Validation of sensor simulation and sensor models
Measuring Image Quality

September 10th, 2024

Ansys

Powering Innovation That Drives Human Advancement

DXOMARK

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Ansys presentation

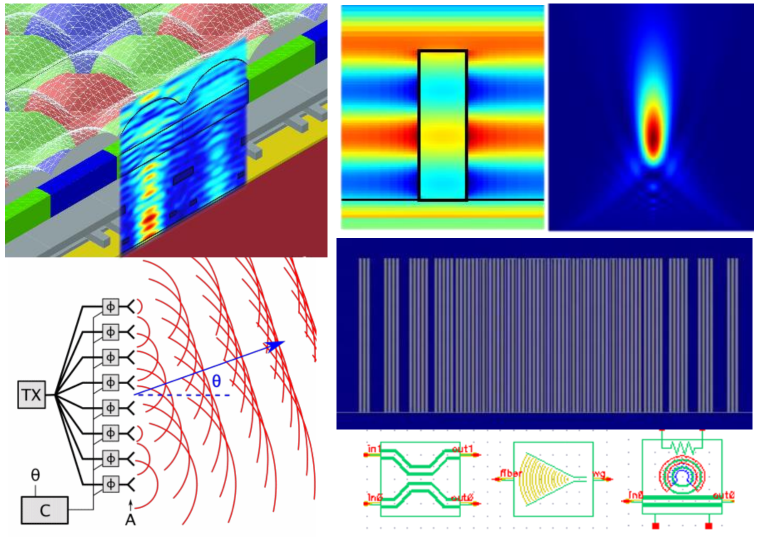
Ansys for Multiphysics simulations across product development life cycle

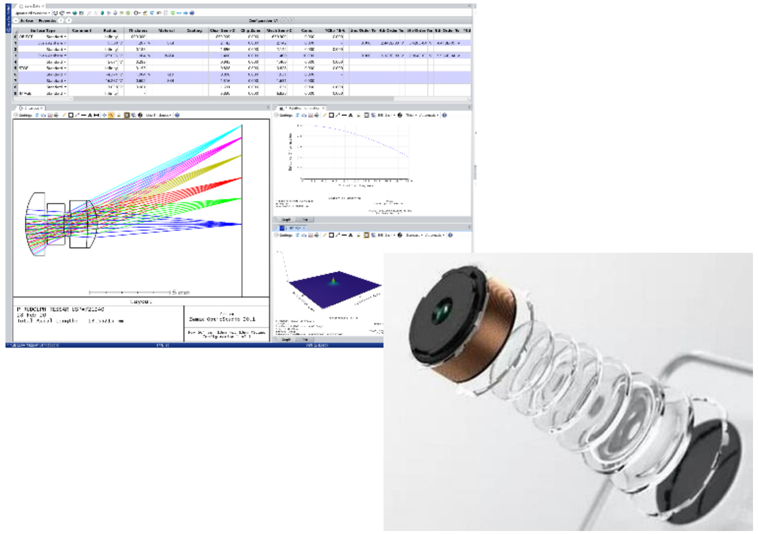
Ansys’ capabilities extend simulation value across the entire product life cycle:

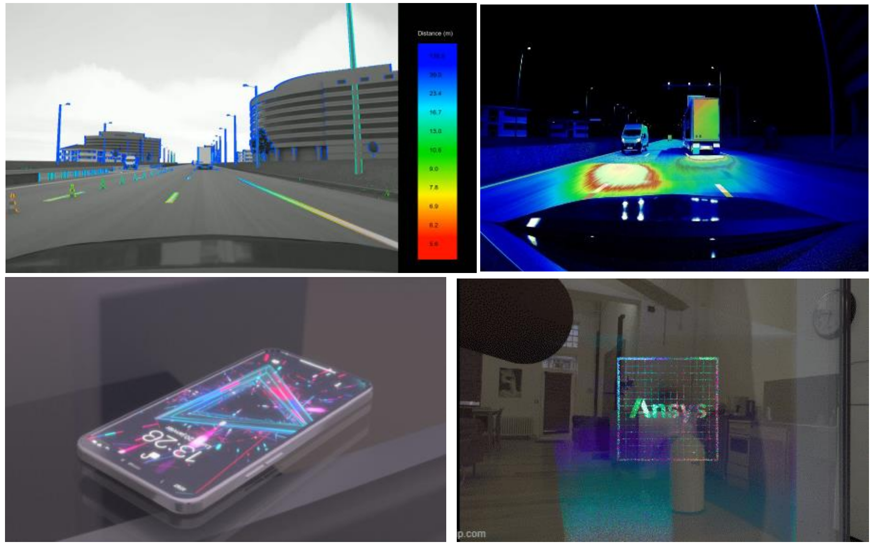
Ansys proposes simulation tools for most physics and so allows multi-physics analysis:

MORE INNOVATION | *FASTER CYCLE TIMES* | *REDUCED COSTS AND RISKS*

Ansys Optics - Multiphysics and multiscale simulation solution







Ansys Lumerical
Photonic Design & Optimization

Nano-Chip-Level

- Photonic components, circuits & systems
- Tolerancing & Yield analysis
- Diffractive optical elements & waveguides
- Emissive and absorbing structures

Ansys OpticStudio (Zemax)
Optical Design & Modeling

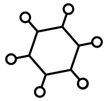
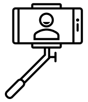
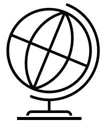
Optical-Design-Level

- Optical design
- Optical validation
- Optical tolerance analysis
- Mechanical tolerance analysis

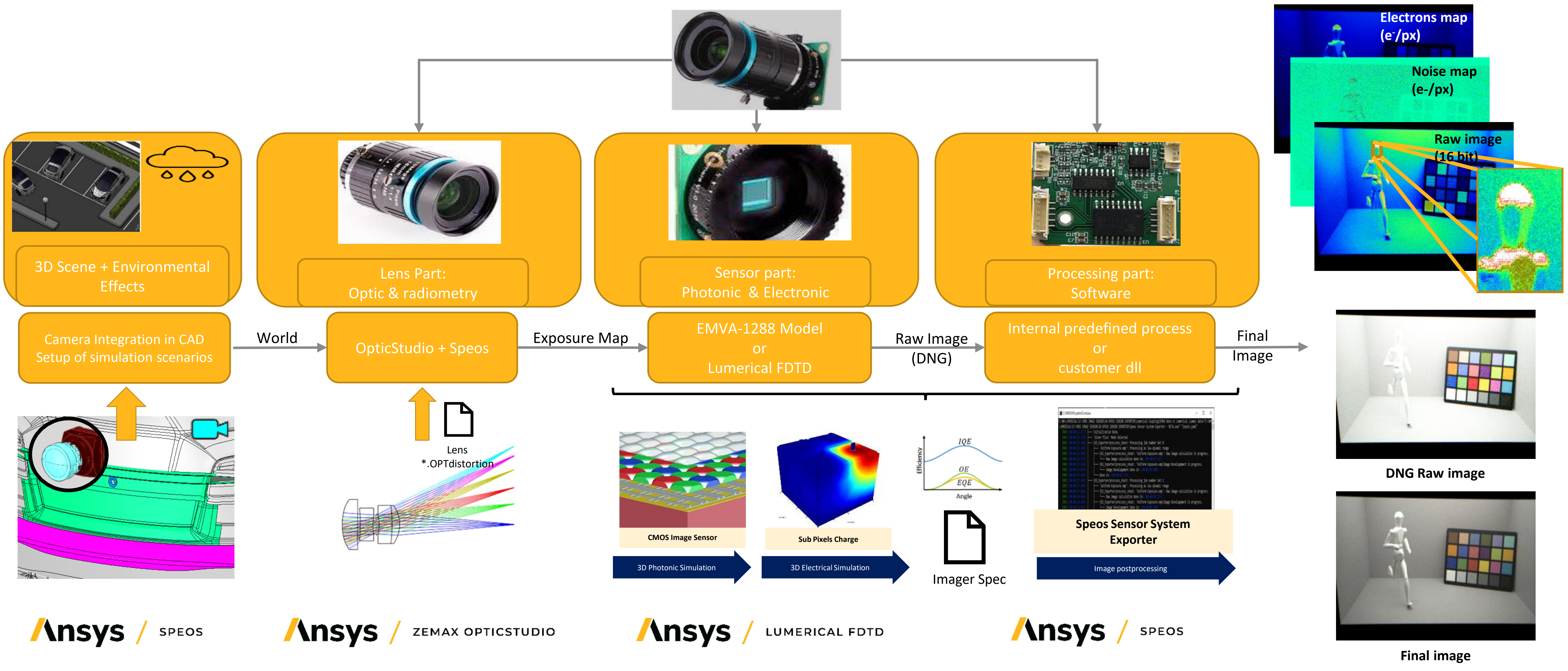
Ansys Speos
Optical System Modelling & Validation

System-Design-Level

- Individual 3D environment integration
- Lighting evaluation
- Human Vision rendering
- Customer's perception for decision making

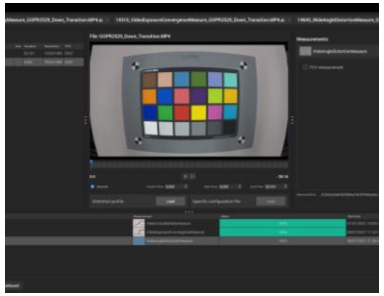
From Nano  → To Macro  → To System 

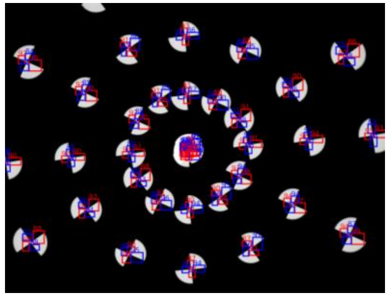
Virtual camera validation workflow overview

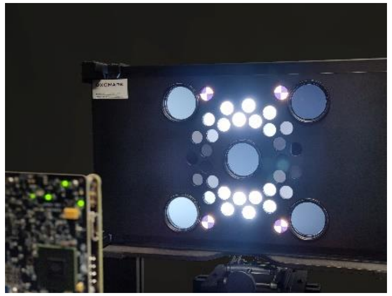


DXOMARK presentation

Our products and services







Benchmarks & Test reports

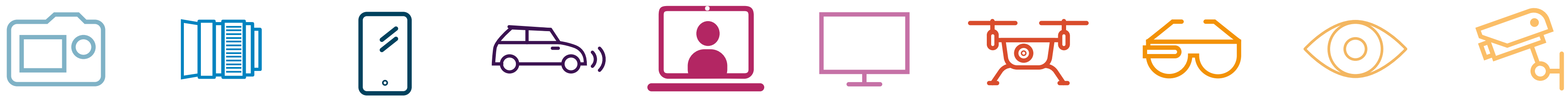
Repeatable and automated labs & measurement tools

Seminars & Training courses

Quick introduction of Analyzer

- **Comprehensive** and **modular** laboratory solution for image and video quality evaluation
- Including, not only equipment such as **charts**, **lights**, and **metrology tools** but also the **software**
- **Fast, accurate, automated, repeatable**, and highly configurable with python **API**

Launched in 2003 | **+200 solutions WW** | **2-3 updates per year**



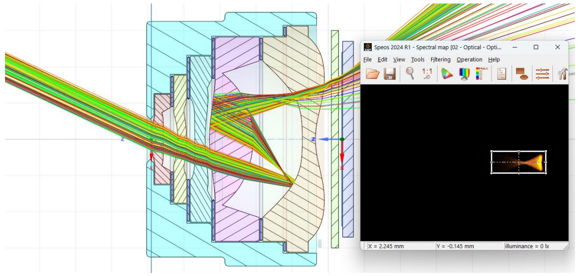
Discover our new catalog:

From simulation to mass production

Partner with a key player in simulation to provide a complete accompaniment to our customers

- Together, we enable easy testing of any Camera Analyzer KPIs at design level before going to prototyping or having a real system

Simulation testing



R&D testing

Production-line testing

DXOMARK and Ansys partnership

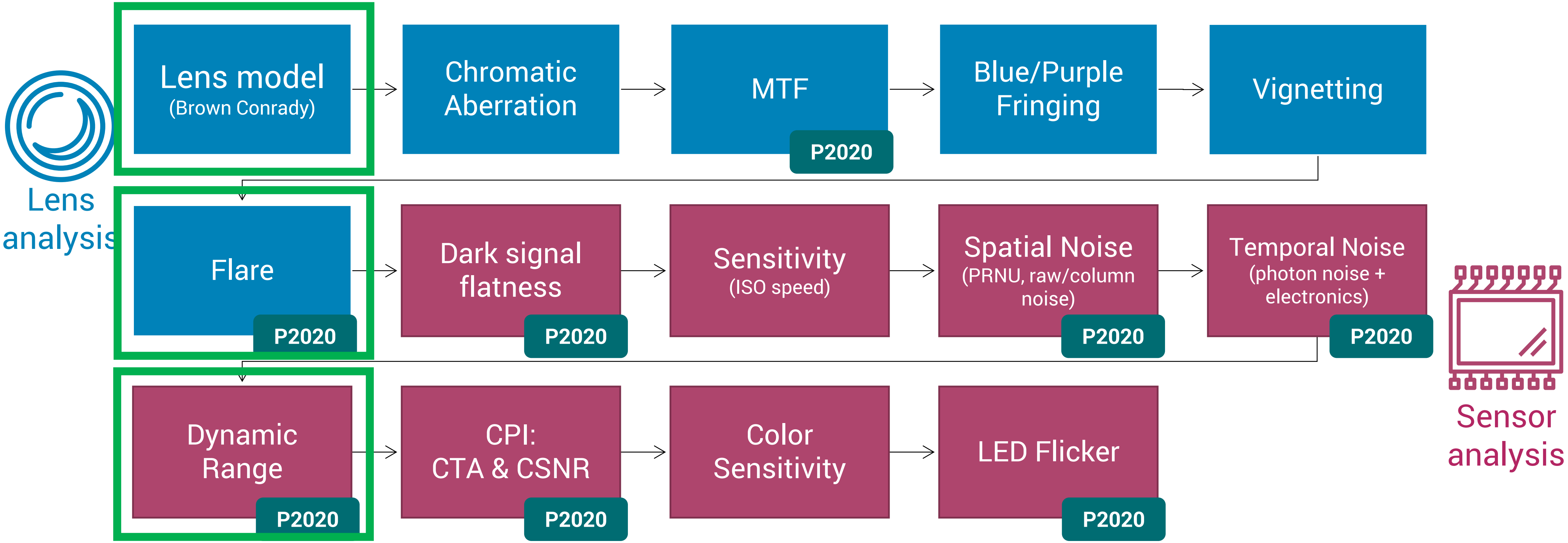
Combining Ansys and DXOMARK's technology enables extreme predictive accuracy when validating virtual camera systems:

- Physical metrics considered during the product development phase to identify potential problems.
- Scene setup in virtual environment (lighting conditions, objects, …) with endless possibilities of scenarios.
- Automated test campaigns at the speed of simulations.

DXOMARK

Scope of today's results: DXOMARK Automotive camera report

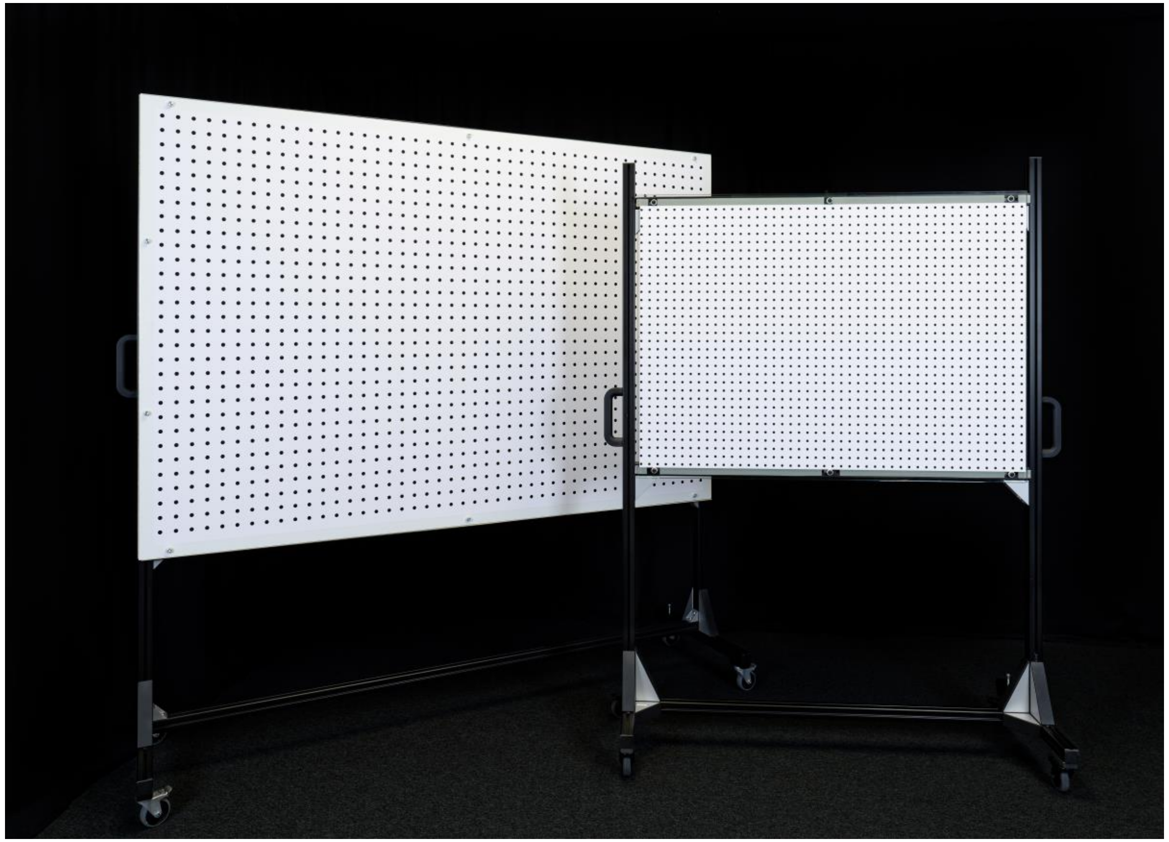
The full evaluation of the physical properties of the camera module:



DXOMARK

Distortion measurement

Distortion



Measured on dot charts available in several formats to fit all possible fields of view.

