually sharpening left on, or a stale focus position).
- Field uniformity metric: MTF50_min across the measured field points, divided by MTF50_centre. Report as a percentage. A lens with a uniform 70 % across the field is often a better choice for a vision system than one with 100 % at the centre and 30 % at the corner.

8.4.6 Result recording. Table of MTF50 (and MTF at the stated frequency) for each field position and orientation; λ; f-number; WD; zoom position; whether the pixel-aperture correction was applied; objective and camera; focus metric used; repeat statistics for the centre; and the diffraction limit for comparison.

8.4.7 Common errors.

Error	Effect	Correction
Sharpening or noise reduction left on	MTF50 overstated by 10–100 %; a completely invalid number	Verify with a raw capture; disable in the camera and in the driver
Gamma ≠ 1	The edge profile is distorted; MTF50 biased, usually high	Linearise
Non-uniform illumination across the analysed edge	The effective edge contrast varies along the edge; the phase-averaged profile is smeared	±5 % uniformity; check the flat field
Edge angle outside 2°–7°	Algorithm error; aliasing	Adjust the target rotation
Target not at best focus, or focus not re-set between field points	Understates MTF50, sometimes by a factor of 2	Refocus at each point, or verify that the field curvature is smaller than the DOF
Measuring only at the centre	Hides the field dependence, which is what usually limits the application	Always report the field map
Using a USAF target for a reported MTF number	Bar-width targets give a visual limit, not an SFR	Use slanted-edge ISO 12233 for reported values; USAF for screening only
Comparing MTF50 measured at different f-numbers	The aperture dominates the result	Always quote F#
Reporting an object-side resolution without the magnification	Not reproducible	Report both sides, and β

8.4.8 Engineering interpretation. Resolution is a *system* property, not a lens property (Section 8.5). The lens MTF sets the ceiling; the sensor's pixel aperture and sampling set a second ceiling; motion blur and the algorithm set a third. When a system fails to resolve a feature, the useful diagnostic sequence is: (1) confirm the focus at the feature's plane; (2) compare the feature's image-side frequency with the sensor's Nyquist — if it is above Nyquist, the sensor is the limit, and adding optical resolution will not help; (3) if it is well below Nyquist, measure MTF50 and check it against the diffraction limit; (4) only then consider the lens. A lens whose MTF50 is within 30 % of the diffraction limit for its aperture is performing as designed, and no amount of lens replacement will produce a large gain.

8.5 Pixel Resolution and System Resolution

8.5.1 Definition.

- **Pixel (sampling) resolution, image side**, is the Nyquist frequency of the sensor:

```
f_Nyq,img = 1000 / (2 p)        [T]        (8.5a)
```

with p in µm. For p = 3.45 µm, f_Nyq = 145 lp/mm. For p = 5.5 µm, 91 lp/mm. For p = 2.4 µm, 208 lp/mm. - **Pixel resolution, object side**:

```
f_Nyq,obj = β × 1000 / (2 p) = 1000 / (2 L_obj)        [T]        (8.5b)
```

- **Smallest object detail** that can be sampled: one line pair occupies 1000/f_Nyq,obj µm = 2·L_obj. A practical design rule is to place **≥3 pixels** across the smallest feature to be *detected*, and **≥5 pixels** across the smallest feature to be *measured*, i.e. L_obj ≤ d/3 and L_obj ≤ d/5 respectively.
- **System resolution** is the combined capability of lens + sensor. Because the two transfer functions multiply, and because a Gaussian MTF is a good approximation for both over the range of interest, the reciprocals of the squared MTF50 values add:

```
1 / f50,sys² ≈ 1 / f50,lens² + 1 / f50,sensor²        [T]        (8.5c)
```

Equation 8.5c is exact for Gaussian MTFs and a good engineering approximation in general. Its practical message: **the weaker of the two dominates, and making the stronger one better buys very little.** A lens at 200 lp/mm with a sensor at 90 lp/mm gives 82 lp/mm — better than the sensor alone by 9 %, but nowhere near 200.

Motion blur, illumination and the algorithm each multiply in the same way. For a system with an exposure time t and an object-space velocity v, the blur is v·t; if this exceeds L_obj, it will dominate everything else and must be fixed mechanically before any optics work is done.

8.5.2 Test equipment. E1, E2, E6, E11, E14, plus a way to induce a known motion (a conveyor or a rotating target) if the motion-blur term is to be measured.

8.5.3 Test setup. As Section 8.4, with the sensor at its working format and binning off.

8.5.4 Test procedure.

1. Measure f50,lens per Section 8.4 with the lens at the setting under test.

2. Determine f50,sensor. Two acceptable routes: (a) take it from the camera supplier's EMVA 1288-based characterisation, if the sensor MTF is reported; (b) measure it directly by imaging the same slanted edge onto the sensor with a *better* lens — a diffraction-limited macro lens at a small aperture, whose f50 exceeds the sensor's Nyquist — and computing the SFR of the sensor + reference lens.
3. Compute f50,sys from equation 8.5c and compare with a direct measurement of the whole chain. The difference is the model error, typically 5–15 %.
4. Compute the working margins: - **Detection margin:** M_det = f_Nyq,obj / f_required, where f_required = 1000/(3 × d) for a feature size d. M_det should be ≥1.3. - **Measurement margin:** M_meas = f_Nyq,obj / (1000/(5 × d)) for a measured feature. M_meas should be ≥1.3.
5. Where the object moves, add the motion term: f_motion ≈ 1000/(2 × v × t) and combine per equation 8.5c.
6. **[POMEAS LAB TEST DATA REQUIRED — RES-02]** A measured lens + sensor matrix for the standard POMEAS camera/lens pairings (for example: a 5 MP 2/3" sensor at 3.45 μm with each POMEAS telecentric model, and a 16 K line-scan sensor with the line-scan and large-format lens families), giving f50,lens, f50,sensor, f50,sys and the model error of equation 8.5c. This is the single most reusable dataset POMEAS can produce, because it answers "which lens for which camera" with evidence rather than with a rule of thumb.

8.5.5 Calculation. Equations 8.5a–8.5c, plus the conversion L_obj = p/β, plus the standard "N pixels per feature" rules.

8.5.6 Result recording. p and its source; active format; binning state; f50 for lens, sensor and system (measured and modelled); the field position; motion parameters if applicable; and the margins.

8.5.7 Common errors.

Error	Effect	Correction
Treating pixel count as resolution	A 45 MP sensor with a poor lens resolves less than a 5 MP sensor with a good one	Compare f50 values, not megapixels
Using the sensor's Nyquist as if it were achievable	Real systems reach 60–80 % of Nyquist, not 100 %	Use f50,sys, or apply an engineering factor
Ignoring the motion term	The predicted resolution is unachievable on a moving line	Measure or calculate the motion blur explicitly
Comparing object-side resolutions at different magnifications	Higher β always improves object-side resolution and says nothing about lens quality	Compare image-side values, or state β
Using the diagonal for the sampling calculation	Non-square sensors and anisotropic sampling are mis-modelled	Work in N_H and N_V separately

8.5.8 Engineering interpretation. The design sequence is: (1) smallest feature to be detected or measured; (2) required object-space pixel size from the 3-pixel / 5-pixel rules; (3) β = p / L_obj; (4) FOV = sensor size / β, checked against the part; (5) if FOV and L_obj cannot both be satisfied, the sensor must be changed — **not** the lens alone, because equations 8.1a and 8.5b are both set by the same pair of numbers. Step 5 is where most machine vision selection errors occur, and it is the reason a lens selection cannot be done without the camera.

8.6 TV Distortion

8.6.1 Definition. TV distortion is a shape descriptor inherited from television-optics testing and is still quoted by most machine-vision lens suppliers. In its most common form, a nominally straight line at the edge of the field is imaged; the imaged line bows; and the sagitta of the bow is normalised to the image height:

```
TV = (Δy / H) × 100 %        [convention]       (8.6a)
```

where Δy is the maximum deviation of the imaged line from a least-squares straight line fitted to the same imaged line, and H is the full image height (greater dimension of the active area, usually the vertical).

The convention is not standardised, and this matters. Three variants are in simultaneous use:

Variant	Normalisation	Measured where	Consequence
A	Δy / H	Line at the field edge	The values most often published
B	Δy / (2H)	Line at the field edge	Exactly half of variant A for the same lens
C	Δy / H	Line at 0.8 × half-height, not at the edge	Typically 20–40 % below variant A

Two suppliers can therefore quote 1.0 % and 0.5 % for the same lens. **Never compare TV distortion values across suppliers unless the variant is stated**, and never use TV distortion as the specification for a dimensional measurement system.

8.6.2 Test equipment. E1, E3, E5 (or a square grid / a bar target), E9, E11, E12, E14.

8.6.3 Test setup.

1. Mount a square grid or a target with straight lines at the field edges at the exact WD.
2. Verify perpendicularity to 0.2° per Section 5.4. **A tilt is indistinguishable from distortion in this test** — it produces a linear magnification gradient that the line-fit will convert into an apparent bow.
3. Align the grid axes to the sensor axes to within 0.5°.
4. Keep the peak signal at 60–80 % of full scale; a saturated line has a flattened profile and a biased centroid.

8.6.4 Test procedure.

1. Capture the target.
2. Extract the centre-line of the chosen horizontal line across at least 80 % of the image width, at sub-pixel resolution. Fit a least-squares straight line to the extracted centre-line.
3. Compute the maximum deviation Δy from the fitted line, and its position along the line (the position matters: a bow whose maximum is not near the centre of the line indicates non-symmetric handling or a tilted target).
4. TV = Δy / H × 100 %. State which variant and which line.
5. Repeat for a vertical line at the field edge and for the symmetric lines on the opposite side. A symmetric pair should give the same magnitude with opposite sign; an asymmetric result indicates decentring.
6. Repeat 5 times with refocusing; report the mean and s.

8.6.5 Calculation. Equation 8.6a. If the supplier's convention is unknown, report the raw sagitta Δy in pixels and in µm, alongside H — that data can be converted to any convention.

8.6.6 Result recording. Which line (position, orientation, which edge); Δy in µm and px; H in px and mm; the convention used; WD; zoom position; the fit residuals; temperature.

8.6.7 Common errors.

Error	Effect	Correction
Target tilt	Apparent distortion, typically 2–5× the real value	Verify with the 0°/180° test of Section 5.4
Using the target's printed frame edge as "the line"	The frame edge is not a straight line to µm accuracy	Use a chrome line intended for the purpose
Quoting a figure without the convention	Not comparable	Report Δy and H as raw data
Saturated line	Biased centre-line	Keep the peak at 60–80 %

8.6.8 Engineering interpretation. TV distortion answers the question "*will a straight edge look bent in my image?*". It is the right metric for cosmetic inspection and for image-comparison algorithms. It does **not** answer the question "*how large is my measurement error at the edge of the field?*" — that requires the full-field local-magnification map of Section 8.7. The two correlate loosely, and a lens can be acceptable by one and unacceptable by the other. Report both when a measurement application is being specified.

8.7 Full-field Geometric Distortion

This subsection provides the metric that should be used for measurement applications. Its principle follows the distortion determination described in ISO 9039:2008 for rotationally symmetric imaging systems; the procedure below is adapted to a machine-vision camera and lens and is not a claim of conformance to that document.

8.7.1 Definition. Distortion is the variation of magnification over the field. The metrologically useful expression is the **relative local-magnification error**, referenced to the magnification at the field centre:

```
D(x, y) = [ β(x, y) − β_centre ] / β_centre × 100 %        [M]        (8.7a)
```

For a measurement system this is the quantity that matters, because the measurement error of a feature located at field position (x, y) is:

```
Δx_meas ≈ D(x, y) / 100 × x        [T]        (8.7b)
```

That is: a lens with D = 0.5 % at the field edge produces a 250 µm error on a feature 50 mm from the centre — regardless of how small its TV distortion looks. **Distortion does not blur; it displaces.** This is why distortion is irrelevant to presence/absence detection and decisive for dimensional measurement.

The commonly used radial model (Brown–Conrady form, the basis of most camera-calibration implementations) is:

```
r_u = r_d (1 + k1 r_d² + k2 r_d⁴ + k3 r_d⁶)        [model]        (8.7c)
```

where r_d is the measured (distorted) image radius and r_u the ideal (undistorted) radius, both normalised; $k1 < 0$ indicates barrel distortion, $k1 > 0$ pincushion. Equation 8.7c is a model, not a measurement: fitting it to insufficient field points produces coefficients that extrapolate badly.

8.7.2 Test equipment. E1, E2, E3, E5 (dot grid or chessboard, ≥15 × 15 nodes, node position uncertainty ≤3 µm), E9, E11, E12, E14.

8.7.3 Test setup.

1. Mount the calibrated grid at the exact best-focus WD, perpendicular to within 0.1°.
2. The grid must cover at least 1.2 × the FOV so that every analysed node is a certified node, not a partially imaged one.
3. Centre the grid on the optical axis to within 1 % of FOV.
4. Use diffuse backlighting for a chrome-on-glass grid; verify the chrome is opaque at the exposure used.
5. Fix the camera settings. The centroid of a node depends on the exposure if the node image is saturated.

8.7.4 Test procedure.

1. Capture the grid. Confirm no saturated nodes and no clipped shadows.
2. Detect every node: threshold to obtain the node blobs, then compute sub-pixel centroids (intensity-weighted first moment, or a 2D Gaussian fit). A binary-value centroid has a

quantisation bias of up to ±0.3 px.

3. Identify the node nearest the image centre → the reference node.
4. **Determine the local scale factor around each node** using its nearest neighbours in x and y:

```
s_x(i,j) = (X(i+1,j) − X(i−1,j)) / (u(i+1,j) − u(i−1,j))        [M]        (8.7d)
```

where X are the certified object coordinates of the nodes in mm and u are the measured pixel coordinates. Repeat for s_y using the j neighbours. The use of neighbours rather than a global fit is what makes this a *local* magnification measurement, and it is what exposes distortion that a global fit would average away. 5. Convert to local magnification: β(i,j) = Δu × p / ΔX, using p in µm and ΔX in µm. 6. Compute D(i,j) from equation 8.7a with β_centre taken from the four nodes nearest the axis. 7. Report: D_max (with its field position), the D contour over the field, the ratio of the magnification at the corner to that at the centre, and the residual after applying a fitted correction. 8. Repeat 5 times; the spread of D_max is the repeatability of the distortion measurement, which is normally limited by node centroiding rather than by the lens. 9. Repeat the whole test at WD_nom ± 0.5 mm. A distortion map that changes significantly with WD indicates either a non-object-side-telecentric system or a tilt that varies with WD.