Follows ISO 17850 and IEEE 1858 standards.

Outputs distortion models:

- OpenCV Brown-Conrady 5/12 coefficients
- XY polynomial

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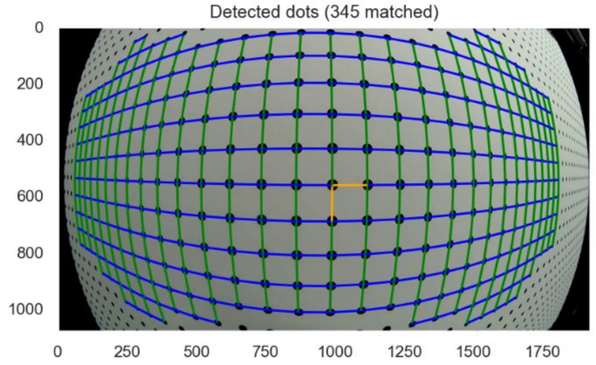
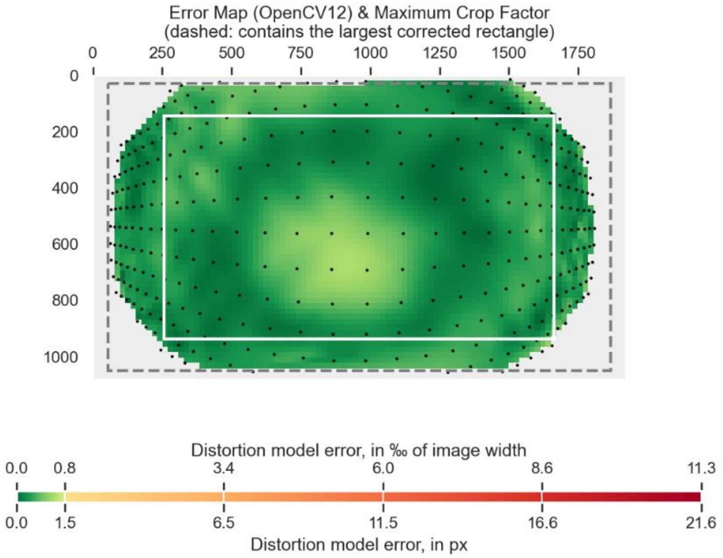
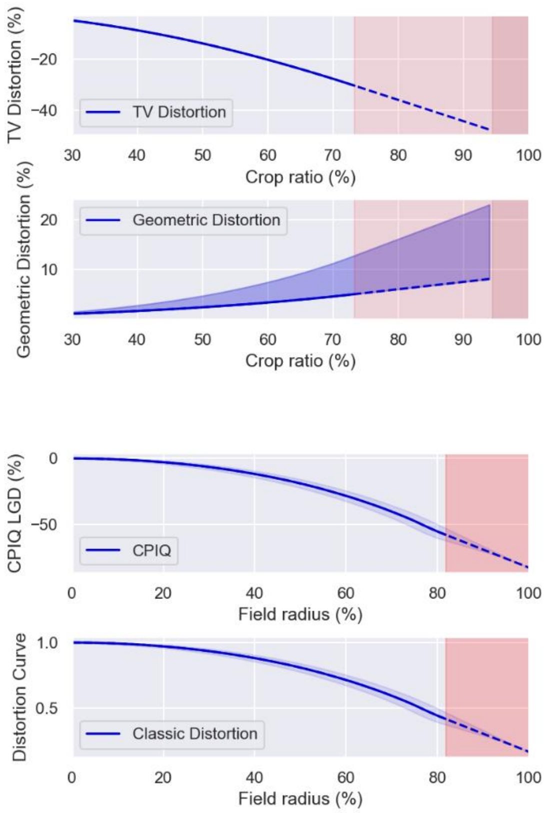
Radial output example

```
- OpenCV (RMSE=4.85, MaximumValidCropFactor=73.3%, RMSE inside=5.58)
- OpenCV12 (RMSE=0.46, MaximumValidCropFactor=73.3%, RMSE inside=0.45)
- PolyXY (RMSE=3.11, MaximumValidCropFactor=73.3%, RMSE inside=6.72)
Selected model OpenCV12
```







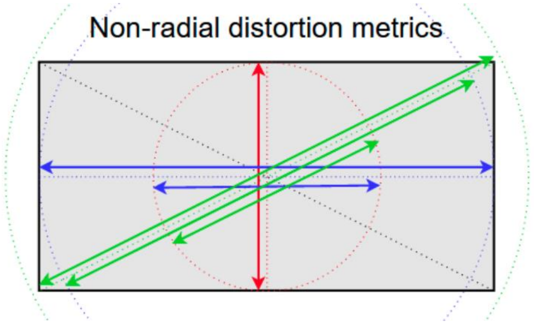
	Results	Results (Non-extrapolated)
TV Distortion	-47.74 %	-30.47 %
Geometric Distortion (Avg)	+8.10 %	+5.07 %
Geometric Distortion (Max)	+22.98 %	+12.84 %
CPIQ LGD (Max)	-82.97 %	-62.42 %
CPIQ LGD (JND)	-15.17	-15.17

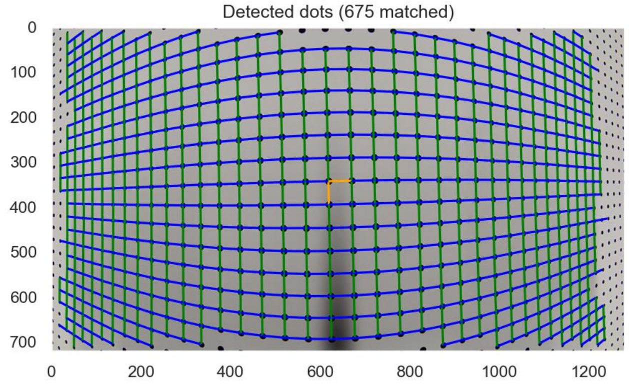
Distortion

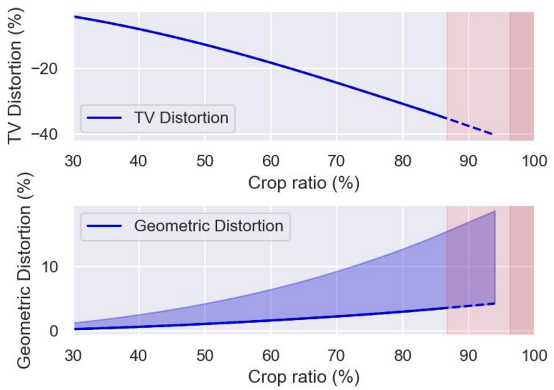
Non-radial output example

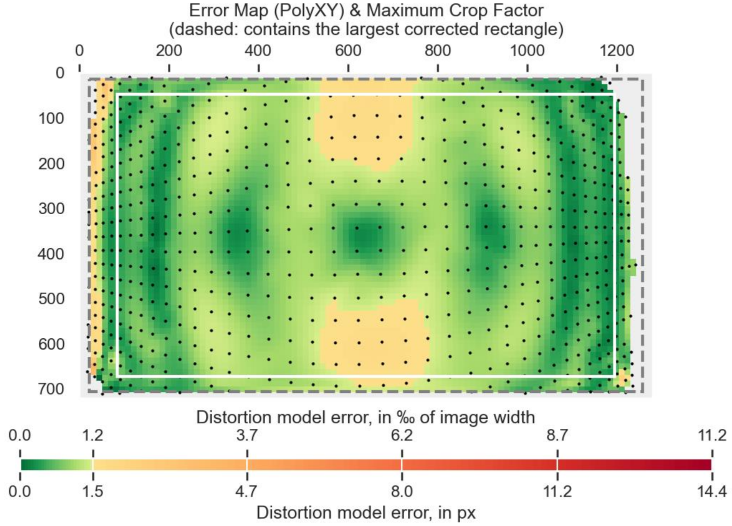
```
- OpenCV (RMSE=11.21, MaximumValidCropFactor=40.7%, RMSE inside=8.45)
- OpenCV12 (RMSE=9.89, MaximumValidCropFactor=58.0%, RMSE inside=10.66)
- PolyXY (RMSE=0.90, MaximumValidCropFactor=86.8%, RMSE inside=0.95)
Selected model PolyXY
```

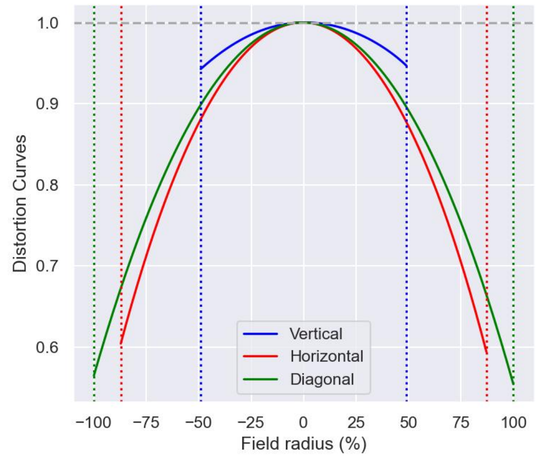
The polynomial distortion model supports well non-radial distortion







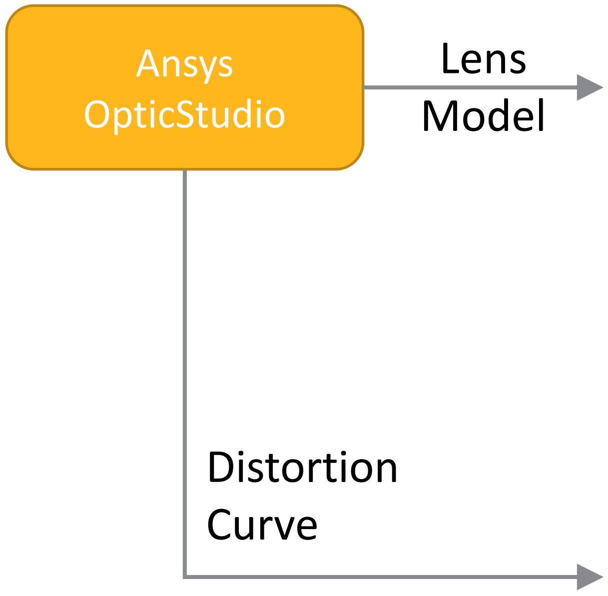


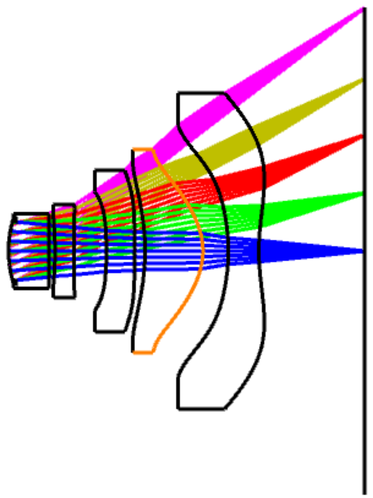


	Results	Results (Non-extrapolated)
TV Distortion	-40.32 %	-35.31 %
Geometric Distortion (Avg)	+4.23 %	+3.56 %
Geometric Distortion (Max)	+18.64 %	+15.50 %
CPIQ LGD (Max)	-52.14 %	-50.50 %
CPIQ LGD (JND)	-15.17	-15.17

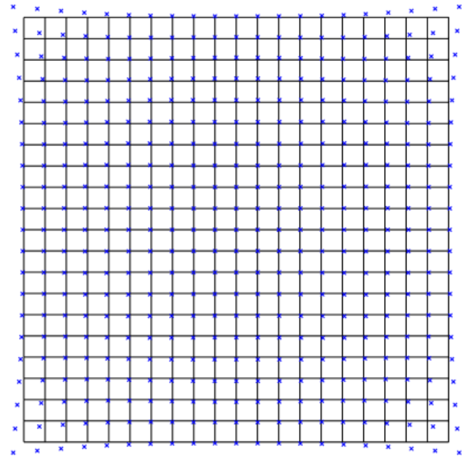
Field Radius	49%	87%	100%
Vertical Distortion Max	0.94	-	-
Horizontal Distortion Max	0.88	0.59	-
Diagonal Distortion Max	0.90	0.66	0.55

Lens Distorsion





OpticStudio system

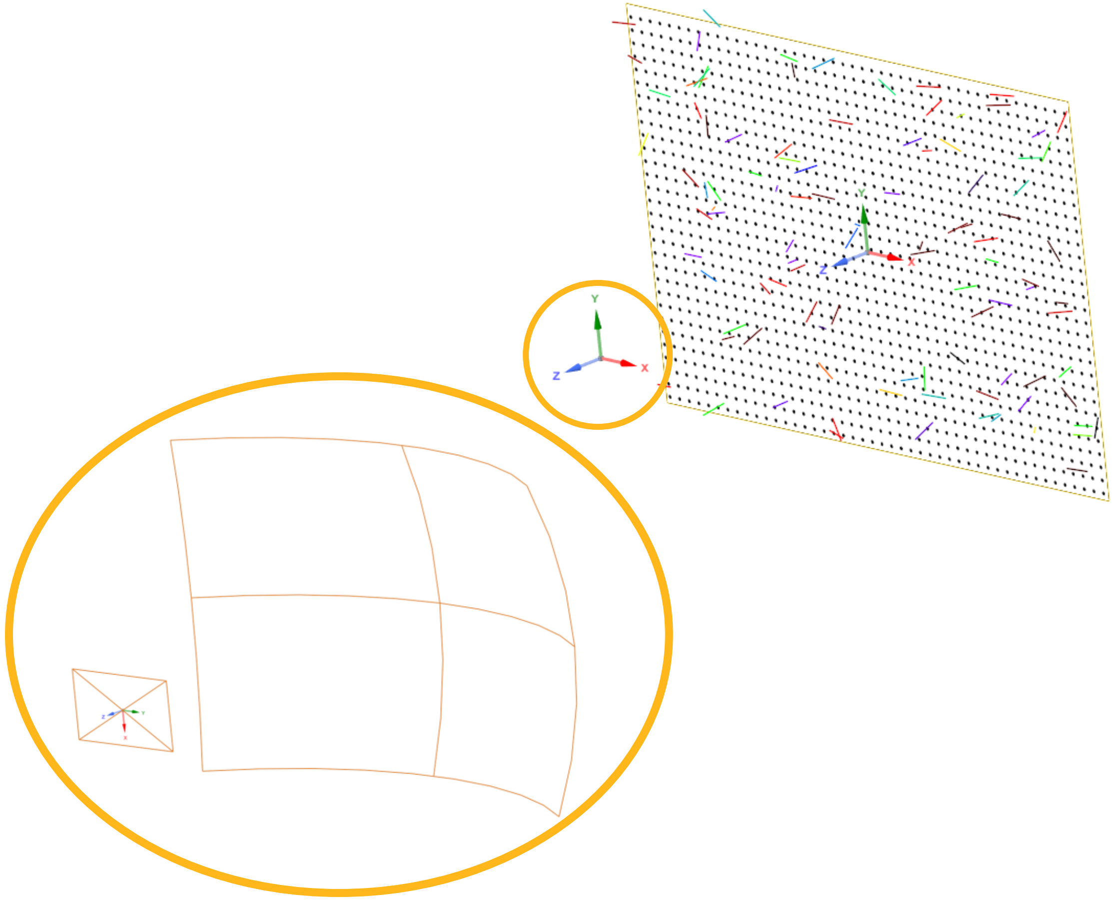


Distortion curve

Lens Distorsion

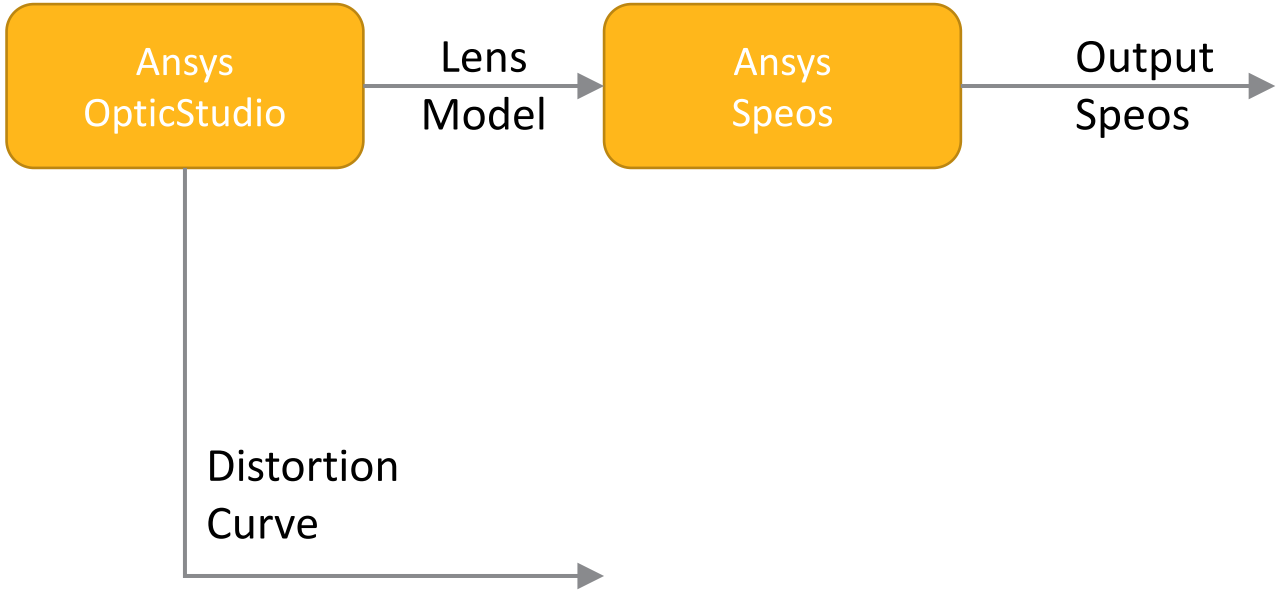
Ansys OpticStudio → Lens Model → Ansys Speos