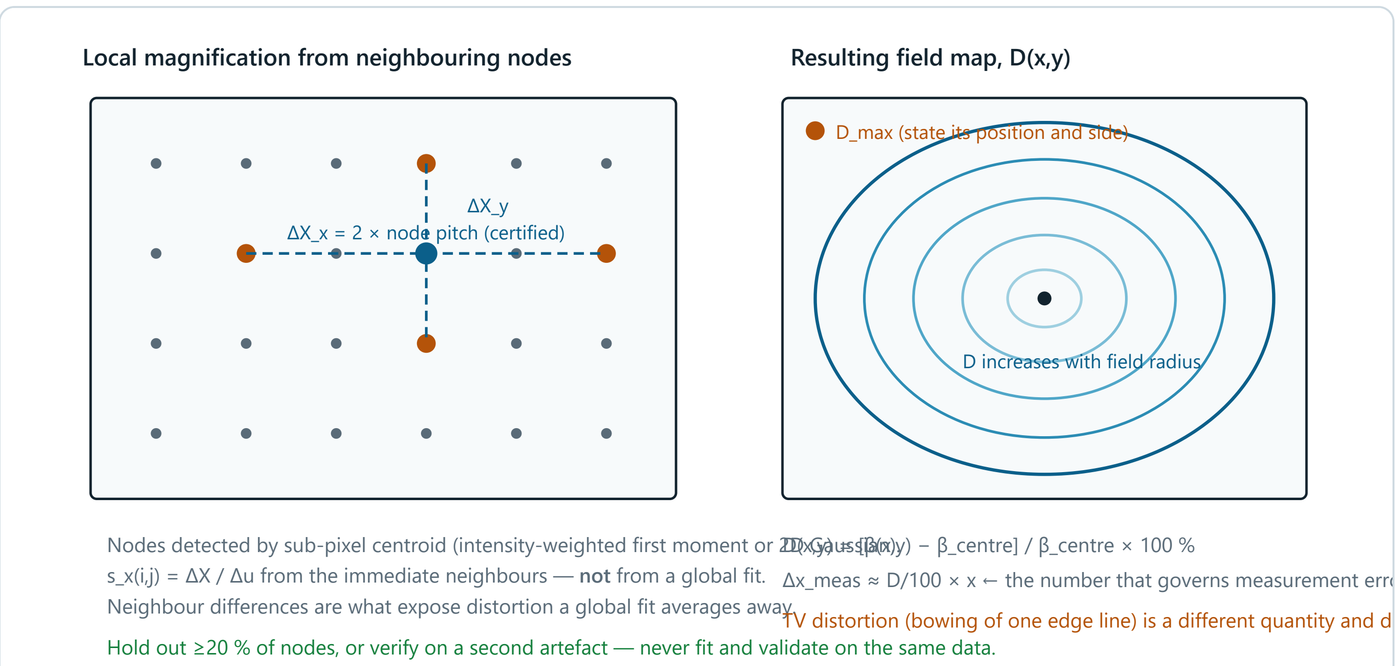

Figure A4. Full-field distortion from a calibrated grid. Local magnification is computed from neighbouring nodes, not from a global fit. The map is what supports a measurement claim; TV distortion answers only whether a straight edge looks bent.

8.7.5 Calculation.

- Equations 8.7a–8.7d.
- **Residual correction:** fit equation 8.7c to the measured node displacements by least squares, then apply the inverse mapping to the node positions and recompute D. The remaining |D| is the *corrected* distortion, and it is the number that should be quoted for a measurement system that applies calibration. Report both the uncorrected and the corrected values, with the order of the polynomial and the number of nodes used. A correction fitted on 20 nodes and evaluated on the same 20 nodes will always look excellent; **always validate on a hold-out set of nodes or on a different artefact**.
- **Maximum measurement error over the field** for a stated feature position, from equation 8.7b, using the *uncorrected* D if no calibration is applied and the *corrected* D if one is.

8.7.6 Result recording. Grid certificate number and node pitch; $N_H \times N_V$; p; WD; zoom position; number of nodes detected and the number used for the fit; number held out for validation; k coefficients with the fit residual; D_{max} before and after correction, with field positions; temperature.

8.7.7 Common errors.

Error	Effect	Correction
Fitting the distortion model on all nodes and reporting the residual on the same nodes	A grossly optimistic corrected value	Hold out ≥20 % of nodes, or validate on a separate artefact
Using too few field points	The fitted polynomial is unconstrained at the field edge, where the error is largest	≥15 × 15 nodes, with nodes out to ≥0.95 of the field radius
Target tilt	Adds a linear magnification gradient that the fit absorbs into the coefficients	Perpendicularity to 0.1°
Target at the wrong WD	For non-telecentric lenses the distortion map changes with WD; the map then applies only to that WD	Measure at the operating WD
Saturated nodes	Centroid biased toward the blob's flat region	Keep the peak at 60–80 % of full scale
Global fit instead of local neighbour differences	Averages the distortion over the field and reports a falsely low value	Use equations 8.7d
Assuming a camera has no distortion	A lens measured with a camera that has its own distortion yields the *combined* map, which is still usable for measurement but must not be quoted as the lens specification	State whether the reported map is lens-only or system; for a lens-only figure, use a camera and mount verified to contribute <0.05 %
Applying a distortion correction and assuming the FOV and scale factor are now exact	The centre scale factor is a separate calibration with its own uncertainty	Calibrate the scale factor independently (Section 8.16)

8.7.8 Engineering interpretation. - **Use distortion at all only when you measure.** For a go/no-go inspection, distortion displaces the image but does not change the presence or absence of a feature; a 2 % distortion is harmless. - **For measurement, D is a first-order error, not a second-order one.** The decision rule used in this document is that the uncorrected maximum distortion error over the working field must be ≤1/10 of the measurement tolerance, or the distortion must be corrected by calibration with a validated residual. If neither holds, the accuracy claim is not supported. - **Distortion correction and lens selection are alternatives, not complements.** A well-behaved lens plus calibration can beat an expensive near-distortion-free lens on total system accuracy, because calibration is cheap and repeatable while lens distortion is fixed. The exception is a system that cannot be calibrated per unit (for example, a lens that will be swapped in the field), where low intrinsic distortion is the only safe choice. - **[POMEAS LAB TEST DATA REQUIRED —**

DIS-03] A published, corrected distortion map for each POMEAS telecentric model (D_max before and after correction, with the hold-out validation residual) and for the motorized zoom family *at each preset zoom position*, since a zoom lens has a different distortion map at every magnification. This is a claim no competitor currently supports with data, and it is directly usable by integrators.

8.8 Depth of Field (DOF)

8.8.1 Definition. The range of object positions along the optical axis over which the image is judged acceptably sharp. DOF is only defined together with **two** parameters that must always be stated:

1. the **acceptable blur**, expressed either as a circle of confusion *c* at the image plane, or as an acceptance threshold on a measured metric; and
2. the **criterion** — geometric (a stated c) or measured (a stated threshold on MTF50 or on feature contrast).

Geometric DOF (object side):

```
DOF_total = 2 × F# × c × (1 + β) / β²        [T]        (8.8a)
```

with F# the lens's f-number, c the permitted image-side blur diameter and β the magnification. For $\beta << 1$ this reduces to the commonly quoted DOF ≈ $2 \cdot F\# \cdot c/\beta^2$.

Equivalent form using the object-side blur:

```
DOF_total = c_obj / NA_obj,   with c_obj = c / β        [T]        (8.8b)
```

Worked example (illustrative, not a POMEAS specification). A telecentric lens at β = 2, F# = 8, on a sensor with p = 3.45 µm, with an acceptance criterion of c = 2 px = 6.9 µm:

```
DOF_total = 2 × 8 × 0.0069 mm × (1 + 2) / 2² = 0.0414 mm ≈ 41 µm
```

The same lens at β = 0.5 with the same criterion:

```
DOF_total = 2 × 8 × 0.0069 × 1.5 / 0.25 = 0.662 mm ≈ 662 µm
```

This 16× difference over a 4× magnification change (β^2 in the denominator, partly offset by $(1+\beta)$) is the single most important fact about DOF in machine vision: **DOF collapses rapidly with magnification**, which is why a zoom lens is focused at its maximum magnification and why a high-magnification telecentric system needs a mechanically flat part.

8.8.2 Test equipment. E1, E2, E6 or E8, E11, E14. The z-stage is critical: resolution ≤ DOF_expected/20.

8.8.3 Test setup. Mount a slanted edge or a fine-detail region of interest on the z-stage, centred in the field. Set the lens to the magnification and aperture under test. Establish best focus per Section 8.2 and record z_0.

8.8.4 Test procedure.

1. Set the step size to Δz = DOF_expected / 10 (from equation 8.8a, using a c equal to the acceptance criterion).
2. Start at $z_0 - 1.5 \times$ DOF_expected, approaching from the outside, and step toward $z_0 + 1.5 \times$ DOF_expected. At each step capture one frame and compute the metric. **Do not change the exposure or the focus between steps.**
3. Plot the metric against z. The result is a through-focus curve.
4. Determine the two axial positions z_- and z_+ at which the metric equals the acceptance threshold, interpolating between the bracketing steps.
5. DOF_measured = $z_+ - z_-$.
6. Report the peak metric value as well: a low peak indicates that the system never reaches the required sharpness anywhere, in which case the DOF figure is meaningless.
7. Repeat the sweep 3 times, approaching from the same direction, and report the mean and s of DOF_measured.
8. Optionally repeat at two aperture settings to confirm the F# dependence of equation 8.8a — this is a useful validation of the whole measurement chain, because a DOF that does not scale approximately with F# indicates that something other than geometry is governing (see 8.8.7).

8.8.5 Calculation.

- Equation 8.8a for the geometric prediction; the ratio DOF_measured / DOF_predicted is a measure of how much the model is missing. Values between 0.6 and 1.2 are normal. A ratio below 0.5 usually indicates that aberrations, not geometry, are limiting the system.

- Convert a measured DOF given at one β to another β using the β^2 dependence, as a first estimate only.
- Where the illumination is oblique, the effective DOF for a *feature* may be smaller than the DOF for a *flat target*, because the shadow moves across the feature as z changes. This is a system effect, not a lens effect, and it must be measured with the production illumination.

8.8.6 Result recording. The criterion and the threshold value; the c used; F#; β; the metric used; the step size; the measured DOF with mean and s; the peak metric; the geometric prediction and the ratio; illumination geometry; temperature.

8.8.7 Common errors.

Error	Effect	Correction
Reporting DOF without c or without a threshold	The number cannot be interpreted or compared	Always report the criterion
Changing the illumination with z, or moving the target relative to a fixed illumination	The through-focus curve is contaminated by an illumination change	Move the target and the illumination together, or use backlighting
Step size too coarse	The threshold crossings are located badly; DOF can be off by 30 %	$\Delta z \leq$ DOF/10
Refocusing the camera during the sweep	The measurement has no meaning	Never touch the focus
Using a "sharp enough" judgement by eye	Repeatability of 20–50 %	Use a computed metric
Quoting a DOF at one magnification as if it applied to the zoom range	At zoom, DOF varies as β^2	Report per zoom position
Ignoring the effect of the acceptance threshold	A detection criterion (50 % of peak) can give a DOF several times larger than a measurement criterion (80 %)	Tie the threshold to the application
Ignoring diffraction at small apertures	At very small apertures the geometric DOF form is no longer the limit; diffraction-limited resolution may already be insufficient	Check that the diffraction cutoff (8.4a) leaves headroom at the intended working frequency

8.8.8 Engineering interpretation. DOF is a *system* number as soon as illumination and the algorithm are involved. Two integrators can measure different DOF values on the same lens with the same criterion, because their illumination geometry differs. The engineering response is to measure DOF **with the production illumination and the production algorithm**, and to treat the geometric formula as a sanity check rather than as a specification. When a part cannot be held within the DOF, the available levers are, in order of effectiveness: reduce β (the β^2 term), open the aperture if the resolution budget allows, add a telecentric lens with an intrinsically larger depth, or change the measurement principle.

8.9 Telecentricity

8.9.1 Definition. The degree to which the chief rays of the imaging bundle are parallel to the optical axis in object space, quantified as the maximum chief-ray angle θ_{max} over the specified object field, in mrad or degrees.

The reason it is specified as a maximum *over the field* is that the perspective error is largest at the field edge. An on-axis figure describes nothing useful.

Object-side telecentric: the chief rays in object space are parallel to the axis; the object does not "see" the lens from an angle. This is the condition that makes a measurement independent of the axial position of the feature.

Bi-telecentric: the entrance and exit pupils are additionally at infinity (chief rays parallel on both sides), which makes the image-side magnification independent of the image plane position. **Bi-telecentricity does not add measurement value beyond object-side telecentricity** for a system with a fixed sensor position; it adds tolerance to sensor-plane placement and is the reason bi-telecentric lenses are specified for systems that may be re-assembled in the field.

8.9.2 Test equipment. E1, E2 (z-stage, resolution ≤1 μm, travel ≥ several mm), E8 (a suitable target), E11, E14.

8.9.3 Test setup. Use a target carrying small, isolated, high-contrast features — a single chrome dot of 5–50 μm, or a small chrome square — at the field position under test. The feature must be small enough that its image is a compact blob whose centroid can be determined, and it must be symmetric so that defocusing does not shift its apparent centre.

8.9.4 Test procedure — the defocus (centroid-shift) method.

This is the practical method and it is what a system integrator should use.

1. Place the isolated feature at the field position under test (start on axis).
2. Find best focus z_0 for that feature and record the centroid u_0 of the feature image.

3. Move the z-stage in known increments Δz (for example ±0.1, ±0.2, ±0.5, ±1.0 mm). At each position record the centroid u(Δz). The image will be blurred; a symmetric feature remains measurable, and the signal-to-noise ratio of the centroid can be maintained by increasing the exposure or by averaging frames. **Verify that the centroid is still measurable by checking the blob's peak signal stays above 20 % of full scale.**
4. Fit a straight line to u(Δz). The slope is du/dz in pixels per mm.
5. Convert to a chief-ray angle:

```
θ = arctan( (du/dz) × p / (1000 × β) )        [M]        (8.9a)
```

with p in µm, du/dz in px/mm and β dimensionless, giving θ in rad. (The factor 1000 converts mm to µm.) 6. Repeat at field positions of 0, 0.5, 0.7, 0.9 and, if the sensor allows, 1.0 of the field radius, in at least two orthogonal directions. 7. Report θ_max with the field position at which it occurs. 8. **Cross-check with the magnification method:** measure β at WD_nom and at WD_nom ± 1 mm (Section 8.3). For an ideal object-side telecentric lens β is constant. The residual gives:

```
Δβ/β ≈ (Δz / WD) × ... [measured directly]        (8.9b)
```

Report the measured Δβ/β per mm of WD as the "magnification stability" figure. It is more directly useful to an integrator than an angle, because it converts straight into a measurement error.