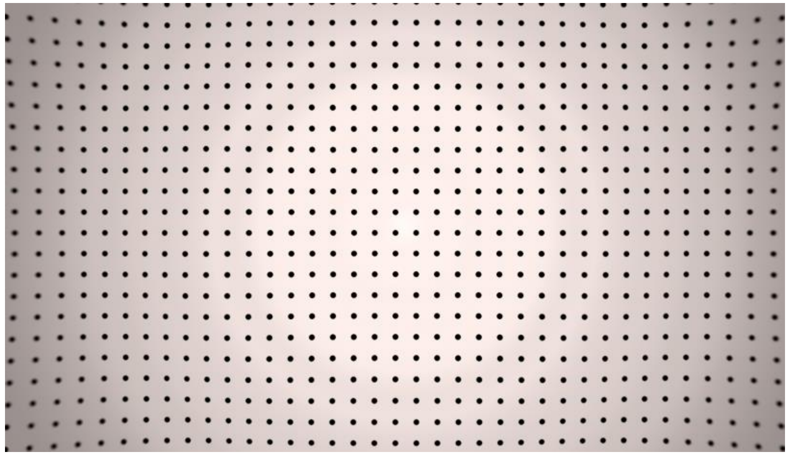
Ansys OpticStudio → Distortion Curve →



Simulation setup using
camera sensor based on OpticStudio lens model

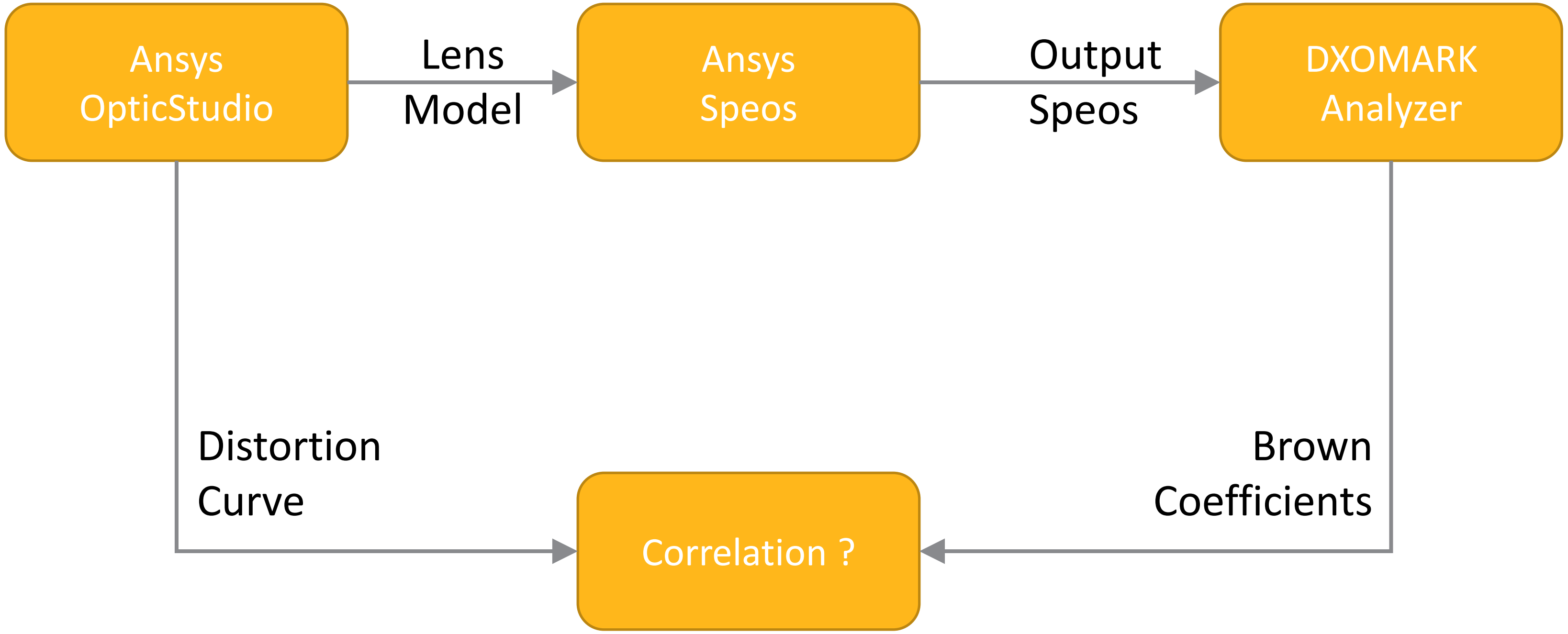
Lens Distorsion





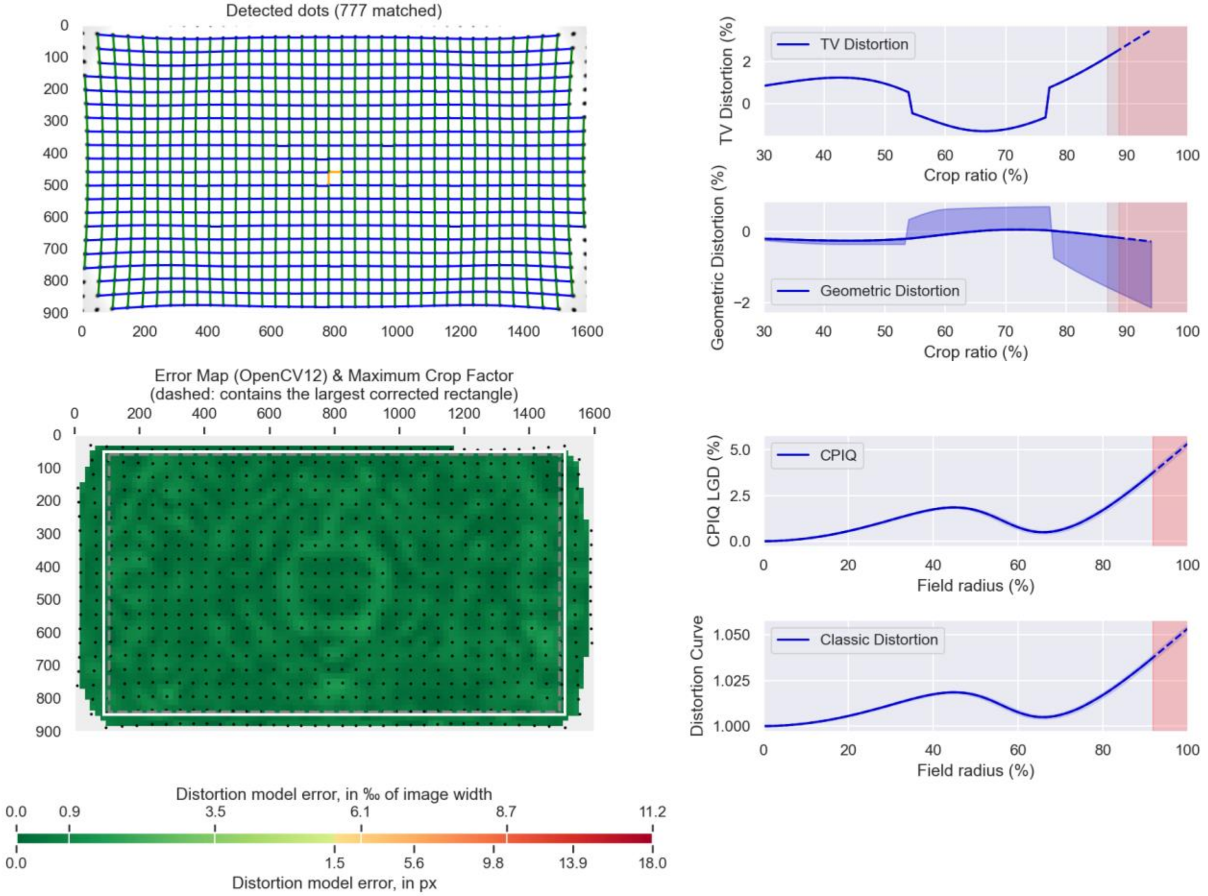
Speos camera simulation result

Lens Distorsion



Results on simulation

```
- OpenCV (RMSE=1.98, MaximumValidCropFactor=90.6%, RMSE inside=2.03)
- OpenCV12 (RMSE=0.16, MaximumValidCropFactor=90.6%, RMSE inside=0.16)
- PolyXY (RMSE=1.45, MaximumValidCropFactor=90.6%, RMSE inside=1.47)
Selected model OpenCV12
```



	Results	Results (Non-extrapolated)
TV Distortion	+3.54 %	+2.58 %
Geometric Distortion (Avg)	-0.27 %	-0.17 %
Geometric Distortion (Max)	-2.15 %	-1.72 %
CPIQ LGD (Max)	+5.54 %	+3.96 %
CPIQ LGD (JND)	-1.21	-0.67

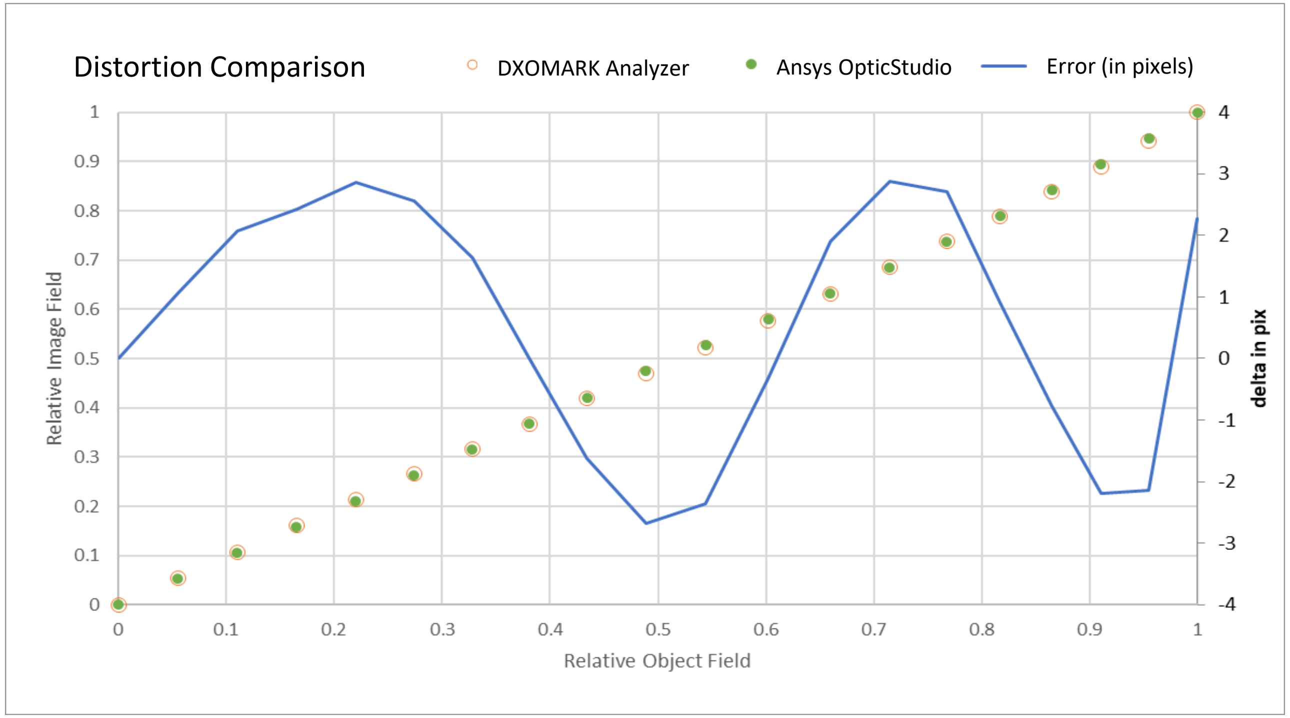
Lens Distortion

Fast analysis generating Brown-Conrady coefficients :
(with axis symmetry assumed)

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = f_d(x_c, y_c) = \begin{bmatrix} x_c\left(1 + k_1 r^2 + k_2 r^4 + k_3 r^6\right) \\ y_c\left(1 + k_1 r^2 + k_2 r^4 + k_3 r^6\right) \end{bmatrix}$$

Brown-Conrady coef. from DXOMARK Analyzer:

k1 =	-0.16591
k2 =	0.333083
k3 =	0.880093



➔ Correlation is better than +/- 3 pixels.

Dynamic Range

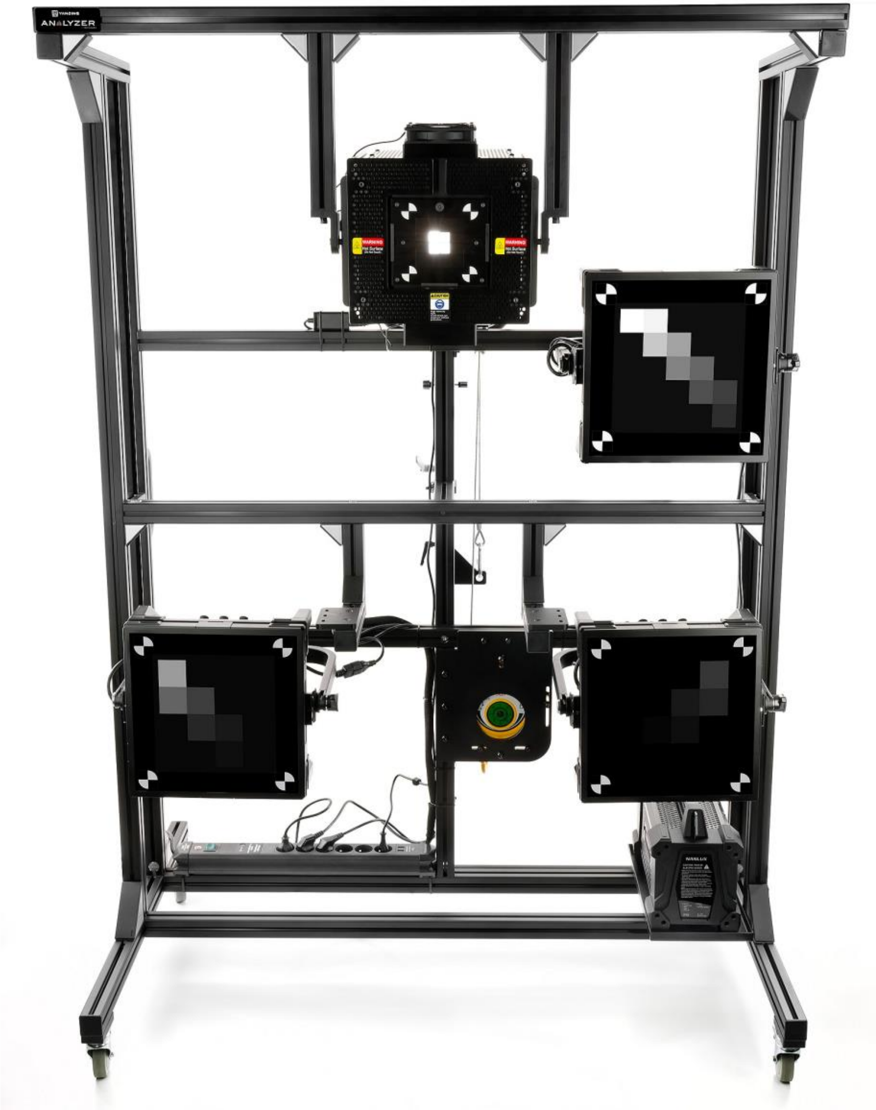
Dynamic Range Setup

Analysis of single capture dynamic range

Up to 170dB between the darkest and the brightest patch

Up to 1.6M cd/m² on the brightest patch

4 adjustable light sources to tune dynamic range interval analysis



Dynamic Range Metrics

Contrast to Noise Ratio (CNR):
measures separability between two populations

$$\mathrm{CNR}_{N:1}(A,B) = \frac{s_A - s_B}{\sqrt{\sigma_A^2 + \sigma_B^2}}$$

With

- A, B: the 2 ROIs of interest
- N: the nominal simple contrast ratio between A and B
- s_A, s_B the signal related to A and B
- σ_A^2, σ_B^2 the noise variance related to A and B