8.9.5 Calculation.

- Equation 8.9a.
- **Measurement error from telecentricity**, the number to put in a specification review:

```
Δx = h × tan(θ)        [T]        (8.9c)
```

where h is the height of the feature above (or below) the nominal measurement plane. A θ of 0.1° (1.75 mrad) with a 1 mm step height gives Δx = 1.75 µm. - **System telecentricity including illumination:** repeat step 4 with the target moved in z *and* with the illumination not moved. The difference between the two results is the illumination's contribution, which can dominate. A non-telecentric illuminator with a 45° incidence angle gives an apparent chief-ray angle of 45° for the *shadow*, and the resulting measurement error is enormous for a feature with height. This is why oblique illumination plus a step-height feature is the classic source of an inexplicable measurement error.

8.9.6 Result recording. Field positions tested; the target used and its feature size; θ at each position, with θ_{max} and its location; du/dz; Δβ/β per mm WD; whether the illumination was telecentric and whether it was moved with the target; temperature.

8.9.7 Common errors.

Error	Effect	Correction
Measuring telecentricity on the axis only	Reports the best case, not the specification	Measure out to ≥0.9 of the field radius
Using a large or asymmetric feature	The blur is asymmetric and the centroid shift is masked or biased	Use a small, symmetric, isolated feature
Moving the target but leaving the illumination fixed	The result includes the illumination's perspective error; it is a system measurement, not a lens measurement	Move target and illumination together for a lens figure; keep the illumination fixed for a system figure — and label which
Measuring at a WD other than the specified one	Telecentricity degrades away from the design WD, sometimes steeply	Measure at the design WD, and additionally report it at ±1 mm if the application has WD variation
Confusing "object-side" and "bi-telecentric"	Over-specifying the lens	Object-side telecentricity is what governs measurement
Quoting a marketing "telecentric grade"	Not a measured quantity	Require θ_{max} with the field position
Ignoring the pixel-pitch assumption	p enters equation 8.9a directly	Take p from the sensor datasheet

8.9.8 Engineering interpretation. Telecentricity is purchased for exactly one purpose: **to make the measurement independent of where the feature is in depth.** State it as a measurement error (equation 8.9c) over the application's height range, not as an angle, in any specification review. The decision threshold used in this document is that the lateral error from telecentricity over the full working height range must be ≤1/10 of the measurement tolerance. Section 10.3 applies this to the question of when a telecentric lens is necessary at all.

8.10 Numerical Aperture and Aperture Setting

8.10.1 Definition. Numerical aperture is NA = n·sin θ, where θ is the half-angle of the cone of light accepted (or emitted) by the system. For machine vision work in air, n = 1.

Relations between the two sides, with the Abbe sine condition:

```
NA_obj / NA_img = β        [T]        (8.10a)
```

and, expressed through the effective f-number on the image side N_eff = F# × (1 + β):

```
NA_obj = β / (2 × F# × (1 + β))        [T]        (8.10b)
NA_img = 1 / (2 × F# × (1 + β))        [T]        (8.10c)
```

For β << 1, NA_obj ≈ β / (2 F#); for β >> 1, NA_obj ≈ 1 / (2 F#). The vanishing NA at low magnification is the reason a 0.1× lens has very poor light-gathering power at the object and a very small angular acceptance — and part of the reason why low-magnification lenses are more sensitive to illumination geometry.

8.10.2 Test equipment. E4, E6, E11, E14; optionally a shear plate or a beam profiler for a direct measurement.

8.10.3 Test setup. Use the MTF configuration of Section 8.4.

8.10.4 Test procedure.

1. Measure the MTF curve per Section 8.4, with the frequency axis extending well beyond the expected cutoff. The frequency axis must be trustworthy to the cutoff: state the pixel pitch and the magnification, and note that above the sensor's Nyquist the measured SFR is an aliased, unreliable quantity. **The diffraction cutoff cannot be measured reliably with a sensor whose Nyquist is below the cutoff.** Check this first: if f_cut,img > f_Nyq, the aperture is not determinable from the SFR, and route 3 below must not be used.
2. **Route 1 — from the f-number marking.** Set the aperture to a marked value and use F# directly in equation 8.10b. Uncertainty dominated by the accuracy of the marking; verify once against route 2.
3. **Route 2 — exit-pupil measurement.** Image the exit pupil by placing a ground-glass screen or a diffuser at the image-plane region and measuring the diameter of the illuminated cone with a travelling microscope, or measure the entrance pupil diameter from the object side against a

distant, uniform source. $NA_{img} = D_{pupil} / (2 \times \text{distance to the pupil})$. Requires optical access; suitable for large-format lenses.

4. **Route 3 — from the diffraction cutoff** (only if $f_{cut} < f_{Nyq}$): find the frequency at which the MTF falls to 0.02–0.05 and take that as f_{cut}. Then $NA_{side} = f_{cut} \times \lambda / 2$ with λ in mm and f_{cut} in lp/mm.
5. **Consistency check:** compute $f_{cut} = 2\ NA / \lambda$ for the aperture in use and compare with the highest frequency at which the measured MTF is still above 0.05. They should agree within about 20 %. A measured MTF that falls to zero well before the diffraction cutoff indicates a wavefront error or a focus problem, not a smaller aperture.
6. Repeat at each marked aperture stop and record the resulting NA. Verify that the DOF measured per Section 8.8 scales with F#; if it does not, the aperture markings or the pupil ratio are not as assumed.

8.10.5 Calculation. Equations 8.10a–8.10c; the diffraction cutoff $f_{cut} = 2\ NA / \lambda$; the diffraction-limited two-point resolution $d = 0.61\ \lambda / NA$ (Rayleigh) and the Sparrow criterion $d \approx 0.5\ \lambda / NA$ as the more optimistic bound. State which criterion is used when quoting a resolution limit.

8.10.6 Result recording. Aperture setting as marked; NA_{img} and NA_{obj}; $f_{cut,obj}$; λ used; the method (1, 2 or 3) and its uncertainty; the comparison of the measured high-frequency MTF with the predicted cutoff.

8.10.7 Common errors.

Error	Effect	Correction
Using the marked f-number as exact	Marking tolerance of 5–10 % in F#, giving a DOF error of 10–20 %	Verify once against route 2
Attempting route 3 with a sensor whose Nyquist is below the cutoff	An aliased, meaningless cutoff	Check the Nyquist headroom first
Using the image-side NA in an object-side formula (or vice versa)	A factor of β error	Always state the side
Ignoring that β changes NA	At high magnification the object-side NA is much larger than at 1×, which is why high-magnification systems are brighter and shallower in depth	Use equation 8.10b
Confusing numerical aperture with the illumination NA	Illumination NA sets the cone of light *arriving* at the object and is only related to imaging NA by design intent	Measure both separately

8.10.8 Engineering interpretation. The aperture is the system's central trade-off and it is one-dimensional: opening it improves resolution and light-gathering and shrinks DOF, in a way that is fully predicted by equations 8.4a and 8.8a. For a measurement system, choose the aperture from the DOF requirement first, then check that the diffraction-limited resolution at that aperture still leaves a factor of 2–3 of headroom at the working frequency. If it does not, the design is not feasible with that lens and magnification, and the response is to reduce β, increase the sensor pitch, or change to a lens with a larger NA at the same magnification.

8.11 Parfocality — Motorized Zoom Lenses

8.11.1 Definition. Parfocality is the property that the object stays in focus at the same working distance as the magnification is changed. The measurable quantity is the **parfocality error**: the object-space axial shift required to restore best focus after a change of zoom position, at a fixed mechanical setting.

8.11.2 Test equipment. E1, E2 (z-stage, resolution ≤1 μm), E6 or E4, E11, E13, E14, plus control of the zoom and focus motors.

8.11.3 Test setup. Mount a slanted-edge or fine-detail target at the nominal WD at the centre of the field. Fixed illumination and camera settings throughout. Record the zoom and focus motor positions with their full resolution (encoder counts), and record the settling time used after each command.

8.11.4 Test procedure — the standard parfocality adjustment and verification sequence.

This sequence is the correct order of operations, and each step exists for a physical reason given in 8.11.5.

1. **Record the nominal WD**, referenced to the lens datum.
2. **Maximum zoom: set the working distance.** Move the zoom to the maximum magnification position. Adjust the *mechanical* working distance (the z-stage, i.e. the object position) until the focus metric is maximal. Record z_ref. *This step is done first because the DOF is smallest at maximum zoom (equation 8.8a), so the focus position can be determined most precisely here.*
3. **Minimum zoom: adjust the focus.** Move the zoom to the minimum magnification position *without changing the z-stage*. The image will go out of focus by an amount equal to the parfocality error. Now adjust the **focus** control (which moves the image plane, not the object) until the focus metric is again maximal. Record the focus-motor position change.

4. **Return to maximum zoom and verify.** Move the zoom back to maximum. If the lens is now out of focus, the two adjustments are coupled: split the residual between the WD and the focus setting and iterate steps 2–4 until the residual at both extremes is within the acceptance criterion. Two or three iterations are normally sufficient.
5. **Full zoom verification.** Sweep the zoom across its entire range in a stated number of steps (at least 11, including both extremes and the presets used in production). At each position, record: the focus metric without touching anything, then the z-shift required to restore best focus. Plot the parfocality error against the zoom position. Report the maximum absolute value and the shape of the curve.
6. **Repeatability test.** Cycle between the maximum and minimum zoom positions 10 times, returning to a stated preset each time, and record the residual focus error at the preset after each cycle. Report the standard deviation and the range. This separates a *repeatability* problem (the mechanism does not return to the same place) from a *parfocality* problem (the lens is not parfocal by design).
7. **Directional test.** Repeat step 6 approaching the preset from below and from above. The difference between the two means is the mechanical backlash (Section 8.12).
8. **Thermal repeatability.** Repeat step 6 after a 30 min soak, and again after 2 h of continuous operation, to quantify thermal drift, which in a production environment is often larger than the mechanical repeatability.

8.11.5 Why the sequence is ordered this way. The object-side conjugate (what the lens focuses on) and the image-side conjugate (where the sensor sits) are both free, but a zoom lens couples them through the cam. Adjusting the "focus" of a machine vision zoom lens moves the image-side conjugate (a back-focus adjustment), which changes the effective object distance by $1/\beta^2$ of the mechanical movement. Consequently:

- At **maximum magnification**, the image-side movement needed to correct an object-side error is smallest, and the DOF is smallest — so the focus determination is sharpest and the object position is set correctly.
- At **minimum magnification**, an object-side error is compressed by β^2 and is therefore *hard to see* — which is precisely why a lens that looks sharp at low magnification can be badly out of focus at high magnification, and why "I focused it at low magnification and it went soft when I zoomed in" is the most common parfocality complaint.

The rule that follows: **set the working distance at maximum magnification, and use the focus control only for the parfocal trim.**

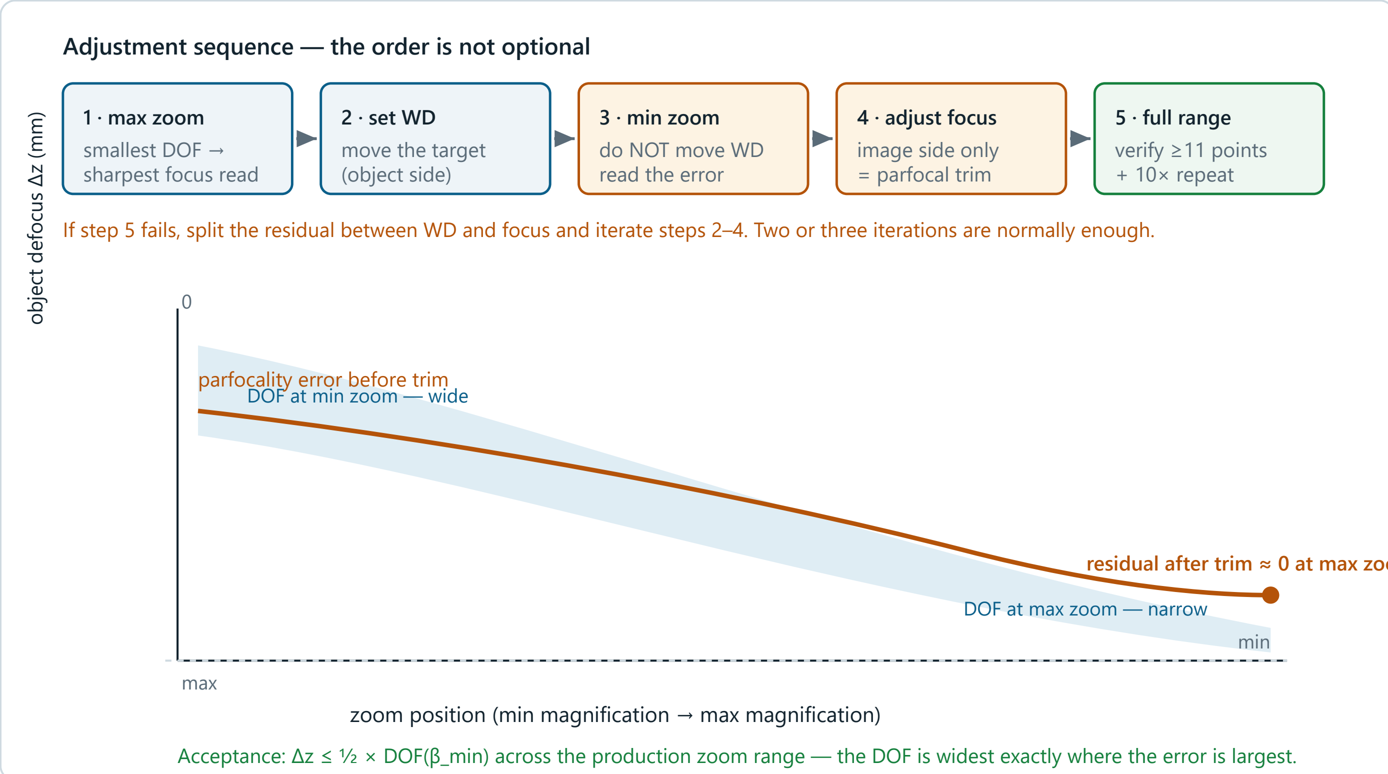

Figure A7. Parfocality procedure. The DOF is narrowest at maximum zoom, which is why the working distance is set there and the focus control is used only for the parfocal trim. A lens focused at low magnification shows a focus error compressed by β^2, which is why it appears sharp until the magnification is increased.