2 definitions:

- **Temporal CNR:** $\mathrm{CNR}_{\mathrm{temp},N:1}$
- **Total CNR:** $\mathrm{CNR}_{\mathrm{tot},N:1}$

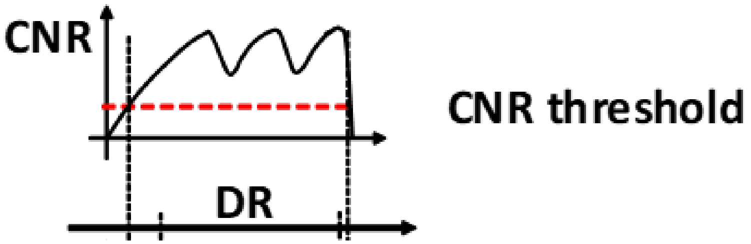
Formulas extracted from IEEE P2020 Draft

DXOMARK

Dynamic Range Metrics

Dynamic Range:

$$R_d[\text{dB}] = 20 \cdot \log_{10}\left(\frac{L_{\text{max}}}{L_{\text{min}}}\right)$$



CNR Thresholding shows separability for machine vision applications

L_{min} and L_{max} the max and min luminance values that verify:

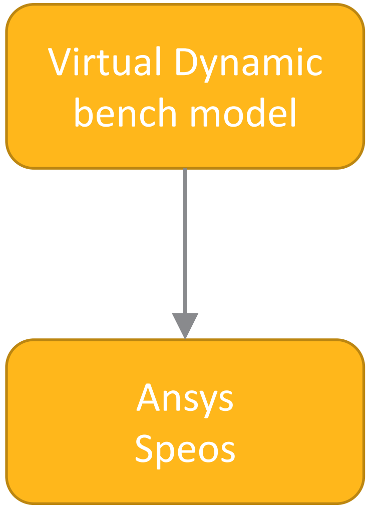
$$\mathbf{CNR_{tot,2:1} > 1}$$

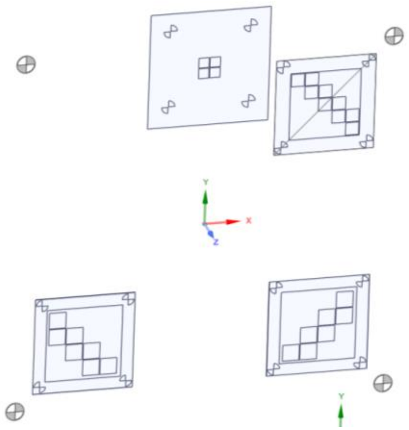
Contrast Detection Ratio (CDR):

$$\text{CDR}_{\text{dB}} = 20 \cdot log_{10}\left(\frac{L_{\text{max}}[\text{CNR} > 1]}{L_{\text{min}}[\text{CNR} > 1]}\right)$$

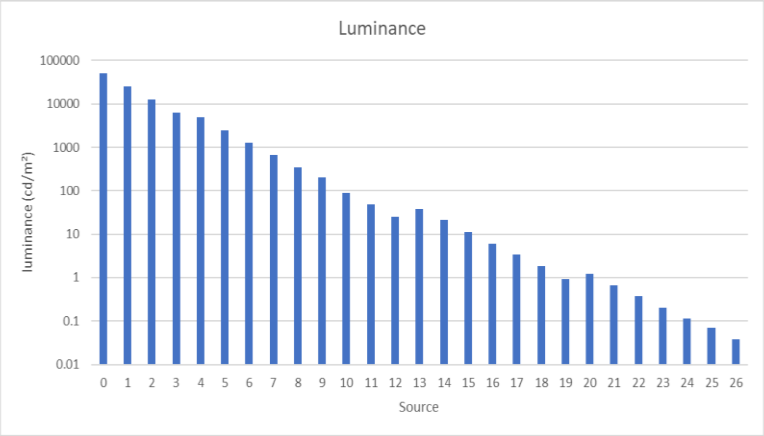
Formulas and Figures extracted from IEEE P2020 Draft

Dynamic Range For Sensor Model



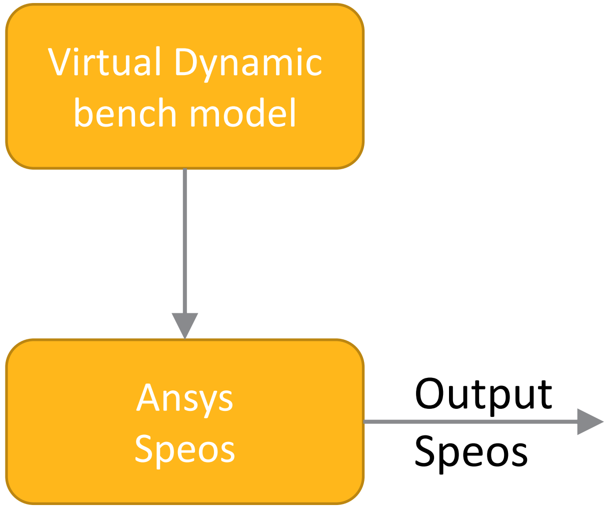


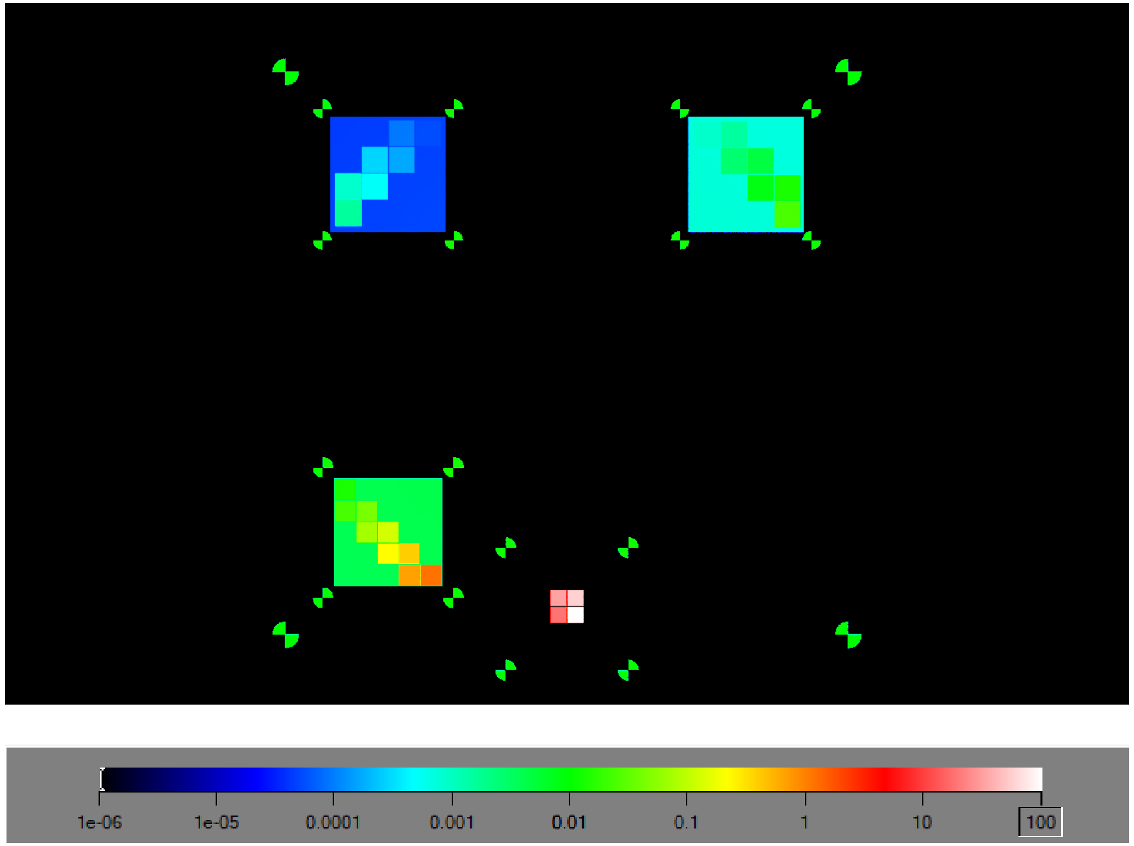
Virtual dynamic bench CAD model



Luminance specifications for sources

Dynamic Range For Sensor Model

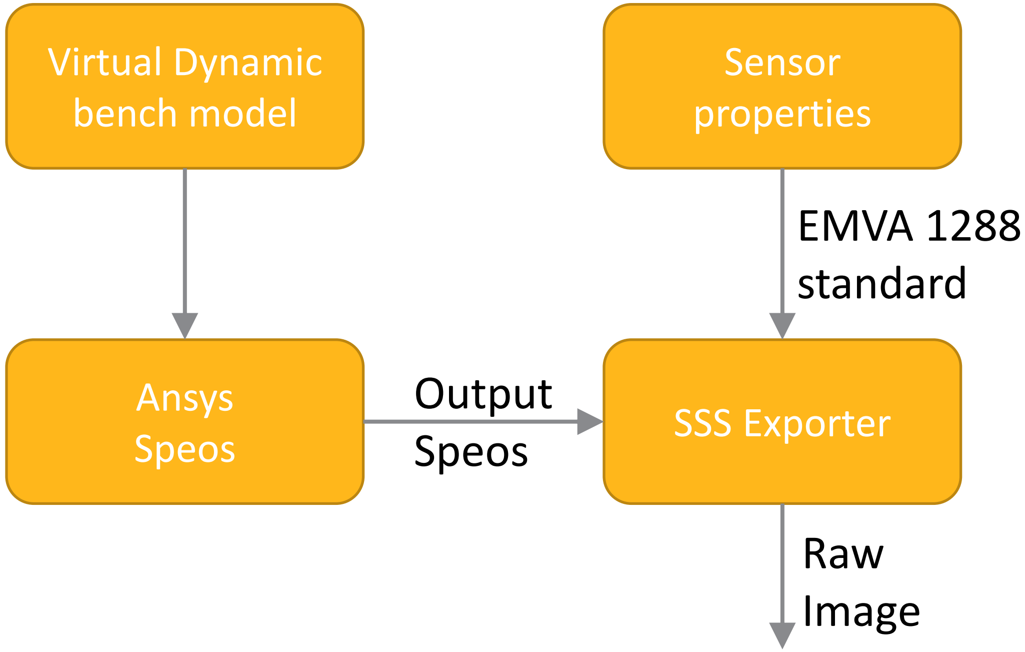


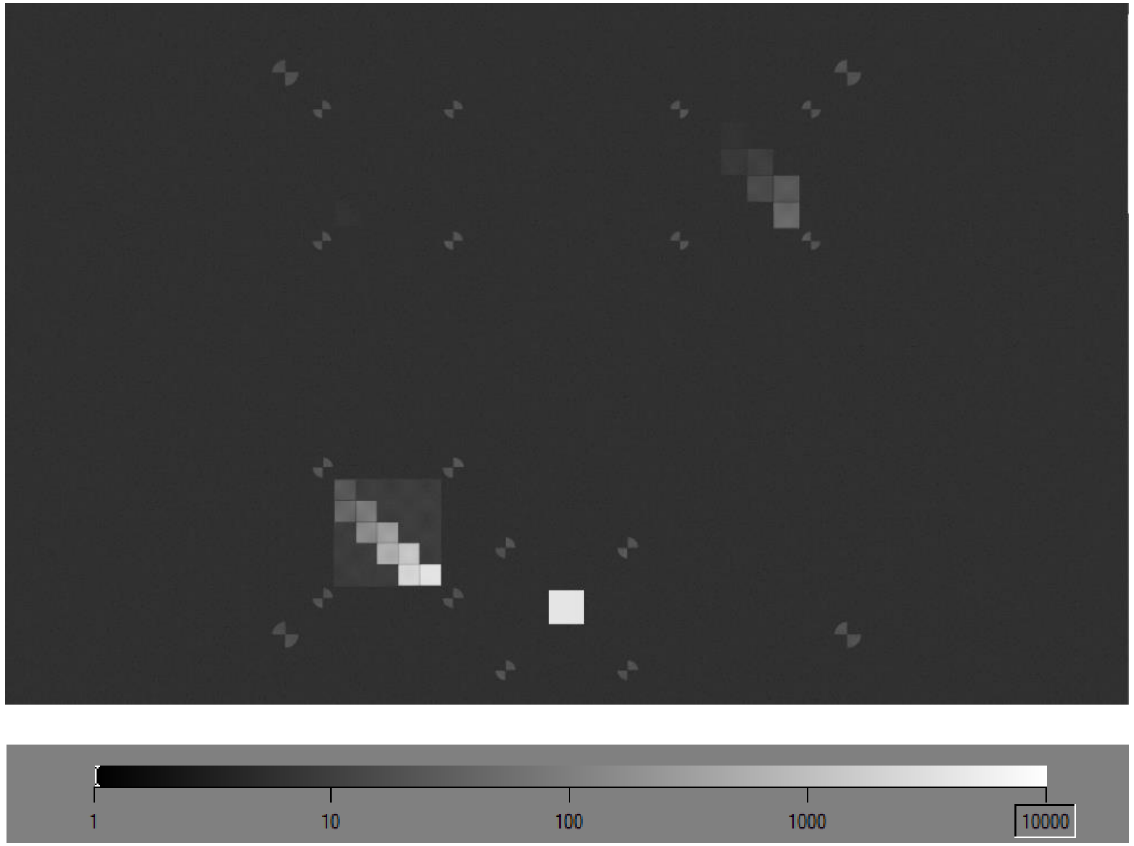


Speos camera simulation result

Exposure map in J/m²/nm

Dynamic Range For Sensor Model

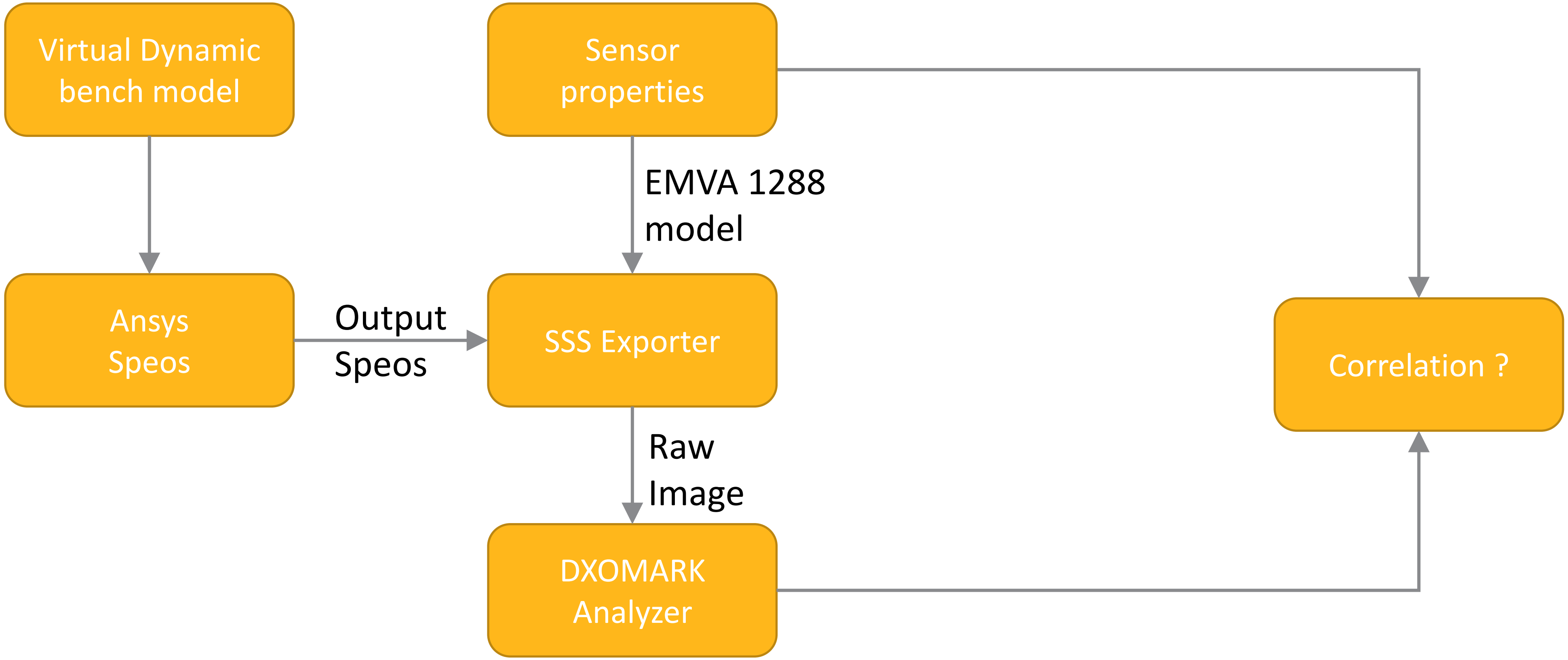




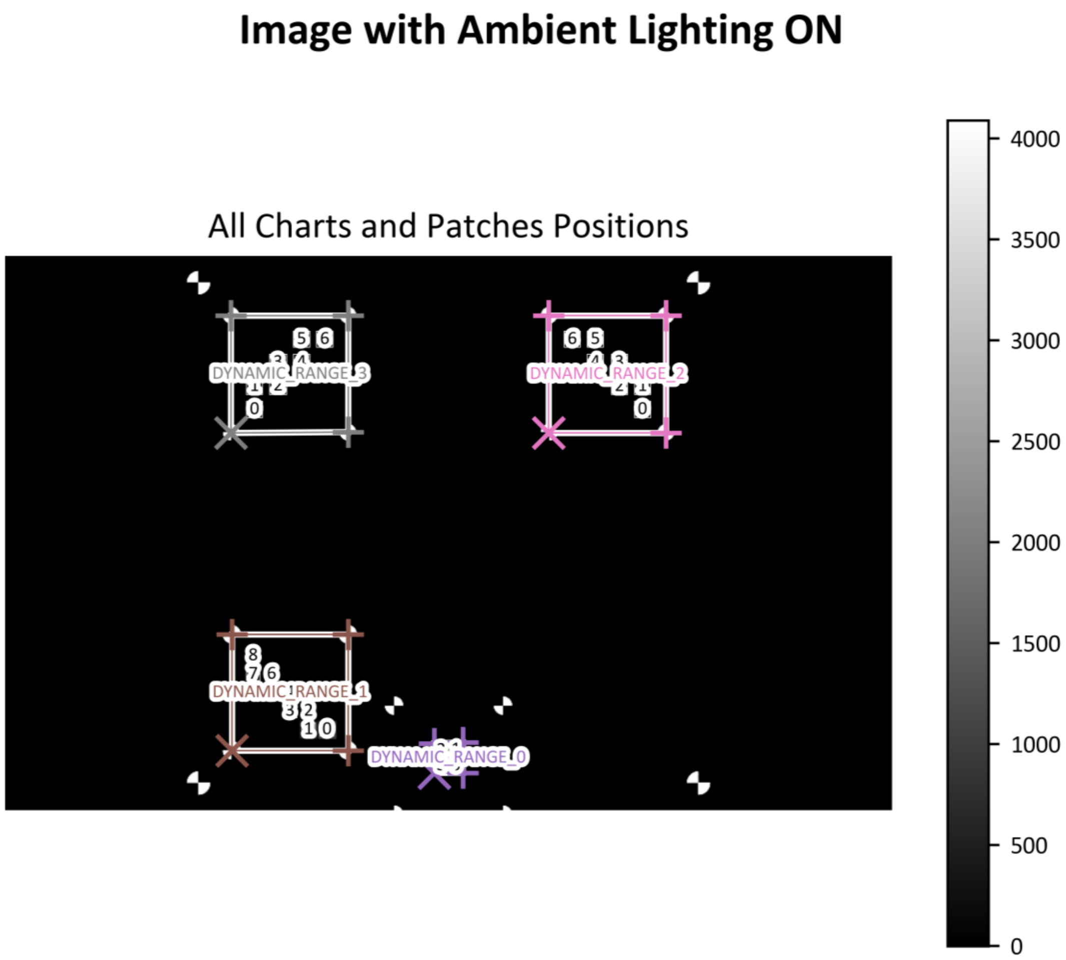
Post processed result using SSS Exporter

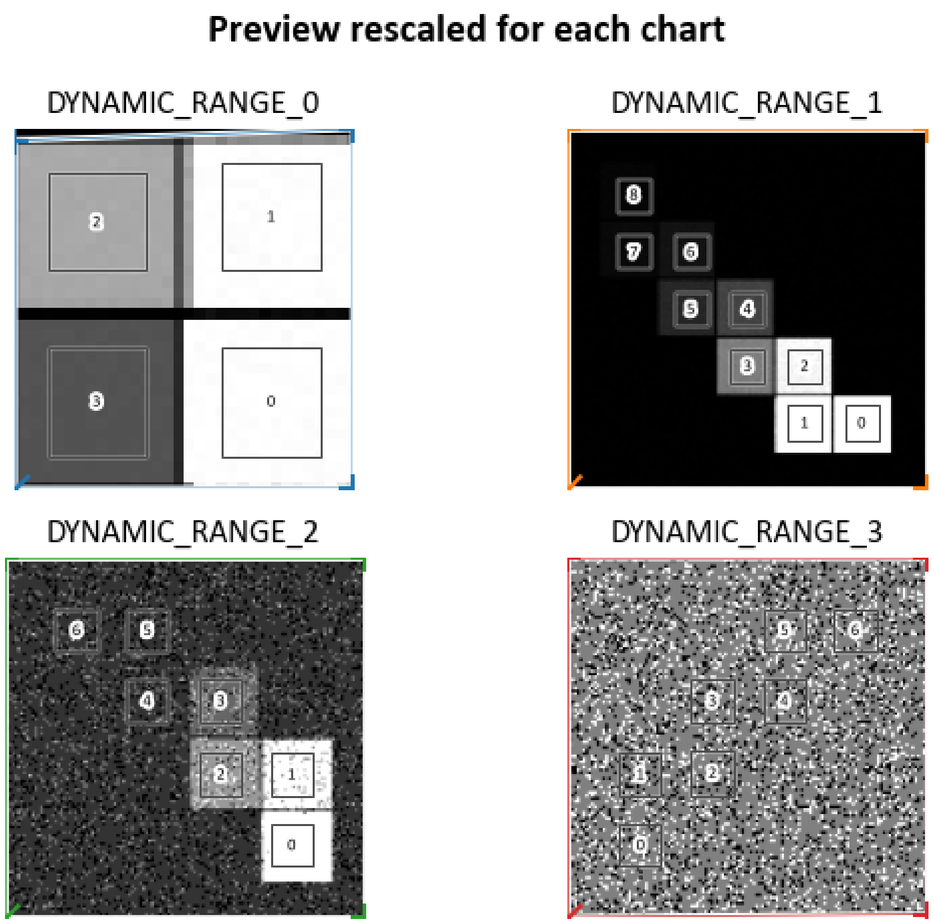
Raw image in Digital Number

Dynamic Range For Sensor Model

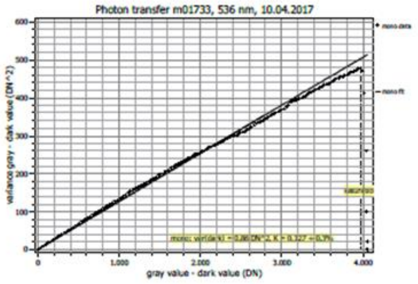


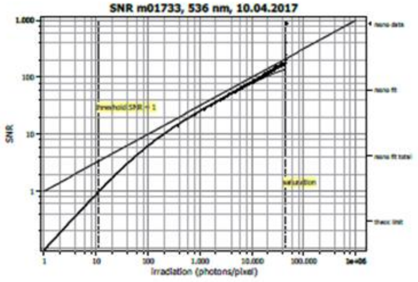
Results on simulation





Results on simulation





Quantum efficiency
η 71.2%

Overall system gain
K 0.127 DN/e^-
$1/K$ 7.891 e^-/DN

Temporal dark noise & DSNU
$\sigma_{y.dark}$ 0.93 DN
$DSNU_{1288}$ 0.12 DN
σ_d 6.94 e^-
$DSNU_{1288}$ 0.92 e^-

Signal-to-noise ratio & PRNU
SNR_{max} 178
45.0 dB
7.5 bit
$1/SNR_{max}$ 0.56 %
$PRNU_{1288}$ 0.45 %

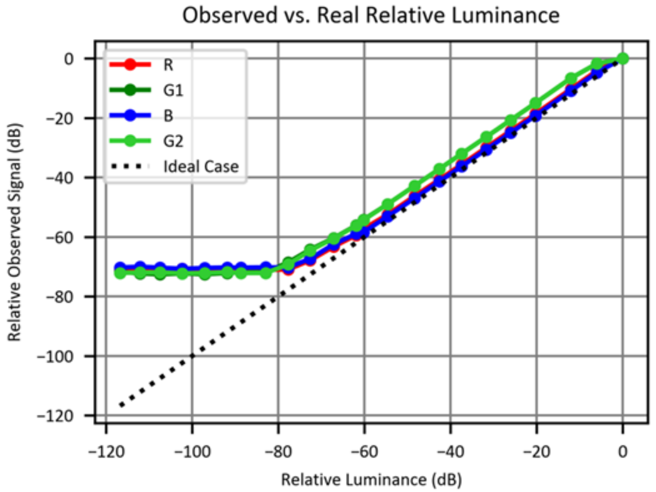
Nonlinearity
LE 0.38%
LE_{min} -0.42%
LE_{max} 0.33%

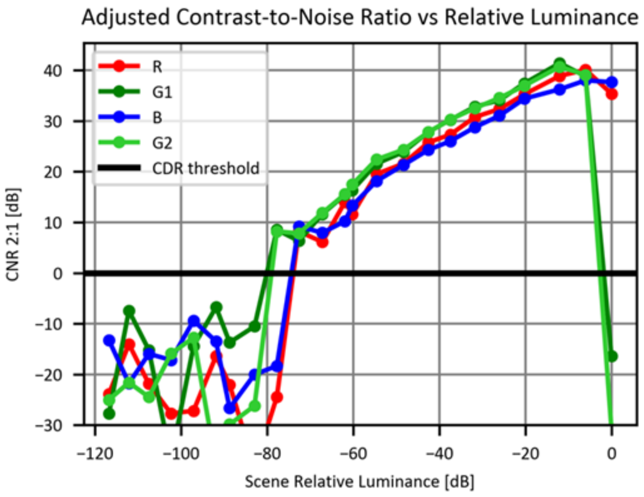
Sensitivity & saturation
$\mu_{p.min}$ 10.99 p
0.320 p/μm^2
$\mu_{p.sat}$ 44540 p
1297 p/μm^2
$\mu_{e.min}$ 7.82 e^-
0.228 e^-/μm^2
$\mu_{e.sat}$ 31693 e^-
923 e^-/μm^2

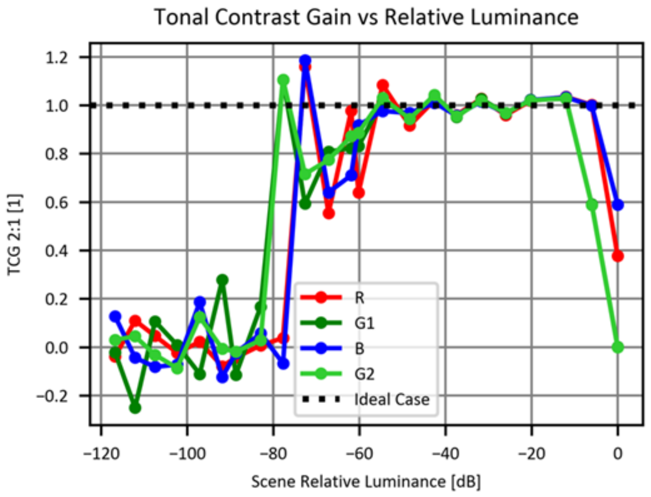
Dynamic range
DR 4053
72.2 dB
12.0 bit

Dark current
$\mu_{c.mean}$ 1.4 DN/s
$\mu_{c.mean}$ 11.1 e^-/s
$\mu_{c.var}$ 5.9 e^-/s

	R	G1	B	G2
CDR (dB)	72.6	71.7	72.6	71.7
Lmin (cd/m^2)	8.3e+00	4.6e+00	8.3e+00	4.6e+00
Lmax (cd/m^2)	3.5e+04	1.8e+04	3.5e+04	1.8e+04







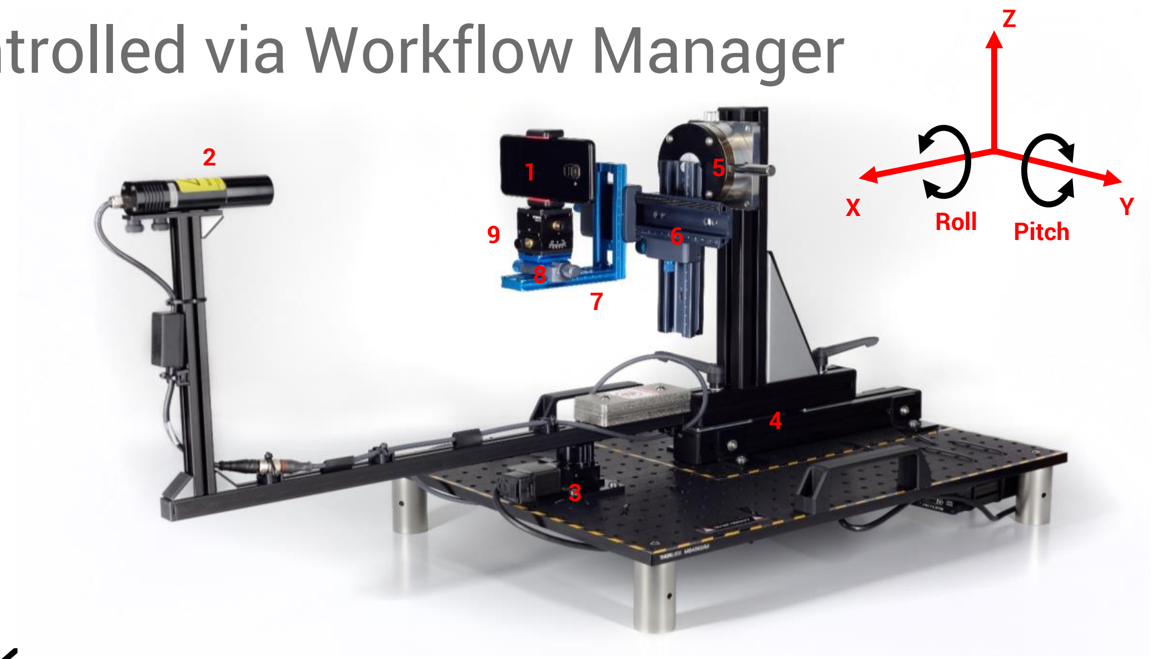
-> Correlation is less than +/- 6dB

Flare

Hardware setup

- Compact and stable
- Intense and repeatable light source
- High linear and angular precision
- Full 2π steradians of angular range
- Easily controlled via Workflow Manager

Watch video

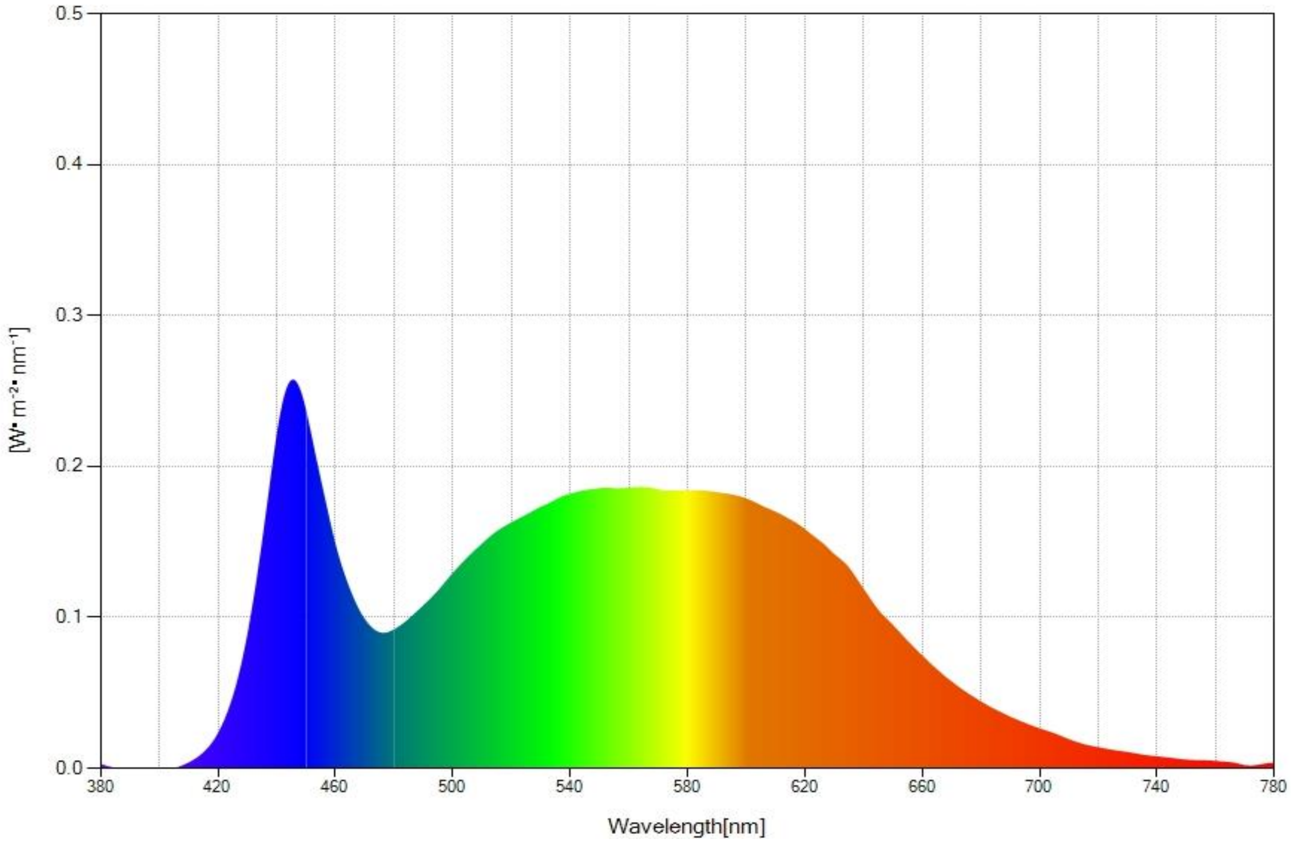


MOTORIZED ROTARY STAGE SPECIFICATIONS	
Rotation range for measurement on every axis	180°
Resolution	1.2 arcmin (0.02°)
Max rotation speed	9°/s (600 steps/s)