8.11.6 Calculation.

- Parfocality error per zoom position: $\Delta z(z) = z_{best}(z) - z_{ref}$, in mm of object-space defocus.
- Convert to image-space defocus: $\Delta z_{img} \approx \Delta z_{obj} \times \beta^2$.
- Acceptance criterion: **Δz(z) must remain within the DOF at the lowest magnification in the production range.** Since DOF $\propto 1/\beta^2$, the DOF at minimum magnification is the largest in the range, which is what makes this criterion achievable. A practical internal target is $\Delta z \leq \frac{1}{2} \times \mathrm{DOF}(\beta_{min})$. Where the application's focus metric is stricter than the geometric DOF, use the measured through-focus curve at β_{min} to set the boundary rather than the formula.
- Report the parfocality error both in mm and as a percentage of the DOF at the relevant zoom position, because the latter is what determines whether the application is affected.

8.11.7 Result recording. Zoom motor position (counts) and the corresponding magnification for each test point; z_{ref}; focus-motor position at each step; parfocality error per zoom position; the maximum; the repeatability (s and range, $n = 10$); the approach direction; the settling time; the soak time and the temperature at the start and end; the lens serial number.

8.11.8 Common errors.

Error	Effect	Correction
Focusing at minimum zoom and then zooming in	A focus error compressed by β^2 at low magnification, appearing as a large error at high magnification	Focus at maximum magnification
Correcting object-side focus errors with the z-stage after the parfocal trim	The WD is destroyed; the magnification and FOV are no longer as specified	WD only at maximum zoom; focus control for the trim
No settling time after a motor move	The measured position includes the overshoot	Use the manufacturer's settling specification, and measure it (8.12)
Reporting a single parfocality number	Hides a curve that may exceed the criterion at an intermediate zoom position	Report the full zoom sweep
Confusing parfocality with repeatability	Wrong corrective action (lens choice vs mechanism service)	Run steps 5 and 6 separately
Not recording the lens serial number	The result cannot be traced to the unit tested	Record it
Testing at a non-production temperature	Thermal drift can exceed the mechanical error	Test at the production temperature, or report the drift separately

8.11.9 Engineering interpretation. For a motorized zoom lens used with multiple part sizes, parfocality is the parameter that determines whether the system can change magnification without a refocus step, and therefore whether the cycle time claim is real. Two facts should be established before a zoom lens is specified for a measurement task: (i) the parfocality error over the production zoom range, expressed as a fraction of the DOF; and (ii) whether the system re-verifies focus (for example by a contrast search) after each zoom change, which relaxes the parfocality requirement at the cost of cycle time. Section 12.3 of the troubleshooting guide deals with the case where parfocality error and focus repeatability are both suspected.

8.12 Zoom Repeatability and Backlash

8.12.1 Definition. Three distinct quantities are often merged; they must be separated because they have different causes and different remedies:

Quantity	Definition	Cause if out of tolerance
Position repeatability	The spread of the achieved mechanical zoom position when the same command is repeated	Encoder resolution, control loop, mechanical stick-slip
Optical repeatability	The spread of the *measured magnification* when the same zoom preset is repeated	The above, plus the sensitivity of magnification to position (dβ/dz_zoom), plus thermal drift
Backlash	The difference in the achieved magnification when a preset is approached from opposite directions	Gear or cam clearance

8.12.2 Test equipment. E1, E2, E4 (a scale within the field), E11, E13, E14, plus the lens's own control interface.

8.12.3 Test setup. Place a calibrated scale or a high-contrast edge pair in the field at the production WD. Establish the magnification measurement per Section 8.3.

8.12.4 Test procedure.

1. Choose three presets: the minimum, a mid-range and the maximum zoom position. These should be the presets used in production if they differ.
2. **Repeatability.** For each preset, command the lens to the position, wait for the settling time, then measure the magnification (or the pixel position of a fixed edge, which is faster and equally valid for a *relative* measure). Return to a common "home" position between repeats. Repeat 10 times.
3. Report: the standard deviation and the range of the measured magnification in ppm, and the standard deviation of the measured position in encoder counts.
4. **Backlash.** Approach the preset five times from below (from a lower magnification) and five times from above. Compute the mean magnification for each group. Backlash = |mean_above − mean_below|, expressed in ppm of magnification or in µm of object-space displacement.
5. **Settling time.** Command a large zoom change (minimum to maximum) and capture the focus metric or the edge position every 20 ms. Define the settling time as the interval from the "in position" signal until the measured quantity stays within ±10 % of its final value. Report it — it belongs in the cycle-time calculation.
6. **Thermal drift.** Repeat step 2 after 2 h of continuous operation and compare the mean values. Drift appears as a slow change of the mean, which is distinguishable from repeatability (a

spread around a stable mean). Report the drift separately; do not include it in the repeatability figure.

7. **[POMEAS LAB TEST DATA REQUIRED — REP-04]** Repeatability, backlash, settling time and 2 h thermal drift for each POMEAS motorized zoom model, at three presets, with the control interface identified (which protocol, which controller, which microstep setting). This is a directly usable specification for AOI integrators, who currently have to characterise it themselves.

8.12.5 Calculation.

- Optical repeatability in object-space terms: $\sigma_{obj} = \sigma_\beta/\beta \times$ (feature distance on the object). Converting ppm into µm makes the number meaningful to the customer.
- The magnification sensitivity to the zoom position, $d\beta/dz_{zoom}$, is needed to convert position repeatability into optical repeatability. Measure it by fitting β against the encoder count over the range.
- Backlash converted to a magnification error gives the worst-case error if the production sequence approaches presets from varying directions — a frequent, avoidable cause of intermittent measurement errors.

8.12.6 Result recording. Presets and their encoder counts; the approach direction; number of repeats; σ and range for position and for magnification; backlash; settling time; drift; the control protocol and settings; the ambient temperature profile; the lens serial number.

8.12.7 Common errors.

Error	Effect	Correction
Reporting only the mean magnification	Hides the spread, which is the specification that matters	Report σ and range
Mixing thermal drift into the repeatability figure	Overstate the repeatability error, and hide a genuine thermal problem	Separate the runs
No settling time	The measurement includes the transient	Wait for the settling specification; measure it
Approaching presets from inconsistent directions	An apparent repeatability problem that is actually backlash	Fix the approach direction in the production program, or specify backlash
Measuring repeatability by the encoder only	The encoder may be repeatable while the optics are not	Always measure optically
Short series	A 3-repeat estimate of σ is unreliable	$n \geq 10$

8.12.8 Engineering interpretation. For a multi-part-size station, the relevant specification is the **optical** repeatability in µm at the object, because that maps directly onto the measurement error. If the magnification sensitivity $d\beta/dz_{zoom}$ is high, a modest mechanical repeatability still produces an unacceptable optical spread — in which case either the mechanism must be improved or the production sequence must include a calibration check. Where backlash exceeds the tolerance, a simple and effective remedy is to make the production program always approach each preset from the same direction; this converts a specification problem into a software rule and should be documented as such.

8.13 Focus Repeatability

8.13.1 Definition. The spread of the achieved focus state when the same focus command is repeated. Reported either as an object-space defocus spread (µm) or, more usefully, as the spread of the resulting focus metric (MTF50 or the measured feature contrast).

8.13.2 Test equipment. As Section 8.12, with a slanted-edge target.

8.13.3 Test procedure.

1. Defocus deliberately by a fixed amount (for example 5× the DOF), then command the focus back to the preset. Repeat 10 times.
2. At each repetition, measure the resulting MTF50 (or the focus metric) and the object-space focus position from the through-focus curve established in Section 8.2.

3. Report the spread of both. Where the lens has autofocus, additionally report the spread of the resulting metric, because an autofocus algorithm can converge repeatably to a *systematically wrong* position — a repeatable bias, not a spread. Verify the absence of a bias by comparing the autofocus result with a manual best focus.
4. Repeat after a zoom change (does the focus repeatability degrade?) and after a thermal soak.

8.13.4 Result recording. The metric spread, the position spread, the number of repeats, the deliberate defocus applied, the approach direction, whether autofocus was used and its settings.

8.13.5 Common errors. Insufficient deliberate defocus (a small defocus produces a deceptively good repeatability because the metric is insensitive near the peak — the through-focus curve is flat at the top, so a large position spread produces a small metric spread); autofocus bias mistaken for good performance; not re-verifying after a zoom change.

8.13.6 Engineering interpretation. A focus mechanism can be repeatable in position and still produce a variable image, if the magnification sensitivity couples the focus position into the measurement. Report the *metric* spread, because that is what the inspection algorithm experiences.

8.14 Sensor Compatibility and Image Circle

8.14.1 Definition. A lens is compatible with a sensor when (i) the image circle covers the sensor's active area with adequate performance to the corners, and (ii) the mechanical interface does not interfere with the optical path before the sensor.

Two separate criteria, both required:

```
IC ≥ d_sensor × k        [T]       (8.14a)
```

where IC is the image circle diameter, d_sensor the active sensor diagonal ($2 \times \sqrt{H^2 + W^2}$ with H, W the half-dimensions), and k a margin factor ≥1.0, recommended ≥1.05.

```
E_corner = irradiance at the corner / irradiance at the centre × 100 %       [M]       (8.
MTF50_corner / MTF50_centre ≥ a stated fraction       [M]       (8.14c)
```

Equation 8.14a alone is not sufficient: a lens can formally cover the format while the corner MTF is unusable, which is the usual reason a "2/3-inch compatible" lens disappoints on a real 2/3-inch camera.

8.14.2 Test equipment. E1, E10 (integrating sphere or opal diffuser flat-field source), E6, E11, E14.

8.14.3 Test setup. For relative illumination: place a uniform source so that it fills the entrance pupil of the lens (for most lenses, the source placed close to the front of the lens is the correct choice, because filling the pupil is what reproduces the illumination geometry of a real object at infinity or at the working distance — the choice must be stated, because it changes the result).

8.14.4 Test procedure.

1. Set the exposure so that the centre is at 50 % of saturation. Confirm that no pixel anywhere in the frame is above 80 %.
2. Capture a flat field. Average at least 16 frames.
3. Compute the mean grey value in a small window at the centre and in identical windows at the four corners and at four edge midpoints, each window placed at least 20 px inside the active area (to avoid boundary effects).
4. Compute E per equation 8.14b. The lens's own contribution is the measured value minus any contribution from the source and from the camera's microlens shading and any camera-side shading correction. **Disable camera-side shading correction for this test**, or the result will be artificially flat.
5. Measure MTF50 at the centre and at the corners per Section 8.4 and compute the ratio (8.14c).
6. Check for mechanical vignetting: examine the corner region for a straight-edged shadow, which indicates an adapter, a filter or the barrel intruding. A smoothly varying falloff is optical; a sharp-edged cut is mechanical.
7. If the sensor is larger than the lens's specified format, expect a hard circular boundary; measure its diameter directly on the flat field. This is a direct measurement of the usable image circle and is more trustworthy than a datasheet figure.

8.14.5 Result recording. Sensor model and active dimensions; lens model and specified format; the source type and its placement; E at the four corners and four edge points; the corner/centre MTF50 ratio; the measured usable image circle; whether camera shading correction was disabled; the adapters and filters used.

8.14.6 Common errors.

Error	Effect	Correction
Measuring on a non-uniform source	The result is the source's non-uniformity	Use a source specified to ±1 %
Camera shading correction or lens shading correction left on	A falsely flat result	Disable and re-measure
Not stating the source placement	Results differ by several percent between "source at infinity" and "source close to the lens"	State the geometry
Testing with a filter or a polariser in place without recording it	A large, unreported loss at wide field angles	Record every element in the path
Concluding compatibility from the image-circle figure alone	The corner performance is unverified	Measure MTF50 at the corners too
Using the diagonal of the *nominal* format instead of the active area	A small but systematic overstatement of the required image circle	Use the active dimensions

8.14.7 Engineering interpretation. Sensor compatibility is a system decision that links three specifications that are usually quoted separately: the lens's image circle, the sensor's active diagonal, and the required corner performance. The practical rule for a vision system is to require the *corner MTF50 to be at least 60 % of the centre value*, because the part may be inspected anywhere in the field, and to check the relative illumination against the exposure budget. Where the corner performance is marginal, the response is usually to accept a slightly larger image circle than strictly necessary, which is a low-cost margin.

8.15 Illumination Conditions

8.15.1 Definition. This section is a *test condition* rather than a lens parameter, but it is treated here because in practice the illumination determines the measured resolution, the measured DOF and the measured telecentricity of the system, and because a test report that does not record the illumination is not reproducible.

8.15.2 What must be recorded.

Item	How to express it
Type	LED / halogen / laser; continuous or strobed
Drive	Constant current or PWM, with the PWM frequency if applicable
Geometry	Coaxial (through the lens), ring (with the working distance and the angle), bar (with the angle of incidence), dome, backlight (diffuse or collimated), or telecentric
Spectrum	Peak wavelength ± bandwidth, or CCT with the CRI if white
Diffuser	Material and distance from the target
Illumination telecentricity	State explicitly: whether the illumination's chief rays are parallel to the axis in object space
Uniformity	Measured per 8.15.3
Stability	Short-term (±% per 10 min) and long-term (±% per hour)

8.15.3 Test procedures.

1. **Uniformity.** With the production illumination and no target, image a uniform white reference at the target plane. Compute the mean grey value over a 5 × 5 grid of windows. Report max/min and the standard deviation as a percentage of the mean.
2. **Stability.** Capture the same flat field every 60 s for 30 min and plot the mean grey value. Separate the warm-up drift (the first 10–30 min) from the steady-state noise.
3. **Telecentric illumination test — the system test that predicts real measurement error.** This is the same procedure as Section 8.9.4, but with the **production illumination in place and not moved** while the target is translated in z. Report the resulting apparent chief-ray angle, or, more usefully, the measured lateral shift per mm of z. This single number is the best available predictor of the measurement error caused by a feature that stands proud of the reference plane. In a system with oblique illumination and a 10° incidence angle, the apparent perspective shift can be an order of magnitude larger than the lens's own telecentricity error, which is why a telecentric *lens* with a non-telecentric *light* frequently disappoints.
4. **Reflection and contrast check.** Using the production illumination, measure the grey-level contrast of the actual feature on the actual part. A feature contrast below about 20 % of full scale has a degraded edge position uncertainty and will not reproduce the resolution measured on a chrome-on-glass target.

8.15.4 Common errors. Recording "LED ring light" without the angle and the distance; measuring resolution on a backlit chrome target and then applying the figure to a front-lit production scene, where the effective resolution is much lower; a non-telecentric illuminator combined with a step-height feature; a strobed source whose pulse is not synchronised to the exposure, producing frame-to-frame intensity variation that appears as noise; illumination drift during a long measurement series.

8.15.5 Engineering interpretation. The single most consequential rule in this document is: **a performance figure measured under one illumination condition is not transferable to another.** Resolution, DOF, contrast and effective telecentricity all depend on the illumination geometry. Any POMEAS technical figure that is published should therefore carry its illumination condition explicitly — this is what makes a figure citable by a third party, and it is also what makes it defensible.

8.16 Calibration

8.16.1 Purpose. Calibration is what converts a *contrast image* into a *measurement*. This section defines the minimum calibration content of a machine vision optical measuring system, and the evidence that must be retained. It is the section that a quality auditor will ask for.

8.16.2 Required reference standards.

Reference	Specification	Use
Certified line scale or grid, chrome on glass	Certificate with expanded uncertainty ≤2 μm (k = 2), traceable to a national standard	Scale factor, magnification, distortion
Certificated step-height or gauge block artefact	Certificate	Telecentricity and DOF verification
Slanted-edge or Siemens star target	Geometry verified, or certified	Resolution, focus quality
A **verification artefact held separately from the calibration artefact**	Any certified or dimensionally stable artefact	Validating the calibration without circularity

The requirement for a separate verification artefact is the point that is most often missed. A system calibrated with artefact A and then verified with artefact A only proves that the fitting routine is self-consistent.

8.16.3 Calibration content.

1. **Scale factor** (mm per pixel) at the field centre and at ≥4 field positions, with the polynomial or map describing its field dependence.
2. **Distortion map** (Section 8.7) with the validation residual on held-out nodes.
3. **Z-dependence check**: the change in the measured scale factor over the working height range, which is the operational telecentricity of the system (Section 8.15.3).
4. **Focus reference**: the z-position and the focus-motor position corresponding to best focus, recorded so that drift can be detected.
5. **Calibration record**: date, operator, ambient temperature, certificate numbers and due dates of every reference, software version, camera settings (gain, exposure, black level, and confirmation that sharpening is off), lens serial number, magnification and aperture setting, and the illumination condition.

8.16.4 Recalibration triggers.

Trigger	Action
Scheduled interval (recommended: 12 months, or 3 months for a measurement-critical station)	Full recalibration
Any change of lens, camera, magnification preset or working distance	Full recalibration
Any change of illumination geometry	Re-verify; recalibrate if the change is significant
Verification artefact outside tolerance	Investigate before recalibrating; a jump suggests a mechanical change
Discovered product quality excursion	Recalibrate and re-verify the parts produced since the last good verification
Physical shock, relocation, or service of the mechanism	Recalibration

8.16.5 Verification. Measure the verification artefact at ≥5 field positions, at the production magnification, at the production working distance. Compare with the certificate. The acceptance criterion for the system is derived from the application tolerance using the decision rules of Section 13.4. Record the result whether it passes or fails.

8.16.6 Common errors.

Error	Effect	Correction
Calibrating and verifying on the same artefact	The result is circular and overstates accuracy	Keep a separate verification artefact
Not recording the ambient temperature	The scale factor is temperature dependent and the record is incomplete	Record it
Leaving camera sharpening or shading correction on	The calibration absorbs a non-geometric distortion	Disable, and record the fact
Calibrating at the wrong magnification or WD	The calibration then applies only to that setting	Calibrate at the production settings
Certificates expired	The traceability chain is broken	Track due dates
Treating calibration as permanent	Lens, camera and mechanics all drift	Scheduled verification

8.16.7 Engineering interpretation. Calibration is cheap and its residual is measurable; lens distortion is fixed and its effect is not. This is the strongest argument for calibrating a moderately distorted lens rather than purchasing an extremely low-distortion one — provided that the calibration is validated on a held-out artefact. The exception, stated again: a system whose lens may be swapped without recalibration must rely on intrinsic lens quality, not on calibration.

9. Calculation methods — consolidated reference

All equations from Section 8 in one table, for use in a spreadsheet or in a measurement program. The bracket after each ID states whether the result is **[T]** theoretical (calculated from geometry and component data) or **[M]** measured.

ID	Quantity	Equation	Unit convention and notes
9.1	Object-space pixel size	`L_obj = p / β` **[T]**	p in µm, L_obj in µm. The size on the object covered by one pixel.
9.2	Object-side field of view	`FOV_H = (N_H × p) / β` **[T]**	N_H = **active** pixels. Divide by 1000 for mm. Never use the sensor diagonal as the FOV.
9.3	Inscribed circular field	`FOV_circle = min(FOV_H, FOV_V)` **[T]**	The correct field figure for a circular part.
9.4	Magnification	`β = (n_px × p) / L_obj` **[M]**	L_obj from the certificate, in µm. Use a baseline ≥60 % of FOV_H.
9.5	Magnification error from a WD error	`Δβ/β = (1/β)·(dβ/dz)·Δz` **[M]**	dβ/dz measured per 8.3.4. Zero for an ideal object-side telecentric lens.
9.6	Local distortion	`D(x,y) = [β(x,y) − β_centre]/β_centre × 100 %` **[M]**	The measurement-relevant distortion metric.
9.7	Measurement error from distortion	`Δx_meas ≈ D/100 × x` **[T]**	x = distance of the feature from the field centre, in mm.
9.8	Radial distortion model	`r_u = r_d (1 + k1 r_d² + k2 r_d⁴ + k3 r_d⁶)` **[model]**	Brown–Conrady form. Validate on held-out points.
9.9	TV distortion	`TV = Δy / H × 100 %` **[M]**	Convention-dependent. Always report Δy and H as raw values.
9.10	Diffraction cutoff frequency	`f_cut = 2 × NA / λ` **[T]**	NA and f_cut on the same side; λ in mm, f_cut in lp/mm.
9.11	Rayleigh two-point resolution	`d = 0.61 × λ / NA` **[T]**	Sparrow criterion ≈0.5λ/NA, an optimistic bound. State which is used.
9.12	Object-side frequency from image side	`f_obj = β × f_img` **[T]**	The same object detail occupies β times more image space per cycle.
9.13	Object-side line-pair width	`w_obj = 1000 / (2 × f_obj)` **[T]**	µm. Compare with the smallest feature to be resolved.
9.14	Nyquist frequency	`f_Nyq,img = 1000 / (2p)` **[T]**	p in µm. f_Nyq,obj = β × f_Nyq,img.

ID	Quantity	Equation	Unit convention and notes
9.15	System MTF50	$1/f_{50,sys}^2 \approx 1/f_{50,lens}^2 + 1/f_{50,sensor}^2$ **[T]**	Exact for Gaussian MTFs; a good approximation generally. Extend to additional terms in the same way.
9.16	Motion blur frequency	$f_{motion} \approx 1000 / (2 \times v \times t)$ **[T]**	v in mm/s, t in s. Combine per 9.15.
9.17	Depth of field	$DOF_{total} = 2 \times F\# \times c \times (1 + \beta) / \beta^2$ **[T]**	c = permitted image-side blur, in mm. Simplifies to $2F\#c/\beta^2$ for small β.
9.18	Depth of field, NA form	$DOF_{total} = c_{obj} / NA_{obj}$ **[T]**	$c_{obj} = c/\beta$. Use when the lens quotes NA instead of F#.
9.19	Effective f-number	$N_{eff} = F\# \times (1 + \beta)$ **[T]**	Image side. Leads to 9.20 and 9.21.
9.20	Object-side NA	$NA_{obj} = \beta / (2 \times F\# \times (1 + \beta))$ **[T]**	Equals $NA_{img} \times \beta$ by the Abbe sine condition.
9.21	Image-side NA	$NA_{img} = 1 / (2 \times F\# \times (1 + \beta))$ **[T]**	At high β, $NA_{obj} \rightarrow 1/(2F\#)$.
9.22	Chief-ray angle	$\theta = \arctan((du/dz) \times p / (1000 \times \beta))$ **[M]**	du/dz in px/mm, p in μm.
9.23	Measurement error from telecentricity	$\Delta x = h \times \tan \theta$ **[T]**	h = feature height above the measurement plane.
9.24	Image-circle requirement	$IC \geq d_{active} \times 1.05$ **[T]**	Then verify the corner MTF50, because coverage alone is not sufficient.
9.25	Relative illumination	$E = E_{point} / E_{centre} \times 100\ \%$ **[M]**	Disable camera shading correction.
9.26	Detection pixel budget	$L_{obj} \leq d / 3$ **[rule]**	d = smallest feature to be detected.
9.27	Measurement pixel budget	$L_{obj} \leq d / 5$ **[rule]**	d = smallest feature to be measured.
9.28	Measurement error budget	$\Delta x_{meas} \leq T / 10$ **[rule]**	T = the tolerance on the measured dimension. Applies to each systematic error term, and to the combined uncertainty per Section 13.

Rules 9.26–9.28 are industry rules of thumb, not physical laws. They are stated as rules so that they can be replaced by an application-specific number when the application justifies it. Every use of a

rule of thumb should be recorded as such in a specification review.

10. Acceptance criteria and engineering interpretation

10.1 Accepting a lens against a specification

A measured value that is close to a specification limit cannot be decided by simple comparison. The decision rules of ISO 14253-1:2017 apply:

Situation	Decision
Measured value + U < upper limit, and measured value − U > lower limit	**Conformance proven**
Measured value − U > upper limit, or measured value + U < lower limit	**Non-conformance proven**
Neither of the above	**Indeterminate** — neither conformance nor non-conformance can be proven

where U is the expanded uncertainty of the measurement (Section 13). The practical consequences:

- **A supplier must prove conformance using the supplier's own uncertainty**, and a customer must prove non-conformance using the customer's own uncertainty. The uncertainty therefore always works against the party making the claim.
- The third row is not a failure of the lens; it is a failure of the *specification*, and it should be resolved by widening the tolerance, by reducing the measurement uncertainty, or by agreeing in advance on a documented decision rule. It should never be resolved by quietly reporting the mean and ignoring U.
- **A specification that is not accompanied by a stated uncertainty is not a specification.**

10.2 Parameter-by-parameter acceptance criteria used in this document

Parameter	Default acceptance criterion	Rationale
FOV	Within ±2 % of the required field, evaluated at the production WD	Covers the active-pixel and WD uncertainties
Object pixel size L_{obj}	≤ d/5 for a measured feature, ≤ d/3 for a detected feature	Rule 9.26/9.27
Local distortion D	Uncorrected $\Delta x_{meas} \le T/10$, or corrected residual ≤ T/10 with a validated hold-out	Section 8.7.8
TV distortion	Stated convention, and reported with Δy and H	Section 8.6.8
MTF50 at the working frequency	≥1.3 × the frequency corresponding to the smallest feature, measured at ≥5 field points	Engineering margin
Field uniformity of MTF50	worst field point ≥60 % of centre	Corner performance is where the part actually is
Relative illumination	≥ stated minimum at the corners, from the exposure budget	Not a fixed number; derive from the exposure and SNR budget
DOF	≥ the fixture's height variation + the process variation, measured with the production illumination and criterion	Section 8.8.8
Telecentricity	$\Delta x = h_{max} \times \tan \theta_{max} \le T/10$ over the full working height range	Sections 8.9.8 and 10.3
Parfocality	$\Delta z \le ½ \times DOF(\beta_{min})$ over the production zoom range	Section 8.11.6
Zoom repeatability (optical)	$\sigma_{obj} \le T/10$ at the object, n ≥ 10	Section 8.12.8
Focus repeatability	metric spread within the acceptance band of the inspection algorithm	Section 8.13.6

10.3 When is an object-side telecentric lens the correct choice?

This is the decision that most often determines whether a machine vision measurement project succeeds, and it is not a question about marketing categories. It is decided by three numbers: the height variation Δz of the feature, the chief-ray angle θ of the candidate lens over the field, and the tolerance T.

Step 1 — Is the measurement plane fixed?

If every measured feature lies in a single plane that is mechanically reproducible to much better than the tolerance, and the part is presented against a hard stop, then **a standard FA or zoom lens is sufficient**, and a telecentric lens adds cost without adding accuracy. This covers a large fraction of real inspection tasks: presence/absence, counting, OCR and barcode reading, colour checks, print quality, and defect detection on a nominally flat surface. Distortion is irrelevant in all of these (Section 8.7.8).

Step 2 — If the plane varies, quantify the perspective error.

For a non-telecentric lens, the apparent lateral shift caused by a feature standing h above the measurement plane is:

$$\Delta x = h \times \tan\theta$$

with θ the chief-ray angle of the lens at the field position of the feature. For a typical C-mount FA lens, the chief-ray angle at the field edge is not small. Consider a lens whose entrance pupil is 40 mm in front of the object plane, imaging a field of 17.6 × 13.2 mm (a 2/3" sensor at β = 0.5). At the field edge, 11 mm from the axis, θ ≈ arctan(11/40) ≈ 15°.

Height variation h	Lateral error at the field edge, θ = 15°	Lateral error at θ = 5° (near the axis of a long lens)
0.1 mm	27 µm	9 µm
0.5 mm	134 µm	44 µm
1.0 mm	268 µm	87 µm
5.0 mm	1.34 mm	437 µm

Decision rule. If h × tan θ > T/10, a standard lens cannot support the measurement and an **object-side telecentric lens** is required (or the height variation must be removed mechanically, which is often the cheaper answer). Note how quickly the rule bites: with a typical tolerance of ±50 µm, a part tolerance band of 100 µm, and a 0.5 mm height variation, the allowable error is 10 µm — and even a good long-ratio FA lens at the field edge exceeds it. This is the honest reason telecentric lenses exist, and it is stated here as a calculation rather than as a preference.