FLARE BENCH SPECIFICATIONS	
Size of the flare bench	Max length in operation: 970.5 mm Length in storage position: 600 mm Width: 450 mm Height: 501 mm
Weight	23 kg
Maximum size of the device under test	200 mm x 200 mm x 200 mm
Main input	100-240 VAC, 50/60 Hz, 3.3 A

Hardware setup – VIS Light source

Designed to have the same appearance as the sun in size and color



Spectrum of the light source

LIGHT SOURCE SPECIFICATIONS	
Light type	Collimated high-power LED
Color temperature	[5000; 5500] K
CRI	85
Illuminance measured at lens surface	>10000 lx
Stability during time (for 1 hour of usage)	>98%
Apparent diameter of the light source (width)	0.95 °
Light beam diameter on the device under test at measurement position	25 mm
Virtual picture distance	Focus to infinity
Uniformity (Area of interest inside a 10 mm diameter circle concentric with the beam diameter on the DUT)	98%

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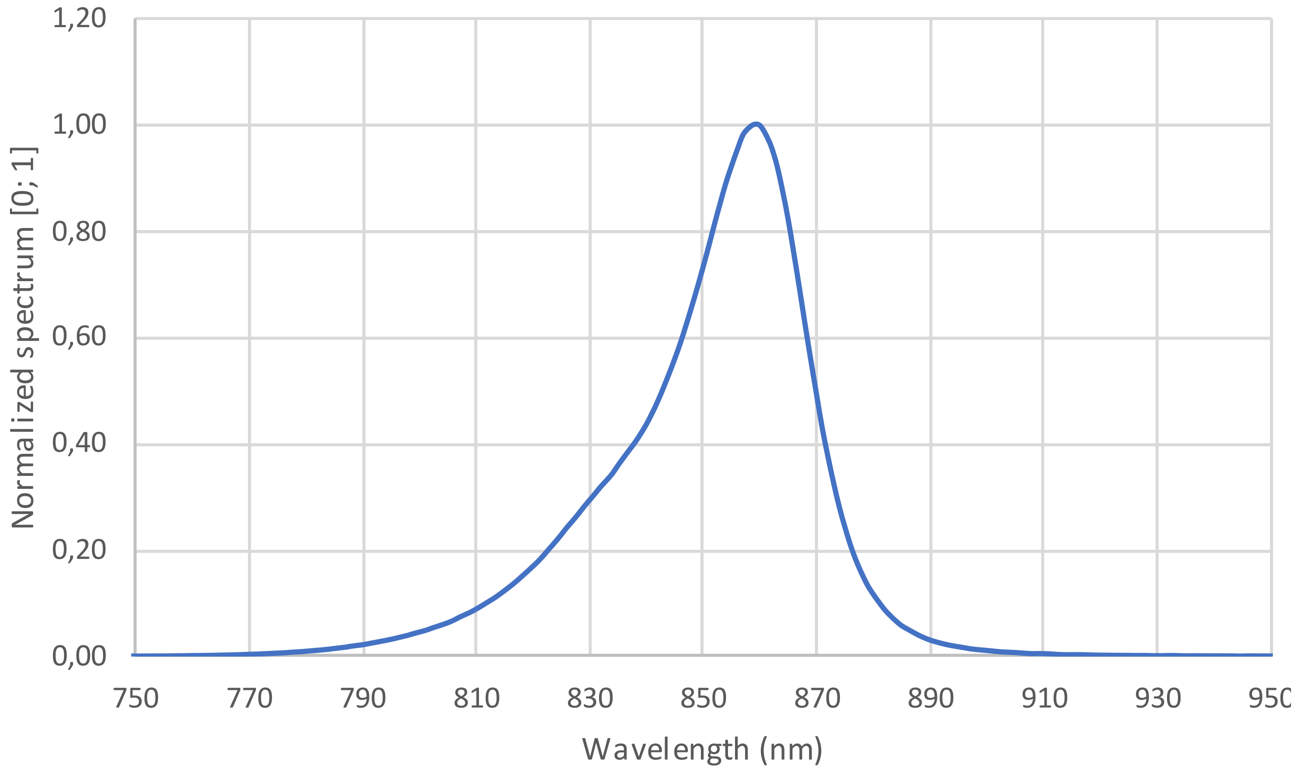
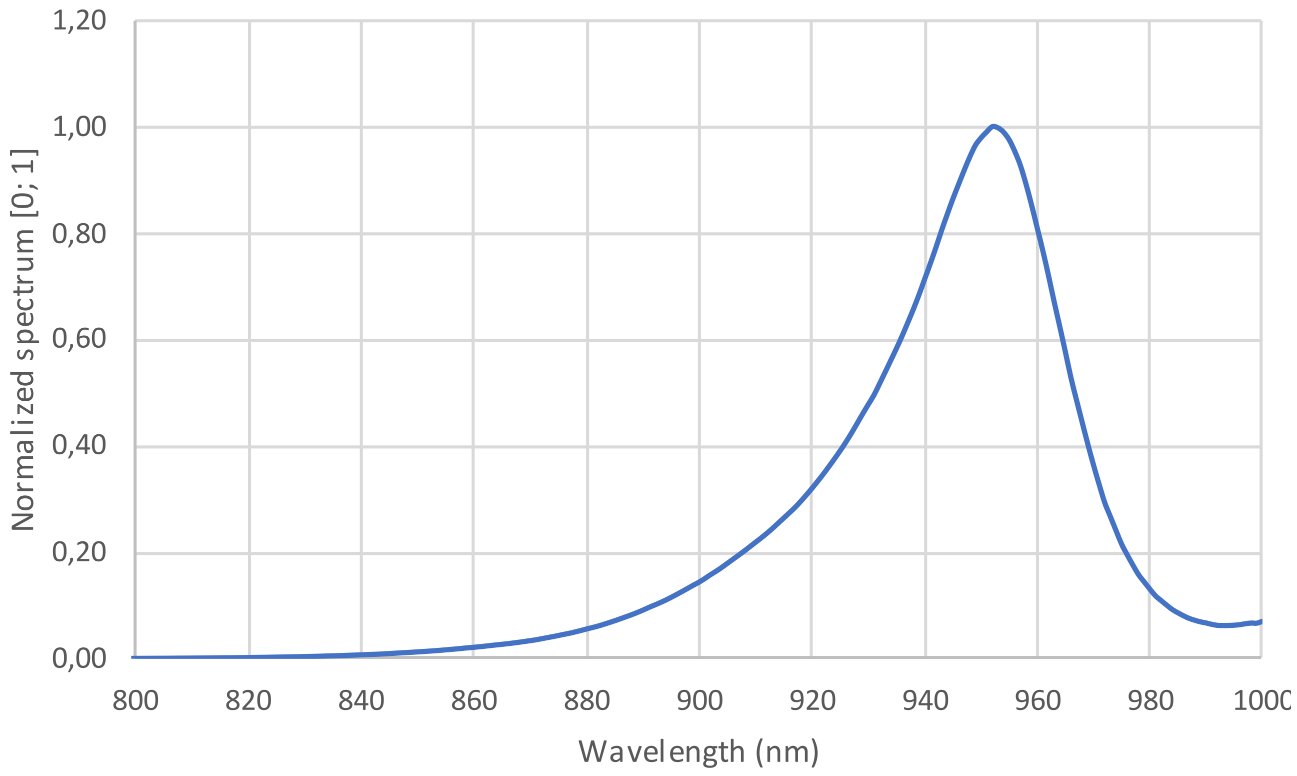
Hardware setup – 850 Light source



Spectrum of the light source

LIGHT SOURCE SPECIFICATIONS	
Light type	Collimated high-power LED
Peak wavelength	860nm
Centroid wavelength	850nm
Irradiance measured at lens surface	>21 W/m²
Stability during time (for 1 hour of usage)	>99%
Apparent diameter of the light source (width)	0.9°
Light beam diameter on the device under test at measurement position	22 mm
Virtual picture distance	Focus to infinity
Uniformity (Area of interest inside a 10 mm diameter circle concentric with the beam diameter on the DUT)	98%

Hardware setup – 940 Light source



Spectrum of the light source

LIGHT SOURCE SPECIFICATIONS	
Light type	Collimated high-power LED
Peak wavelength	950nm
Centroid wavelength	940nm
Irradiance measured at lens surface	>41 W/m²
Stability during time (for 1 hour of usage)	>98%
Apparent diameter of the light source (width)	0.9°
Light beam diameter on the device under test at measurement position	22 mm
Virtual picture distance	Focus to infinity
Uniformity (Area of interest inside a 10 mm diameter circle concentric with the beam diameter on the DUT)	98%

Unitary measurement

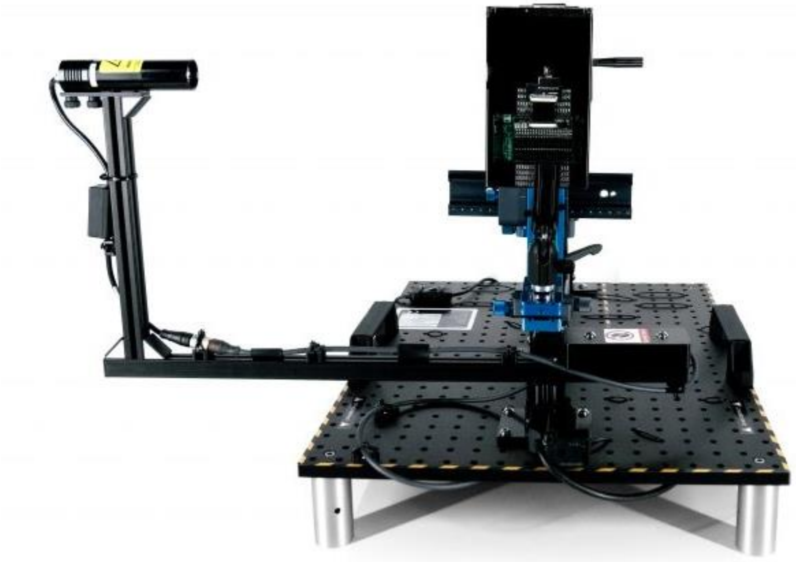
E_{source} is the illuminance of the source **measured** at the lens with a light-meter

E_{flare} is the illuminance in lux **computed** on the RAW file

E_{flare} is obtained using the sensor of the device as a light meter

We can do this thanks to the results of the ISO speed measurement

The flare metric measures the ratio between the two: $Flare_{intensity} = \frac{\mathrm{E}_{flare}}{\mathrm{E}_{source}}$



$$E_{flare} = \pi . L_0 . \frac{t_0}{t_{flare}} . \frac{x_{flare}}{x_0}$$

With:
x_0 the linearized gray level with a luminance of L_0 and an exposure time of t_0
x_f the linearized gray level of the pixel with an exposure time of t_f

Compliant with IEEE P2020 flare clause

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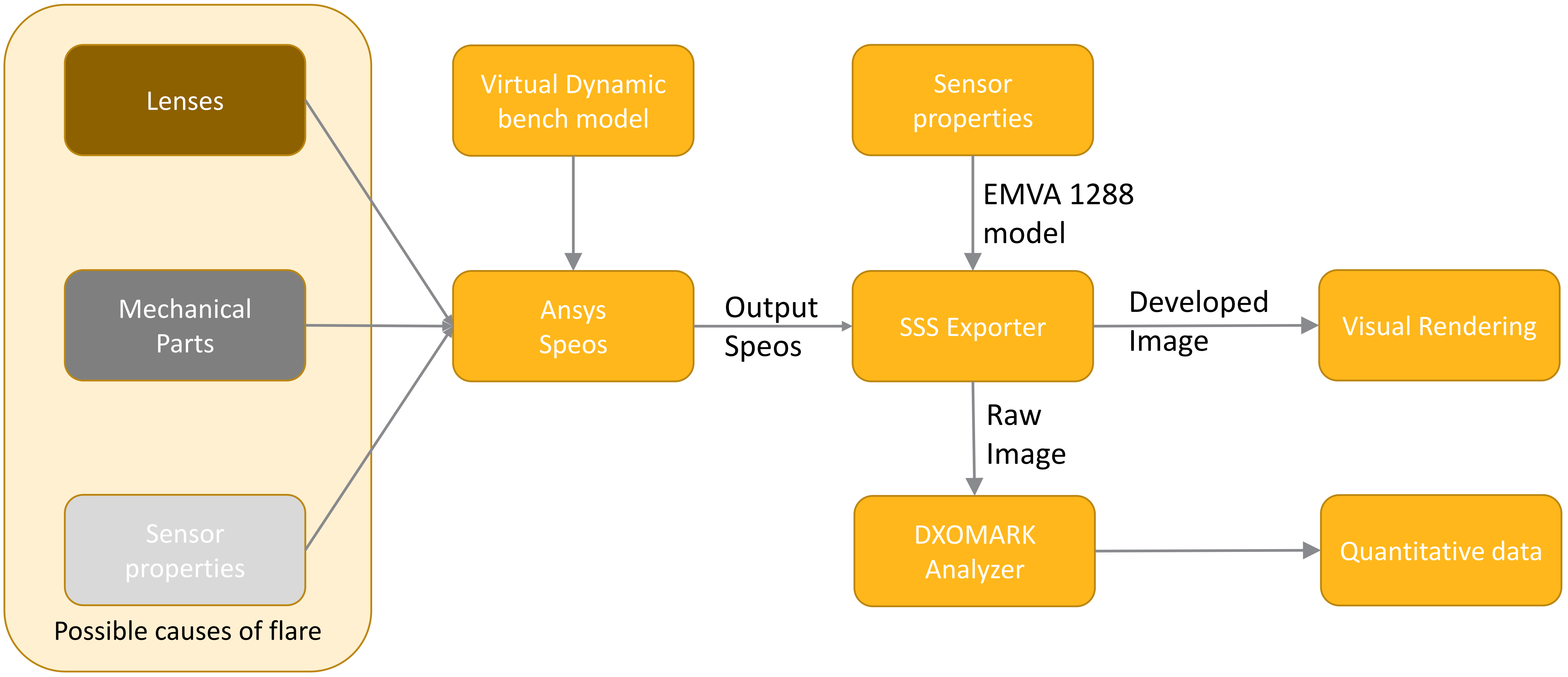
Unitary measurement

We can define a quality metric as:

$$Flare_{dB} = 20 \cdot \log_{10}\left(\frac{\mathrm{E}_{flare}}{\mathrm{E}_{source}}\right)$$

Lower values mean better quality

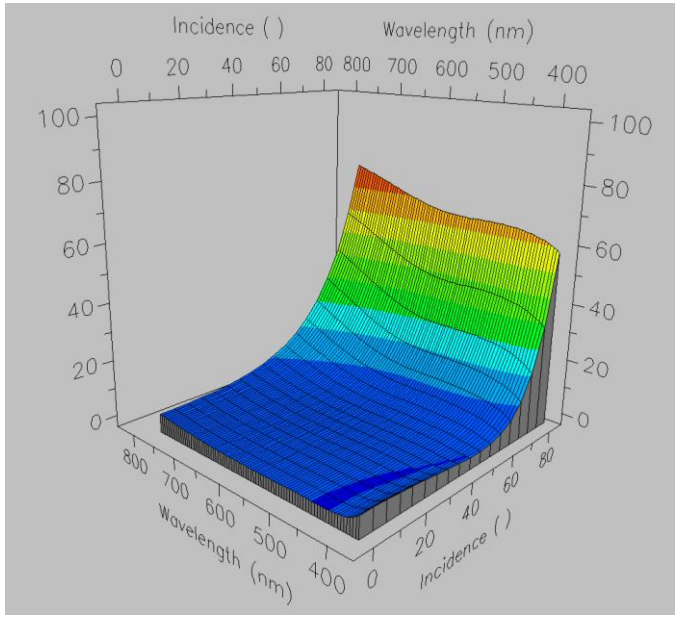
Camera Flare



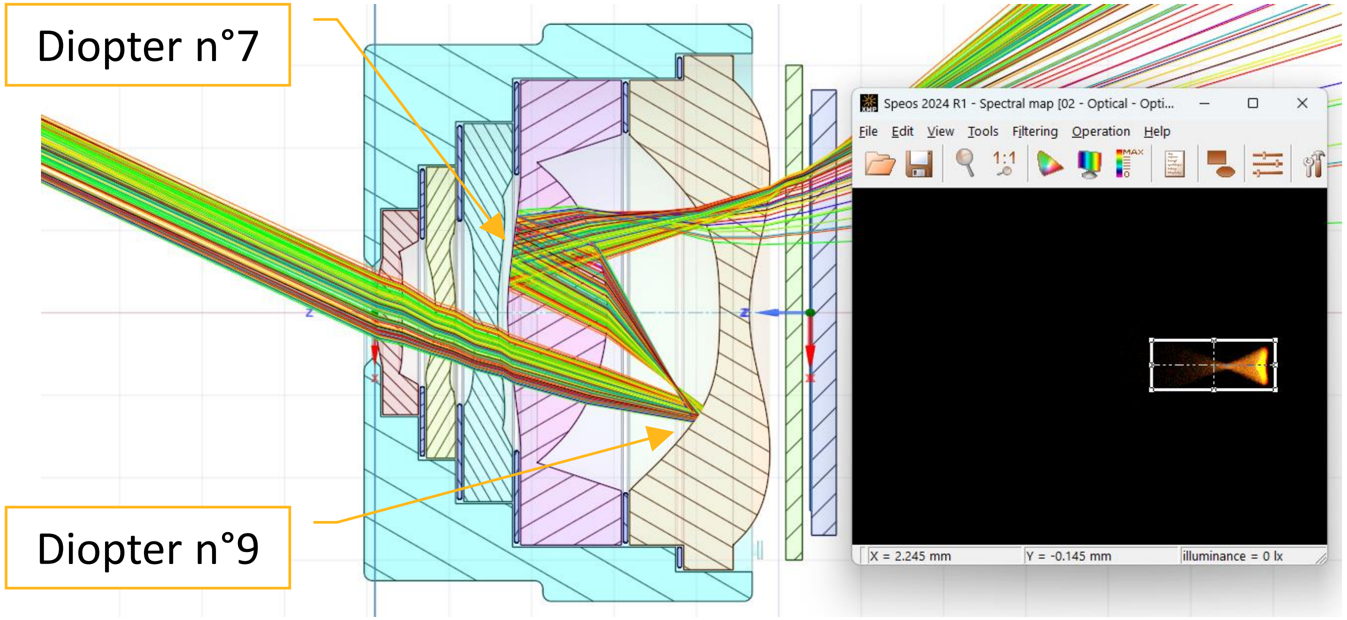
Camera Flare from lenses

Non perfect anti reflection coating has been applied on the optical surfaces to get parasite light due to Fresnel reflections.