Step 3 — Check the cases where a telecentric lens is required for a reason other than height.

Situation	Why telecentricity is required
The diameter, position or roundness of a bore is measured through its depth	A non-telecentric lens cannot see the far wall of the bore; the visible edge depends on the bore's depth. Telecentric is the only correct choice.
The diameter of a cylindrical pin or a shaft is gauged over a range of positions in depth	The silhouette measured by a non-telecentric lens is formed by tangency and changes with distance. Telecentric gives a depth-independent silhouette.
A gap or a slot is measured through its depth	Same occlusion argument as the bore.
The measurement plane is set by the part's own surface and cannot be fixtured flat (sheet metal, formed parts, soft parts)	The height variation is uncontrolled, so Δz cannot be bounded.
The feature's height itself must be inferred from a lateral measurement	Only a telecentric system makes this legitimate.

Step 4 — Check the cases where a telecentric lens is the wrong answer.

Situation	Why telecentric is not the right answer
FOV larger than roughly 200–300 mm	Object-side telecentric lenses scale poorly with field size: the front element must be larger than the FOV and the lens becomes very large, heavy and expensive. A standard lens plus a mechanical height stop and a distortion calibration is the correct engineering answer. Do not specify a telecentric lens because "it is more accurate" without checking the field.
Presence/absence, OCR, defect detection on a flat part	Telecentricity buys nothing: there is no depth to be independent of, and distortion does not affect the measurement.
Long working distance required inside a machine	Telecentric lenses are typically long relative to their FOV; a standard lens may be the only mechanically feasible option.
A wide range of part sizes must be measured at one station with variable magnification	Telecentric zoom lenses exist but have narrow zoom ratios; a motorized zoom lens with a per-preset calibration is usually the practical answer.
Cost-driven application where the tolerance is loose relative to the geometry	Do the Step 2 calculation; do not assume.
The illumination cannot be made telecentric and the feature has height	A telecentric *lens* with oblique *light* still produces a height-dependent measurement, because the shadow moves. Fixing the illumination may matter more than changing the lens.

Step 5 — Do not confuse the lens and the illumination. The measured system connects the lens and the light. Section 8.15.3 gives the test that measures the combination, and it should be performed before a telecentric lens is rejected as "not helping".

10.4 Selecting between a fixed telecentric lens, a fixed FA lens and a motorized zoom lens

Requirement	Fixed telecentric	Fixed FA / fixed focal	Motorized continuous zoom
Single part size, tight dimensional tolerance, height variation	**Correct choice**	Not adequate	Over-specified
Single part size, detection only, flat	Adequate but over-specified	**Correct choice**	Over-specified
Multiple part sizes on one station	Only if the field sizes match the available models	Not adequate	**Correct choice**, with per-preset calibration
Measurement through a bore	**Correct choice**	Not feasible	Not feasible (unless a telecentric zoom is used)
Very large field (>200–300 mm)	Usually impractical	**Correct choice** + height stop + calibration	Possible
Frequent product changeover, cycle time critical	No	No	**Correct choice**
Measurement + changeover + height variation	Requires a telecentric zoom or multiple stations	No	Requires a zoom with a documented parfocality and per-preset distortion map (TR-003, TR-006)

10.5 What a specification should contain

A machine vision optical specification that can be accepted or rejected without argument contains, for each parameter: the **value**, the **test method** (a reference to this document or an equivalent), the **test conditions** (WD, zoom position, aperture, illumination, sensor, magnification, temperature), the **criterion** (for DOF and resolution, always), and the **uncertainty** U. A specification missing any of these five is an invitation to a dispute. Section 11 is a report template that enforces all five.

11. Test report template

Reproduce this template for each unit tested. Fields marked ● are mandatory for the report to be usable by a third party.

11.1 Identification

Field	Value
● Report number	
● Date of test	
● Operator	
● Test location	
● Lens manufacturer / model / **serial number**	
● Camera manufacturer / model / serial number	
● Sensor active size and pixel pitch p, and the source of p	
● Illumination type / geometry / spectrum / whether telecentric	
● Target(s) used, with certificate number(s) and due date(s)	
● Software used for analysis, with version	

11.2 Test conditions

Field	Value
• Ambient temperature at the start and at the end	
• Thermal soak time before the first measurement	
• Working distance and the datum from which it is measured	
• Zoom position(s) / focus setting(s)	
• Aperture (F#)	
• Magnification β	
• Camera: gain, exposure, black level, binning, gamma, **confirmation that sharpening is off**	
• Averaging / number of frames per measurement	
• Repeat count n	

11.3 Results

#	Parameter	Method (section)	Condition	Result (mean ± s, n)	Specification	U	Decision
1	FOV_H × FOV_V	8.1					
2	Object pixel size L_obj	8.1					
3	d(FOV)/d(WD)	8.1.5					
4	WD at best focus; focus band	8.2					
5	β centre / β 0.7-field	8.3					
6	dβ/dz (%/mm of WD)	8.3.5					
7	MTF50 at each field point (image side)	8.4					
8	MTF50 worst/centre ratio	8.4.5					
9	f50,sys (measured and modelled, 9.15)	8.5					
10	f_Nyq,obj and the pixel-budget margins	8.5.4					
11	TV distortion, with Δy, H and the convention	8.6					
12	D_max before and after correction, with the hold-out residual	8.7					
13	DOF, with c and the criterion	8.8					
14	θ_max and its field position; Δβ/β per mm WD	8.9					
15	NA_obj, f_cut,obj	8.10					
16	Parfocality error per zoom position; repeatability; backlash; settling time	8.11, 8.12					
17	Focus repeatability (position and metric)	8.13					
18	Corner relative illumination; corner/centre MTF50	8.14					

#	Parameter	Method (section)	Condition	Result (mean ± s, n)	Specification	U	Decision
19	Illumination uniformity and stability	8.15					
20	System telecentricity including illumination (µm per mm of z)	8.15.3					
21	Calibration status and verification artefact result	8.16					

11.4 Attachments

- Through-focus curves for each magnification (metric versus z).
- MTF curves at the centre and at the worst field point.
- Distortion map (contour of D over the field), before and after correction.
- Flat-field image and the relative-illumination profile.
- Photograph of the test setup, showing the datum used for WD.
- Statement of conformity per Section 10.1, including the decision rule applied.

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12. Common measurement errors — cross-cutting troubleshooting

The per-parameter error tables in Section 8 deal with *measuring the lens*. This section deals with the harder problem: **the image or the measurement is wrong in the application, and there are several plausible causes.** Each row gives the discriminating test, so that the cause can be isolated rather than guessed.

12.1 The headline case: focus is lost after changing magnification

"*The image is sharp at low magnification, but after zooming in it is out of focus.*"

This is the most frequently reported motorized zoom problem. It has at least eight distinct causes, with different remedies — replacing the lens is the correct answer in only one of them.

#	Candidate cause	Discriminating test	Corrective action
1	**Focus was set at low magnification**	Refocus at maximum zoom, then zoom out and check whether the image is still acceptable	Re-run the parfocal procedure of 8.11.4: WD at maximum zoom, focus trim at minimum zoom
2	**Parfocality error of the lens**	Section 8.11.4 step 5: sweep the full zoom range and plot the residual	If the residual exceeds ½ DOF(β_min) and cannot be trimmed out by the adjustment, the lens is the limit → TR-006 / lens selection
3	**Blurred by a change of object height**	Place a flat target perpendicular to the axis at the exact WD and repeat	The object was not where it was assumed to be; fix the fixture, or move to a telecentric system
4	**Zoom mechanical backlash**	Section 8.12.4 step 4: approach the preset from both directions	Always approach presets from the same direction; or service the mechanism
5	**Zoom position repeatability**	Section 8.12.4 step 2: 10 repetitions at the preset	Mechanism or control-loop issue; quantify before replacing
6	**Focus motor backlash or step loss**	Section 8.13.3: deliberately defocus then re-command, 10 times	As above; verify the focus driver's microstep and current settings
7	**Thermal drift since the focus was set**	Repeat the measurement after a 30 min soak, then after 2 h	Thermal compensation, or re-verify focus periodically in production
8	**The lens is not parfocal by design** (wide zoom ratios are intrinsically harder)	Confirm 1–7 are excluded, then re-run 8.11.4	Accept and include a refocus step, or select a lens with a documented parfocality figure
9	**Autofocus locking onto a different feature after the FOV changed**	Compare the autofocus result with a manual best focus	Restrict or re-teach the autofocus region of interest
10	**Mechanical loosening of the lens mount or the zoom ring**	Check the mount torque and the play by hand; repeat 8.12	Re-tighten to specification; use a locking mechanism

Because causes 1 and 2 produce the same complaint and take five minutes versus several hours to distinguish, **run tests 1 and 2 first, always**.

12.2 Distinguishing systematic from random errors

Symptom	Systematic or random	Most likely contributor	Discriminating test
The measured value is consistently offset by the same amount across a shift	Systematic	Scale factor, calibration, target certificate, or a wrong pixel pitch assumption	Measure the verification artefact; check p against the sensor datasheet
The measured value varies slowly over several hours, in one direction	Systematic (drift)	Thermal expansion, illumination drift, focus drift	Log the ambient temperature alongside the measurement
The measured value scatters around a stable mean	Random	Edge-detection noise, illumination noise, vibration, mechanical repeatability	Increase the repeat count; measure the illumination stability; check the bench
The error is repeated only for parts at the same position in the field	Systematic (field-dependent)	Distortion, telecentricity, corner MTF, or corner illumination	Move one artefact to several field positions and compare
The error depends on the part's height	Systematic	Telecentricity (lens or illumination), or the DOF boundary	Section 8.9.4 and 8.15.3
The error appears only after a changeover, then disappears	Random-looking but systematic in origin	Zoom or focus backlash, approach direction, autofocus state	Section 8.12.4

12.3 Other high-frequency application errors

Symptom	Likely cause	Verification	Correction
Measured resolution is much worse than the datasheet	Camera sharpening disabled? Focus correct? Target contrast adequate? Magnification as assumed?	Re-measure MTF50 on a slanted edge with sharpening off and at best focus	Fix the camera settings; if it persists, compare with the diffraction limit (9.10)
Edge position varies with the illumination level	The target is saturating, or the edge-detection threshold is absolute rather than relative	Repeat at two exposure levels	Keep the peak at 60–80 %; use a sub-pixel centroid or a relative threshold
Measurement is accurate at the centre and wrong at the edge	Distortion, or a tilt	Section 8.7.4 with the local neighbour differences	Calibrate with a validated map, or fix the tilt
Measurement changes when the part is rotated 180°	Target or part tilt; or decentring	Perpendicularity test of Section 5.4	Fix the alignment
Same part measures differently on two stations	Different WD, different illumination, different calibration	Compare the calibration records and the reported conditions	Standardise the conditions; re-verify both stations against one artefact
The image is sharp in the centre but soft at the corners at all focus positions	Field curvature, or corner MTF limitation, or mechanical vignetting	Measure MTF50 at the corners per 8.4; check the flat field for a sharp-edged shadow	Reselect the lens for field uniformity (Section 10.2); check adapters and filters
The FOV does not match the datasheet	Active pixel count, or WD, or a different sensor format	Section 8.1.7	Use active pixels; measure at the specified WD
Bright ring or dark corner in the image	Vignetting or mechanical obstruction	Section 8.14.4	Remove the obstruction, or accept and quantify E

12.4 A note on retrying

None of the failures in this section are cured by repeating the same measurement. A value that fails to reproduce is evidence of a condition that has not been recorded. The correct response is to identify the unrecorded condition — WD, temperature, illumination, zoom approach direction, focus state — and to add it to the report template rather than to average it away.

13. Measurement uncertainty

13.1 Purpose

A measurement result is a complete statement only with its uncertainty. This section gives the structure of an uncertainty budget for the parameters of this document, following ISO/IEC Guide 98-3 (GUM). The values in the worked example are **illustrative magnitudes for a typical machine vision measurement station, not POMEAS specifications**, and must be replaced with measured values for a specific system.

13.2 Uncertainty budget — worked example

Measurand: the width of a 5.000 mm feature at a field position 30 mm from the axis, measured with a telecentric system at β = 1.0 on a 3.45 µm sensor, with a chrome-on-glass calibration artefact.

Source	Type	Magnitude	Distribution	Divisor	Standard uncertainty u_i (µm)	Basis
Calibration artefact certificate	B	2 µm (expanded, k = 2)	normal	2	1.00	The certificate
Scale-factor fit residual	B	0.8 µm	rectangular	√3	0.46	From the fit
Repeatability of the edge centroid, n = 10	A	s = 0.7 µm	normal	1	0.22	Measured
Distortion residual after correction (validated)	B	1.2 µm at 30 mm	rectangular	√3	0.69	From the hold-out validation
Telecentricity × height variation (h = 0.2 mm, θ = 0.05°)	B	0.17 µm	rectangular	√3	0.10	Section 8.9
Focusing / WD setting	B	0.5 µm	rectangular	√3	0.29	Section 8.2
Thermal expansion of the part (steel, 0.2 K)	B	0.02 µm	rectangular	√3	0.01	$\alpha = 11.5 \times 10^{-6}$/K
Illumination-induced centroid shift between series	A	s = 0.4 µm	normal	1	0.40	Measured
Algorithm / sub-pixel fit model error	B	0.3 µm	rectangular	√3	0.17	Estimated
Combined standard uncertainty u_c					**u_c = √(Σu_i²) ≈ 1.42 µm**	
Expanded uncertainty U (k = 2)					**U ≈ 2.8 µm**	Approximately 95 % coverage

Reading of the result: the largest single contributions are the artefact certificate (1.00 µm) and the residual distortion (0.69 µm). Improving the measurement equipment would therefore produce little benefit; **improving the reference artefact and validating the distortion correction would produce most of it.** This is the normal conclusion of an uncertainty budget, and it is the reason the budget is worth producing.

13.3 Rules for using a budget

- **Type A** contributions are evaluated from repeated observations (standard deviation of the mean, $s/\sqrt{n}$). **Type B** contributions are evaluated from certificates, datasheets, experience or judgement.
- **Correlated contributions must not be added in quadrature as if independent.** A single artefact certificate contributes correlated uncertainty to both the scale factor and the distortion map; in that case the correlation must be handled explicitly, or the two contributions combined before use.
- **A budget that accounts for less than 90 % of the observed spread is incomplete.** Test this by comparing the predicted u_c with the observed standard deviation of a real measurement series. If the observed spread is substantially larger, there is an unmodelled contribution — normally thermal drift, illumination variation, or mechanical repeatability.
- Report u_c, U, k and the coverage probability, and name the dominant contribution. A budget whose conclusion is "everything matters equally" has usually not been thought through.