Coating properties can be adding in Speos Model



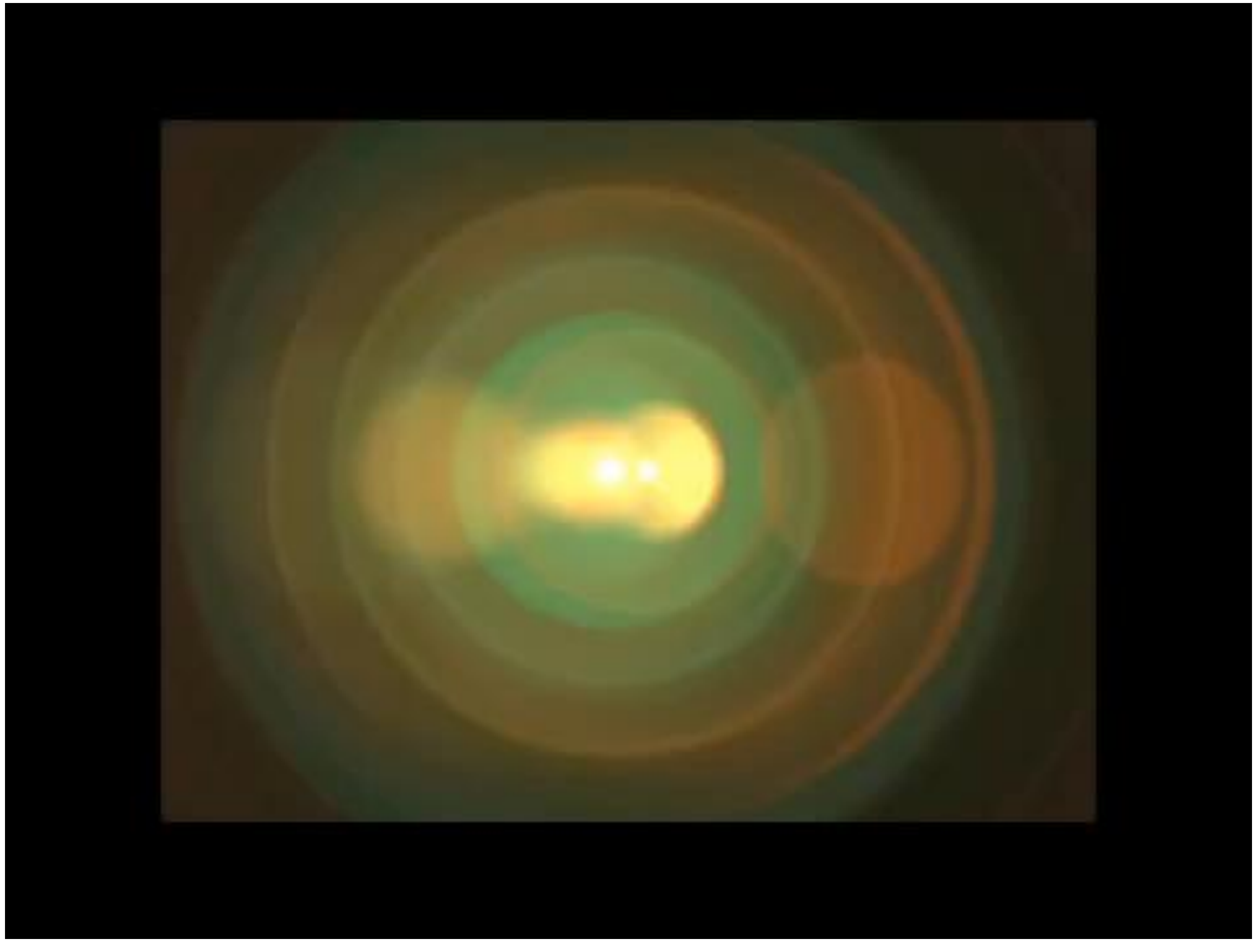
Coating applied on optical diopters



Example of additional propagation sequence due to reflections on diopters 9 and 7

Camera Flare from lenses

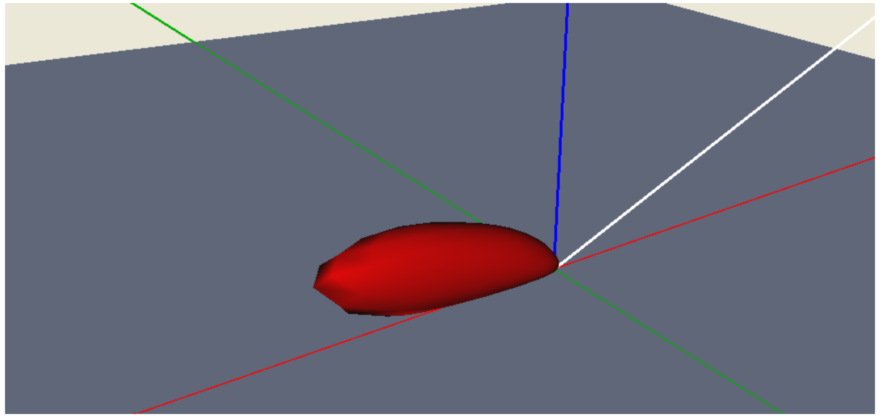
Typical optical flare simulation result obtained with Speos for a spot incidence moving from 5° to 85°:



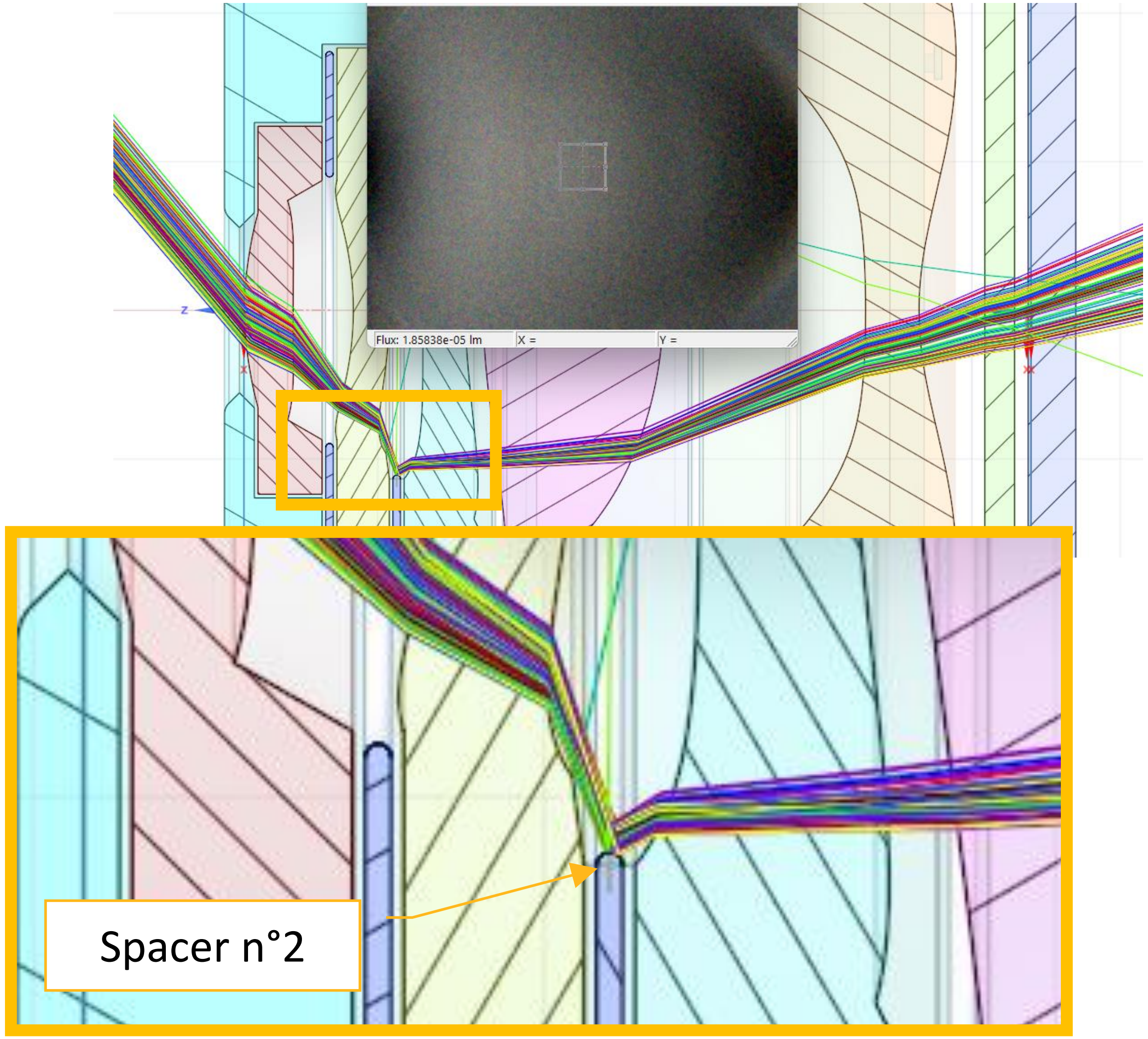
Camera Flare from mechanical parts

Mechanical surfaces with not fully absorbing optical properties introduce parasite light inside the lens system that may reach the sensor.

BRDF properties of mechanical surfaces can be added in Speos model.



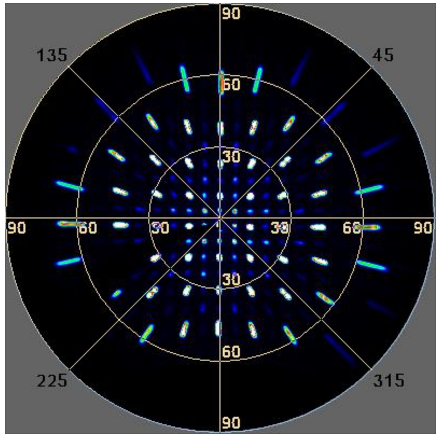
BRDF surface property applied on mechanical parts (spacers)



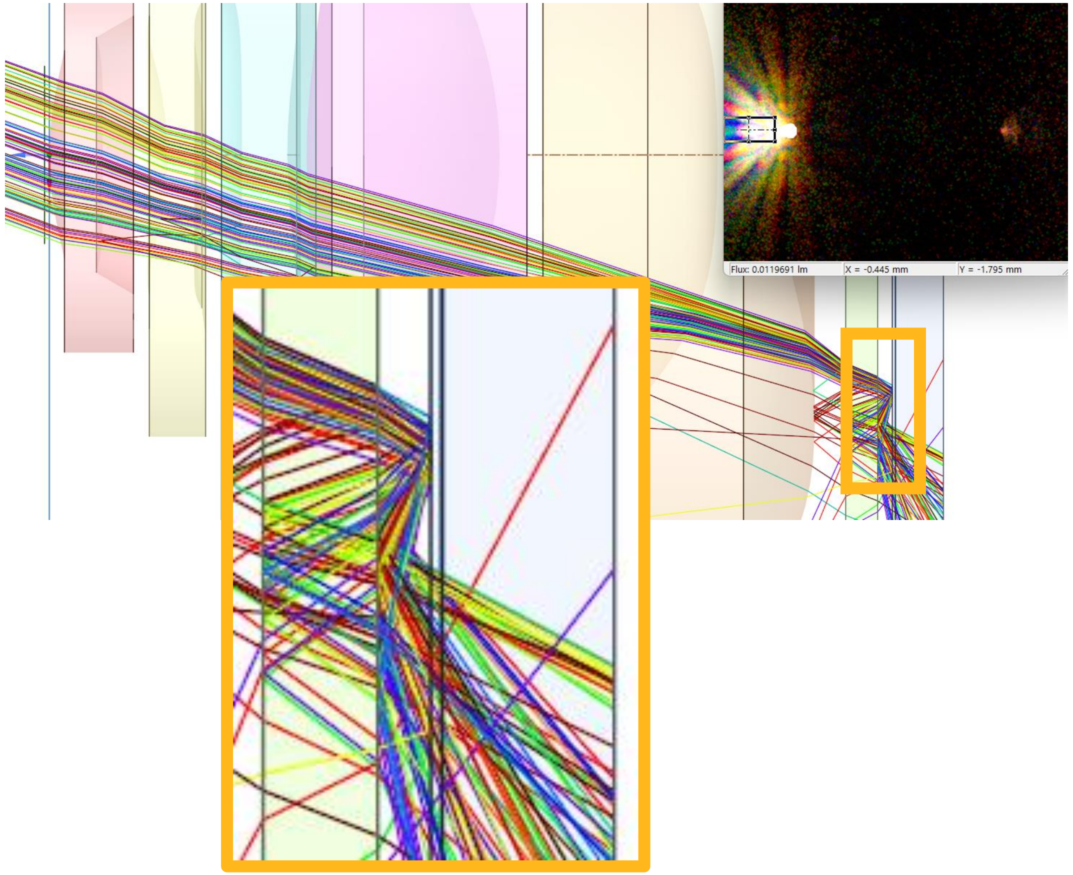
Camera Flare from sensor properties

Sensor structure (microlens, pixels, etc.) behaves like a diffraction grating and reflects a part of the incoming light.

This diffractive effect can be modeled using Ansys Lumerical and considered during Speos simulation.

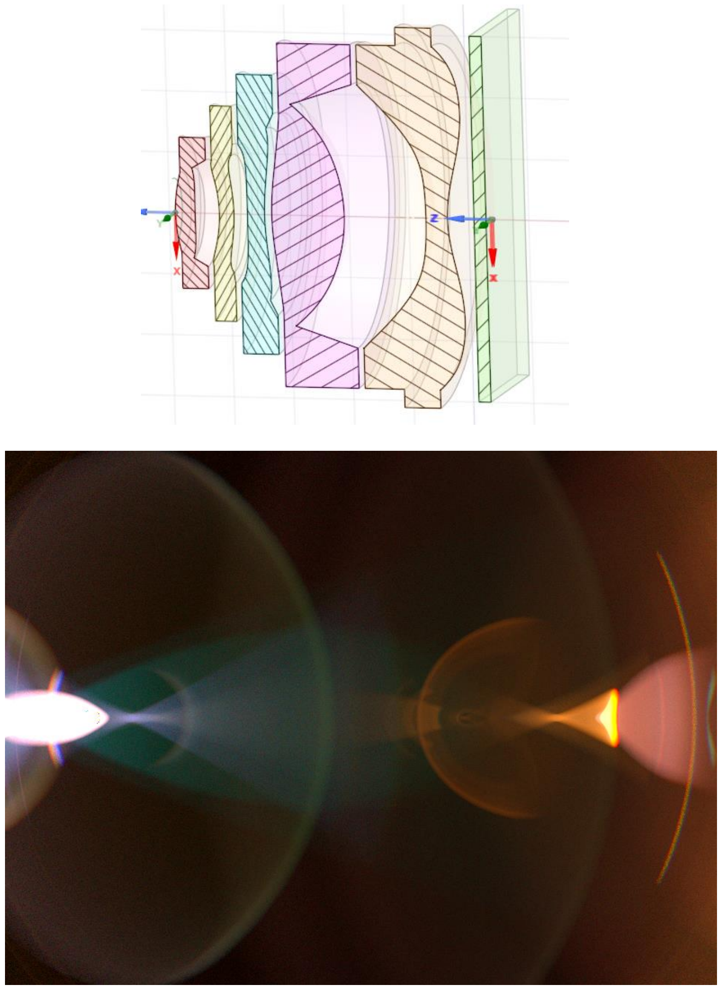


Conoscopic view of the sensor back reflection

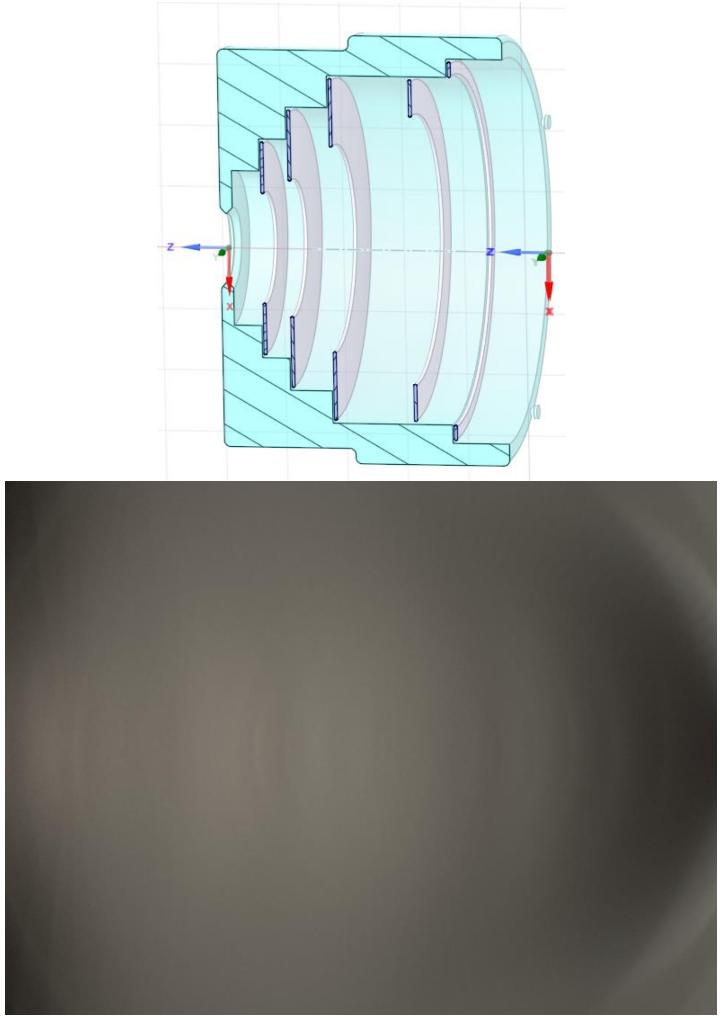


Typical back reflection from the sensor

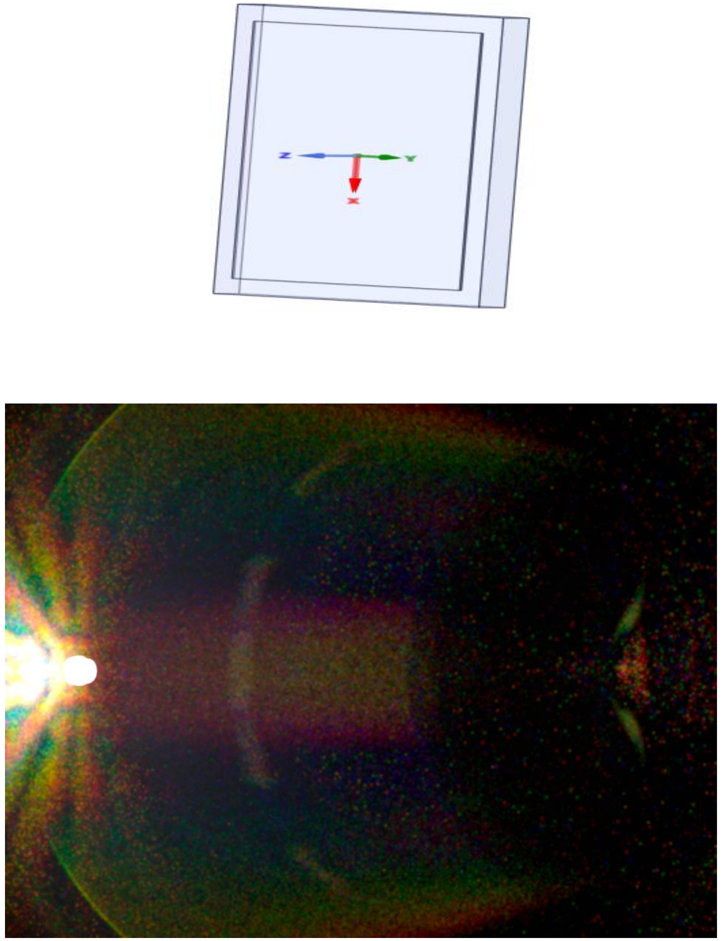
Camera Flare - highlight on the three individual contributions



From lenses



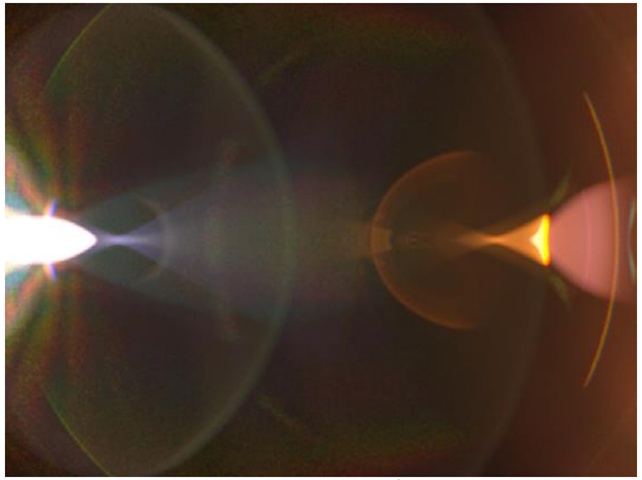
From mechanical parts



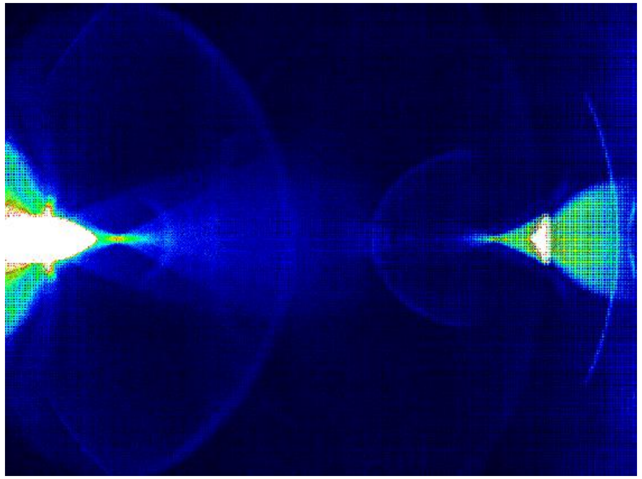
From sensor properties

Camera Flare – From Ansys to DXOMARK

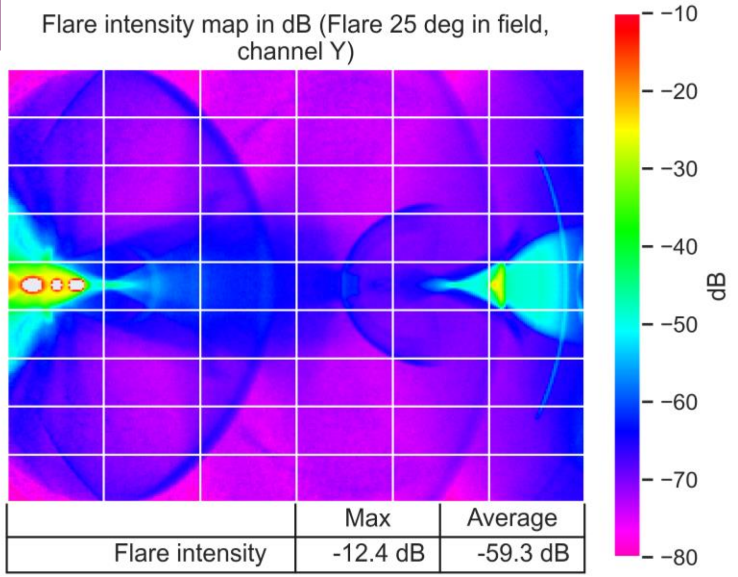
Flare simulation for a 25° incident spot source

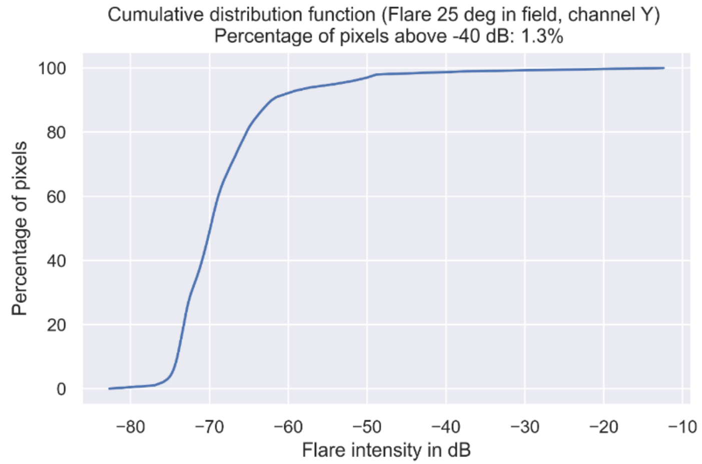


Simulation result from Ansys Speos



Raw Image from Ansys SSS Exporter





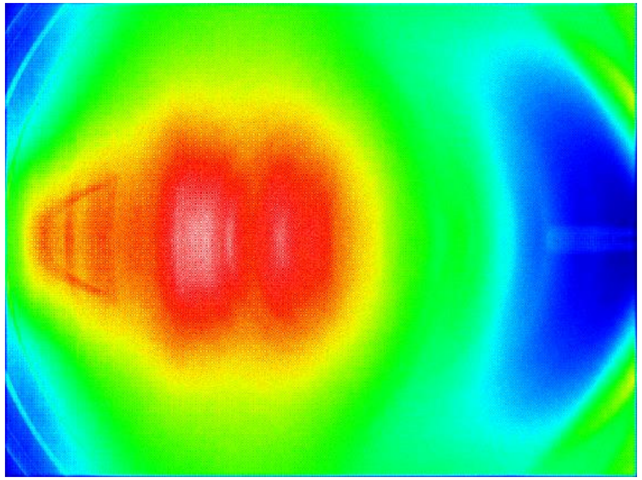
Quantitative analysis from DXOMARK Analyzer

➔ For low light incidence, flare is mainly due to Optical and Sensor contribution

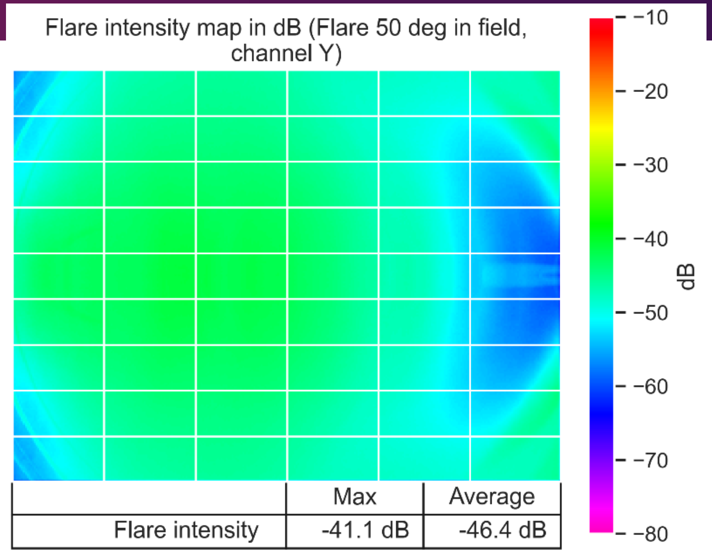
Camera Flare – From Ansys to DXOMARK

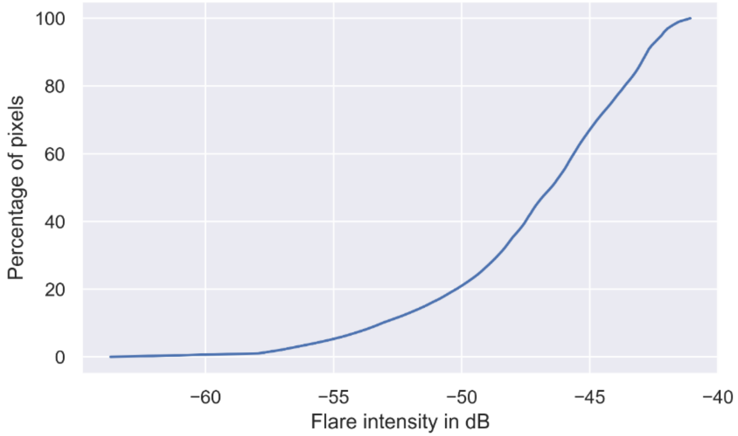
Flare simulation for a 50° incident spot source

Simulation result from Ansys Speos



Raw Image from Ansys SSS Exporter



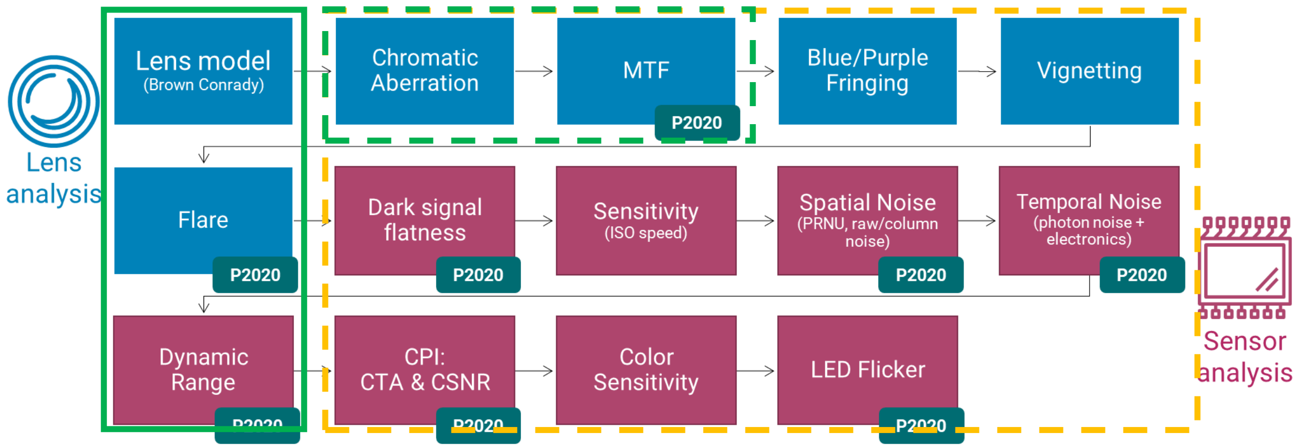


Quantitative analysis from DXOMARK Analyzer

➔ When spot is outside the field of view, flare is mainly due to mechanical contribution

Conclusion

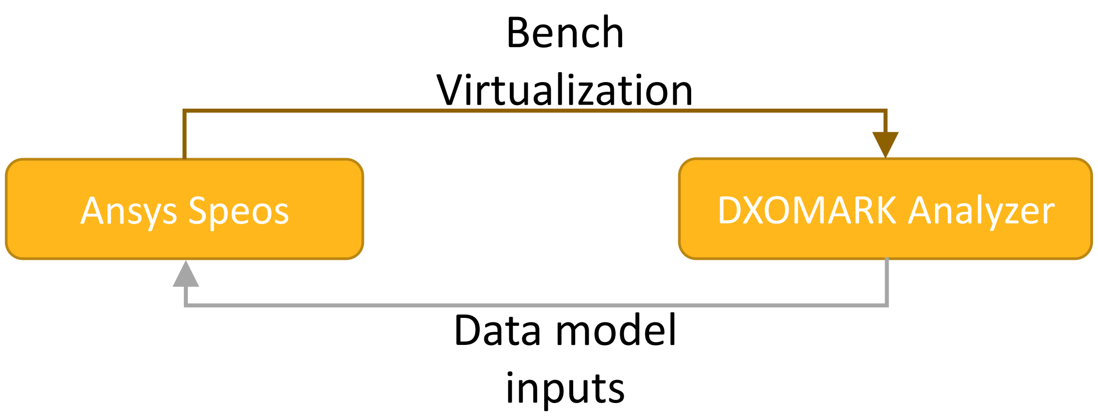
Measurements on simulated images correlate well with simulation data.



Evaluation of more physical properties for automotive camera modules, such as MTF, Chromatic aberration are on-going, as well as comparison between real and simulated cameras.

In addition, DXOMARK Analyzer measurement outputs could be used to generate inputs for Ansys Speos camera model:

- (spectrally dependent) Distortion file,
- Data characterizing the sensor part.



Ansys