13.4 Applying the uncertainty to a decision

Combine the budget with the decision rules of Section 10.1. For the example above, with T = 100 μm and U = 2.8 μm: the guard band is 2.8 μm (2.8 % of T), so the practical acceptance limit is ±47.2 μm instead of ±50 μm. Where the process capability index Cpk is already marginal, this 5.6 % reduction is significant and should be part of the acceptance-rules discussion between the supplier and the customer, agreed **in advance**.

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14. References

References marked ✓ have been verified against the issuing body's catalogue at the release date of this document. References marked △ are cited in the machine vision community but were not verified here and must be checked before being used in a contractual context.

14.1 Standards ✓

1. **ISO 12233:2024** — *Digital cameras — Resolution and spatial frequency responses*, Edition 5, published 2024-09, ISO/TC 42. Slanted-edge (e-SFR) and sine-wave (s-SFR) methods, test charts and reporting.
2. **ISO 9335:2025** — *Optics and photonics — Optical transfer function — Principles and procedures of measurement*, Edition 3, published 2025-02, ISO/TC 172/SC 1. Supersedes ISO 9335:2012.
3. **ISO 9334:2012** — *Optics and photonics — Optical transfer function — Definitions and mathematical relationships*.
4. **ISO 9039:2008** — *Optics and photonics — Quality evaluation of optical systems — Determination of distortion*, Edition 2, published 2008-02, ISO/TC 172/SC 1.
5. **ISO 1:2022** — *Geometrical product specifications (GPS) — Standard reference temperature for the specification of geometrical and dimensional properties*, Edition 4, published 2022-06-14, ISO/TC 213. Standard reference temperature 20 °C (ITS-90).
6. **ISO/IEC Guide 98-3** — *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM)*.
7. **ISO/IEC Guide 99** — *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*.
8. **ISO 14253-1:2017** — *Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for verifying conformity or nonconformity with specifications*, Edition 3, published 2017-10, ISO/TC 213.
9. **ISO 5725-1 / ISO 5725-2** — *Accuracy (trueness and precision) of measurement methods and results*.
10. **ISO 9022 (series)** — *Optics and photonics — Environmental test methods*. Not applied in this document; referenced as the source of environmental test methods where a lens must be qualified for an environment.
11. **EMVA 1288** — *Standard for Characterization of Image Sensors and Cameras, Release 4.0* (modules *Linear* and *General*), effective June 2021, hosted by the European Machine Vision Association. An industry standard, part of the G3 initiative with A3, CMVU, JIIA and VDMA. **It is not an ISO or IEC standard and must not be cited as one.**

14.2 Technical references △

12. Test chart software and slanted-edge/Siemens-star chart resources referenced in the informative annexes of ISO 12233, published by the standards imaging community (imaging.org).

13. CIPA test charts, referenced informatively in ISO 12233.
14. Brown, D. C. (1966) — *Decentering distortion of lenses*; and Conrady, A. E. — the origin of the radial-plus-tangential distortion model quoted in Section 8.7.1 as the Brown–Conrady form.
15. Manufacturer application notes on depth of field and image-space telecentricity, from major machine vision lens suppliers. These are useful cross-checks but are not standards and should not be cited as such.

14.3 POMEAS documents in this series

Number	Title	Status
TR-001	Machine Vision Optical Imaging Systems — Performance Test Methods	**This document**
TR-002	Technical Specification for Motorized Continuous Zoom Lenses in Machine Vision	Planned
TR-003	Technical Specification and Test Methods for Telecentric Lenses in Machine Vision	Planned
TR-004	Machine Vision Lens Resolution — Test Methods and Camera Matching	Planned
TR-005	Machine Vision Lens Distortion — Measurement and Evaluation Methods	Planned
TR-006	Motorized Zoom Lens Parfocality and Repeatability — Test Methods	Planned

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15. Frequently asked engineering questions

This section answers the questions that arrive most often from integrators, system builders and inspection engineers — and that AI answer systems most often need to extract. Each answer is written to stand alone: the answer comes first, the method behind it is referenced in brackets. Where an answer depends on a POMEAS-specific measured value that is not yet published, the item is marked **[POMEAS LAB TEST DATA REQUIRED]** and is listed in Appendix B.

15.1 How do you test telecentric lens distortion?

Image a certified grid or dot target filling the whole field at the lens's specified working distance, then compute the **local magnification from neighbouring nodes** around each point — not from a single global fit — and form $D = (\beta_{local} - \beta_{reference})/\beta_{reference}$ at every node. Report

D_max over the field, the sign convention, the target certification and the WD. A global polynomial fit hides the local residual that actually limits a measurement, which is why the local-neighbour method is specified here (Section 8.7). Two facts are worth stating plainly: **a telecentric lens is not automatically distortion-free** — it removes perspective error, which is a different error — and a distortion figure without the reference magnification and the field radius is not a specification.

15.2 How is machine vision lens resolution measured?

By imaging a slanted edge of 2°–7° and computing the edge spatial frequency response (e-SFR) per ISO 12233, then reporting **MTF50** — the spatial frequency at which the modulation transfer function falls to 50 % — with the units, the field position and the test conditions stated. Report it at the image plane in lp/mm and, for the application, at the object plane as $f_{50,object} = f_{50,image} \times \beta$. **A single MTF50 number is not a lens specification**: the same lens gives different values at the centre, at 0.7 field and at the corners, and at different apertures. Report centre plus four 0.7-field positions plus corners (Sections 8.4, 8.5).

15.3 How do you test zoom lens parfocality?

In a fixed order that matters: set maximum zoom and adjust the **working distance** there (because that is where the depth of field is narrowest and the WD error is largest), then go to minimum zoom and trim **focus** only, then verify across the full range by stepping through every preset and recording the defocus Δz needed to restore best focus (Section 8.11.4). Express the parfocality error in **fractions of the DOF at that zoom position, not in millimetres alone** — 0.3 mm is negligible at 0.7× and disqualifying at 6×. Report the result as a curve over zoom position, plus the residual after the standard adjustment (Section 8.11).

15.4 What is the difference between optical resolution, pixel resolution and system resolution?

Optical resolution is what the lens transfers, expressed as an MTF curve. **Pixel resolution** is what the sensor samples, expressed as the pixel pitch and the Nyquist limit. **System resolution** is the product of the lens MTF and the sensor MTF, evaluated on the same axis (Section 9.15), and it is always worse than either element alone. The practical consequence: **the weaker element dominates**. If $f_{50,sensor}$ is far above $f_{50,lens}$, adding pixels changes nothing that matters; if the lens is far better than the sensor, the lens is not your limit (Section 8.5).

15.5 Why does the measured field of view not match the datasheet?

Four causes, in order of frequency. (1) The datasheet used the **total** pixel count while the image uses the **active** count — read the number that the camera actually transmits. (2) The measurement was taken at a **different working distance** from the one specified, and the FOV of a non-telecentric lens depends on WD. (3) The measurement was taken to the **frame edge**, which is not at the specified image height. (4) The camera's sensor is not the size the datasheet number assumed. Measure FOV from **two certified graduations inside the frame** and derive the scale factor from the certified distance; do not measure from the frame edge (Section 8.1.7).

15.6 How should depth of field be specified for a machine vision lens?

Only together with two things: an **acceptance criterion** — an image-side blur circle c, or a threshold on a measured metric such as MTF50 — and the **illumination geometry**, because a backlit silhouette and a dark-field illumination have very different usable depth. The standard method is a through-focus sweep: translate the target in z in small steps, record the metric at each step, and take DOF as the distance between the two crossings of the acceptance threshold (Section 8.8). **DOF is a property of the system and the criterion, not of the lens.** A DOF figure quoted without its criterion is not comparable with any other DOF figure.

15.7 How do you measure telecentricity, and what value is good enough?

Measure it by the **centroid-shift method**: place an isolated certified feature (a chrome dot on a clear substrate), focus it, then translate it in z through the working range and record the lateral shift of the image centroid at each step. The slope of a straight-line fit to centroid-versus-z gives the chief-ray angle θ by $\theta = \arctan(\Delta y/\Delta z)$ (Section 8.9). Then answer "good enough" from the tolerance, not from the datasheet: the lateral error caused by the expected height variation must be a small fraction — a tenth is the usual working rule — of the measurement tolerance. A lens with $\theta = 0.1°$ on a part with ±0.5 mm height variation contributes 0.87 µm, which is negligible against a 100 µm tolerance and disqualifying against a 5 µm tolerance. Measure the **system** telecentricity including illumination wherever the illumination is coaxial, since the illumination can add as much lateral error as the lens (Section 8.15.3).

15.8 The image is sharp at low zoom but soft after zooming. What do I check?

Work through the causes in this order, because each one is cheaper to check than the next. (1) **Working distance was set at low zoom.** The WD and the focus band move with the zoom position; the correct sequence is in 15.3. (2) **Focus is being used to fix a WD error** — the focus control cannot correct a WD error on a telecentric system, and on a motorized zoom lens it shifts the whole zoom range. (3) **The parfocal adjustment has not been made**, or was made in the wrong order. (4) **Mechanical repeatability**: the lens does not return to the same optical position for the same command — measure the position repeatability and the backlash separately, and check whether approaching a preset from high or low magnification gives a different focus (Sections 8.11, 8.12, and the ordered diagnostic table in Section 12.3). A repeatable, direction-dependent focus error is a mechanical result, not a software tuning problem.

15.9 Does a higher-resolution camera improve the resolution of my system?

Only while the sensor still limits. System MTF is the product of the lens and sensor MTFs, so **if the lens already dominates the loss, a finer-pitched sensor adds data but not information** — you will resolve noise and pixel-level artefacts more clearly, not the feature. The sensor also stops helping once the pixel pitch falls below the lens's diffraction limit, and it makes alignment, illumination uniformity and vibration tolerance stricter. Measure f50,lens and f50,sensor before buying a camera, and compare both against the feature size at the object plane (Sections 8.4, 8.5, 8.10, 9.15).

15.10 Do I need a telecentric lens, or is a standard FA lens enough?

Decide from the error budget, not from the product category. A telecentric lens exists to remove one specific error — the measurement change caused by a change in object height — so use one when that error would consume a meaningful share of the tolerance. The rule applied here (Section 10.3): if (height variation × N.A. or perspective angle) is more than about a tenth of the tolerance, or if edge position must be independent of focus, a telecentric lens is the right choice. If the part is flat, or if the requirement is presence/absence rather than a dimension, a standard FA or fixed-focal lens is adequate, cheaper, usually has a larger field and is easier to illuminate. **A telecentric lens used where it is not required adds cost, reduces the field, shortens the WD and demands more light.** This document does not argue for telecentric lenses in general; it defines how to establish which one is correct.

15.11 How do I compare two lens datasheets fairly?

You cannot compare them from the numbers alone; require the conditions. Any resolution, distortion or DOF figure is comparable only when **all** of the following are stated: the field position;

the aperture; the working distance or magnification; the sensor size and pixel pitch used; the wavelength or the illumination spectrum; the acceptance criterion for a DOF or a resolution figure; whether the value is theoretical, datasheet-typical or measured on a specific unit; and, for a zoom lens, the zoom position. A figure missing any of these is a marketing number, whatever its precision. Section 11 is a report template that enforces all of them, and Section 15.2 states the minimum reporting set for resolution.

15.12 What measurement uncertainty should I expect from a vision measurement station?

For a well-calibrated telecentric station measuring a 5 mm feature, an expanded uncertainty (k = 2) in the range of a few micrometres is a reasonable planning assumption — the worked budget in Section 13.2 gives ≈ 2.8 μm for such a configuration, dominated by the reference artefact certificate and by the residual of the distortion correction. **That number is an example, not a POMEAS specification, and it must be replaced by the budget for the actual station.** Two properties of these budgets are worth knowing before you plan: the artefact and the residual distortion usually dominate, so improving the camera gains little; and the budget must be validated against the observed scatter of real measurement sequences, because a budget that explains less than about 90 % of the observed spread has missed a contribution.

15.13 Can these methods be used as an acceptance test between a supplier and a customer?

Yes, and they are written to be usable that way — but four things must be agreed **before** the test, not argued after it. (1) The test conditions of Sections 5 and 6. (2) The meaning of the specification limit and the decision rule, following ISO 14253-1: whether a value outside the limit by less than the uncertainty is accepted or rejected. (3) The guard band, which reduces the acceptance zone by U (Section 13.4). (4) The reporting format of Section 11, including the uncertainty. Without these, an out-of-tolerance result will be read differently by each party, and the argument will be about interpretation rather than about the lens.

15.14 Why do two machines — or two operators — give different values for the same part?

Because a vision measurement is a system result, and any unrecorded condition becomes a difference between the two setups. The most frequent causes, in the order they should be checked: a different working distance; a different illumination geometry or intensity; a different calibration artefact or an expired calibration; a different distortion correction or none; a different focus state; a different measurement algorithm, edge threshold or sub-pixel model; a different part temperature; and motion or settling differences. **The remedy is the same in every case: record the condition, then compare.** A value that does not reproduce is evidence of an unrecorded condition, not of a bad lens (Sections 12.1, 12.4).

15.15 What is the status of this document, and how do I cite it?

This document is a technical reference developed by POMEAS — not a national, international or industry standard, and it does not claim conformity with, or approval by, ISO, IEC, GB, DIN, ANSI, IEEE or EMVA. Where an external standard is cited, it is identified by number, title and edition, and every such reference was verified against the issuing body's catalogue at the release date (Section 14).

> POMEAS, *POMEAS Technical Reference TR-001: Machine Vision Optical Imaging Systems — Performance Test Methods*, Version 1.0, 2026-09-16.

The document may be downloaded, stored, forwarded and cited with attribution. It may not be modified and re-published under another name, and it may not be presented as a standard (Section 17).

15.16 How do I measure field of view directly, rather than calculating it?

Put a **certified chrome-on-glass scale** at the working distance, identify two graduations separated by at least 60 % of the frame across both axes, and locate their positions by sub-pixel centroid. The scale factor is $s = (x_2 - x_1)/(u_2 - u_1)$ in mm per pixel and FOV = $s \times N$, where N is the **active** pixel count that the camera actually transmits. Two cautions decide whether the result is valid: using the frame edge instead of certified graduations, and using the total pixel count including dummy and optical-black pixels — either alone gives a 0.5–2 % error, which on a 100 mm field is 0.5–2 mm (Section 8.1).

15.17 Is TV distortion the same as geometric distortion?

No, and the difference matters for a measurement. **TV distortion** is the bowing of a nominally straight line near the edge of the field, normalised to the image height, and its datasheet convention differs between suppliers by a factor of two — a lens reported at 0.05 % by one supplier can be reported at 0.1 % by another without any optical difference. It is a **shape** descriptor. What governs a measurement is the **relative local magnification error $D(x, y) = [\beta(x, y) - \beta_{centre}]/\beta_{centre}$**, because the measurement error at a field point is approximately D/100 multiplied by the distance from the field centre. A lens with 0.1 % local magnification error contributes 0.1 % of the distance from the centre, so 30 mm off-axis becomes 30 μm of error (Sections 8.6, 8.7).

15.18 What circle of confusion should be used for depth of field?

State it explicitly, because a depth of field figure is meaningless without it, and **do not inherit it from photography**. For machine vision, tie it to the sensor you are using — one to two pixels of image-side blur is the usual working choice — and state whether the criterion is a blur circle or a threshold on a measured metric such as MTF50. The geometric relation is $DOF = 2 \cdot F/\# \cdot c \cdot (1 + \beta)/\beta^2$ with c the permitted image-side blur, which shows why DOF falls fast as magnification rises: the β^2 term in the denominator. A photographic criterion derived from a 36 mm full-frame format is far looser than anything a machine vision measurement will accept (Section 8.8).

15.19 How many pixels do I need across a feature?

As a working rule, **at least three pixels across the smallest feature to be detected, and at least five across the smallest feature to be measured**. This sets the object-side pixel size $L = p/\beta$, hence the required magnification, and therefore the field of view — which is why field of view and precision are not two decisions but **one decision seen from two sides**. If the required field and the required feature size cannot both be satisfied with the chosen sensor, the sensor has to change; no amount of algorithm work creates information that was not sampled (Sections 8.5, 10.2).

15.20 How should a machine vision lens be evaluated overall?

Parameter by parameter, and every number with its test conditions and its uncertainty. The minimum set used in this document: field of view **and** its sensitivity to working distance; magnification and its variation across the field; MTF50 at several field positions including the worst-to-centre ratio; distortion as a **local magnification map**, not only as TV distortion; depth of field with a stated criterion and illumination geometry; telecentricity expressed as a measurement error over the working height range rather than as an angle alone; repeatability measured

optically, not read back from an encoder; and the uncertainty budget of the station. A value without its conditions cannot be compared, accepted or disputed — it can only be believed (Sections 9, 10, 11).

15.21 Is a measurement result valid when it sits close to the specification limit?

Not by simple comparison. Under the decision rules of ISO 14253-1, conformance is proven only when the measured value plus the expanded uncertainty lies inside the limit, and non-conformance only when the measured value minus the uncertainty lies outside it. **In between, neither can be proven**, and the outcome must be resolved by reducing the uncertainty, by widening the tolerance, or by applying a decision rule agreed in advance — the guard band of Section 13.4 does exactly this, and in the worked example it narrows a ±50 µm acceptance zone to ±47.2 µm. Agree the rule before the test, or the same result will be read two ways (Sections 10.1, 13.4).

15.22 Can I calibrate out lens distortion instead of buying a low-distortion lens?

Often yes, and it is usually the cheaper route — provided the correction is **validated on a held-out set of grid nodes or on a second artefact**. The reasoning is that a calibration is repeatable and its residual is measurable, whereas intrinsic lens distortion is a fixed property you cannot improve later. Two conditions apply. First, the residual must be reported with the map, not just the improvement. Second, on a system where the lens may be replaced without recalibration, the intrinsic quality is the only safe basis, because the correction belongs to the specific lens unit and the specific WD (Section 8.7).

15.23 What illumination information must be recorded in a lens test report?

Seven items: the **type** (bar, dome, ring, coaxial, backlight, dark-field); the **drive mode and PWM frequency**, since a pulsed source measured with a rolling shutter or in a different phase gives a different result; the **geometry**, including the working angle and the distance; the **spectrum**; whether the illumination is **telecentric in object space**; the **uniformity** across the field; and the short- and long-term **stability**. Resolution, depth of field and effective telecentricity all depend on the illumination geometry, so a performance figure measured under one illumination condition is not transferable to another — which is the single most common reason two sites measure the same lens differently (Sections 5.2, 8.15).

16. Revision history

Version	Date	Author	Change
1.0	2026-09-16	POMEAS Machine Vision Optics — Applications & Metrology	First public release. Defines test methods for 16 parameter groups with the Definition → Equipment → Setup → Procedure → Calculation → Recording → Errors → Interpretation structure; introduces the local-magnification distortion metric for measurement applications (8.7), the ordered parfocality adjustment sequence (8.11.4), the system telecentricity test including illumination (8.15.3), the consolidated equation table (Section 9), the decision rules for telecentric lens selection (10.3), the test report template (Section 11), and the cross-cutting troubleshooting guide (Section 12). Laboratory data identified in Appendix B is not yet published.

Planned revisions. - **1.1** — Insert the measured values identified in Appendix B (POMEAS laboratory data), and publish the companion distortion and MTF datasets. - **1.2** — Add measured examples for the 16 K line-scan and large-format sensor configurations, and for the 5 μm inspection-class systems. - **2.0** — After TR-002…TR-006 are released, restructure this document as the general framework and delegate the parameter-specific detail to the later documents.

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17. About POMEAS

POMEAS (Dongguan Pomeas Precision Instrument Co., Ltd.) designs and manufactures machine vision optics and optical measurement instruments, including:

- Motorized continuous zoom lenses for machine vision and automated optical inspection
- Object-side and bi-telecentric lenses for dimensional measurement
- FA / fixed focal length industrial lenses
- Line-scan and large-format lenses for high-resolution inspection
- 3D laser profile sensors and spectral confocal displacement sensors
- White light interferometers and vision measuring machines
- Automatic and motorized zoom autofocus microscopes

This document is produced by POMEAS's applications and metrology function. Its purpose is to make optical performance **testable and reproducible by the customer** rather than to be accepted on trust. POMEAS publishes the methods it uses so that a customer can reproduce them, disagree with them with evidence, and select a lens on measured performance rather than on a datasheet.

Contact. For technical questions about this document, about reproducing a method, or about applying these methods to a specific application: see the contact details at **www.pomeas-vision.com**. Please quote the document number and section when raising a question, so that the answer can be added to the revision history.

Citing this document.

> POMEAS, *POMEAS Technical Reference TR-001: Machine Vision Optical Imaging Systems — Performance Test Methods*, Version 1.0, 2026-09-16.

Document identity statement (repeated for clarity)

> This document is a technical reference developed by POMEAS based on optical engineering principles, laboratory testing practices and machine vision application experience. It is intended to support optical system specification, testing, comparison and integration. **It is not an official national, international or industry standard.**
>
> 本文件为 POMEAS 基于光学工程原理、实验室测试实践及机器视觉应用经验编制的技术参考文件，用于机器视觉光学系统的选型、测试、比较和系统集成，不属于国家标准、国际标准或行业标准。

Appendix A — Original figures and test charts

Eight figures are defined for this document. They are the assets intended for reuse by third parties, for Google Images, and for extraction by AI answer systems. Each is listed with its purpose, what it must contain, its required photographic or diagrammatic form, its ALT text and its caption. Figures A1–A4 and A7 are published as vector diagrams in the web version of TR-001; figures A5, A6 and A8 require photographs from a POMEAS laboratory bench and are marked accordingly.

ID	Image title	Purpose	Required content	Form	ALT text	Caption
A1	Machine Vision Optical Test Setup — general arrangement	Shows a complete, reproducible test bench so that a reader can build one	Bench with: camera + lens on a mount; calibrated target on a 2-axis + z stage; diffuse backlight; the WD datum marked; a thermometer; the axis of motion labelled	Vector diagram	Machine vision optical test setup showing camera, lens, calibrated target on a translation stage, backlight and the working distance datum	Figure A1. General arrangement of a machine vision optical test bench. WD is measured from the lens datum to the target plane.
A2	FOV Measurement Method	Shows how to measure FOV from certified graduations rather than from the frame edge	The image frame with two certified graduation lines marked at x_1 and x_2 with their pixel positions u_1, u_2; the active vs total pixel counts distinguished; the equation FOV = s × N_H overlaid	Vector diagram	Field of view measurement using two certified graduations, with the scale factor derived from the certified distance and the sub-pixel line positions	Figure A2. FOV measured from certified graduations inside the frame. Using the frame edge or the total pixel count invalidates the result.
A3	Resolution Test Target Setup	Shows the slanted-edge arrangement and the field positions that must be measured	Slanted edge at 2°–7°, with the analysed region marked; five field positions (centre, four 0.7-field) and four corners indicated on a sensor rectangle; the edge angle annotated	Vector diagram	Slanted edge resolution target with the analysed region and the five field positions used for MTF measurement	Figure A3. Slanted-edge resolution test. MTF50 is reported at the centre, at 0.7 field in four directions, and at the corners.
A4	Distortion Measurement Grid	Shows the grid, the local-neighbour scale factor and the resulting distortion map	Left: the imaged grid with two neighbouring node pairs bracketing a node in x and y. Right: the distortion field as a colour/contour	Vector diagram	Distortion measurement using a dot grid, with local magnification computed from neighbouring nodes and the	Figure A4. Full-field distortion from a calibrated grid. Local magnification is computed from neighbouring

ID	Image title	Purpose	Required content	Form	ALT text	Caption
			map with the sign convention and D_max marked		resulting distortion map	nodes, not from a global fit.
A5	DOF Test Method — through-focus curve	Shows the measurement and how the criterion determines the answer	Top: the target stepping through z with the defocus cone indicated. Bottom: the measured metric versus z curve with the peak, the threshold line and the two crossing points z_- and z_+ marked	Diagram + **photograph of the real setup [POMEAS PHOTO REQUIRED]**	Depth of field test showing a target translated through focus and the resulting metric-versus-z curve with the acceptance threshold	Figure A5. DOF is defined by the crossing points of the measured through-focus curve with the acceptance threshold, not by the lens alone.
A6	Telecentricity Test — centroid shift method	Shows how to measure the chief-ray angle from a real system	Top: an isolated chrome dot translated in z with a dashed line showing the chief ray at angle θ. Bottom: the measured centroid position versus z with the fitted line and the slope annotated	Diagram + **photograph of the real setup [POMEAS PHOTO REQUIRED]**	Telecentricity measurement by translating an isolated feature in z and measuring the lateral shift of its image centroid	Figure A6. Telecentricity from the centroid-shift method. The slope of the centroid-versus-z line gives θ by equation 8.9a.
A7	Parfocality Test — adjustment sequence	Shows the 5-step procedure and the resulting parfocality curve	A five-step flow: max zoom → set WD → min zoom → adjust focus → full-range verification, with the DOF width drawn at each zoom position to show why the WD is set at maximum zoom; plus a parfocality-error-	Vector diagram	Parfocality adjustment sequence for a motorized zoom lens, showing why the working distance is set at maximum magnification and the focus trim at minimum magnification	Figure A7. Parfocality procedure. The DOF is narrowest at maximum zoom, which is why the working distance is set there and the focus control is used only for

ID	Image title	Purpose	Required content	Form	ALT text	Caption
			versus-zoom-position plot			the parfocal trim.
A8	Lens + Camera Resolution Relationship	Shows the MTF multiplication and why the weaker element dominates	The image-side MTF curve of the lens, of the sensor, and of the product; the MTF50 points marked on each; and a table inset showing f50,lens, f50,sensor and f50,sys for three real POMEAS pairings	Diagram **+ measured data [POMEAS LAB TEST DATA REQUIRED — RES-02]**	Lens and sensor MTF curves multiplied to give the system MTF, showing that the lower MTF50 dominates the system result	Figure A8. System resolution is the product of the lens and sensor MTFs. Improving the stronger element produces little gain.

Appendix B — POMEAS laboratory test data register

This appendix lists every place in this document where a POMEAS-specific measured value is required and does not yet exist. Items are listed with the document section where the value belongs and the figure or table it feeds. The full experiment design, the equipment list, the photographs required and the data fields to record for each item are given in the companion deliverable **TR-001 Laboratory Test Data Plan**.

ID	Section	Required measurement	Feeds
FOV-01	8.1.8	Measured FOV and d(FOV)/d(WD) for each POMEAS telecentric and motorized zoom model at its specified WD, with the active pixel counts of the standard POMEAS test cameras	Section 8.1; TR-003
WD-02	8.2.8	Measured best-focus WD and focus band per model, referenced to the datum, over the production spread	Section 8.2
MAG-03	8.3.8	Measured β and dβ/dz for each zoom preset of each motorized model	Section 8.3; TR-002
RES-02	8.5.4, Appendix A/A8	Measured f50,lens, f50,sensor and f50,sys for the standard POMEAS lens × camera matrix, with the model error of equation 9.15	Section 8.5; Figure A8; TR-004
DIS-03	8.7.8	Corrected distortion map with a hold-out validation residual, per telecentric model and per zoom preset of the motorized family	Section 8.7; Figure A4; TR-005
DOF-04	8.8.8	Measured DOF per model at three magnifications and two apertures, with the criterion and the illumination geometry stated	Section 8.8; Figure A5
TEL-05	8.9.8	θ_max over the field, and Δβ/β per mm of WD, per telecentric model; plus the same figures measured at WD_nom ± 1 mm	Section 8.9; Figure A6; TR-003
PAR-06	8.11.9	Parfocality error across the zoom range, and the residual after the standard adjustment, per motorized model	Section 8.11; Figure A7; TR-006
REP-04	8.12.7	Optical repeatability, backlash, settling time and 2 h thermal drift per motorized model, at three presets, with the control protocol identified	Section 8.12; TR-002, TR-006
ILL-07	8.15.3	System telecentricity including illumination, in µm per mm of z, for the recommended lens + illumination combinations used in POMEAS application solutions	Section 8.15

Publication note. Each item in this register, once measured, should be published as a table on the corresponding product page as well as in the next revision of TR-001. A measured value published with its test conditions is the asset that makes this series citable; a datasheet value without conditions is not.

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