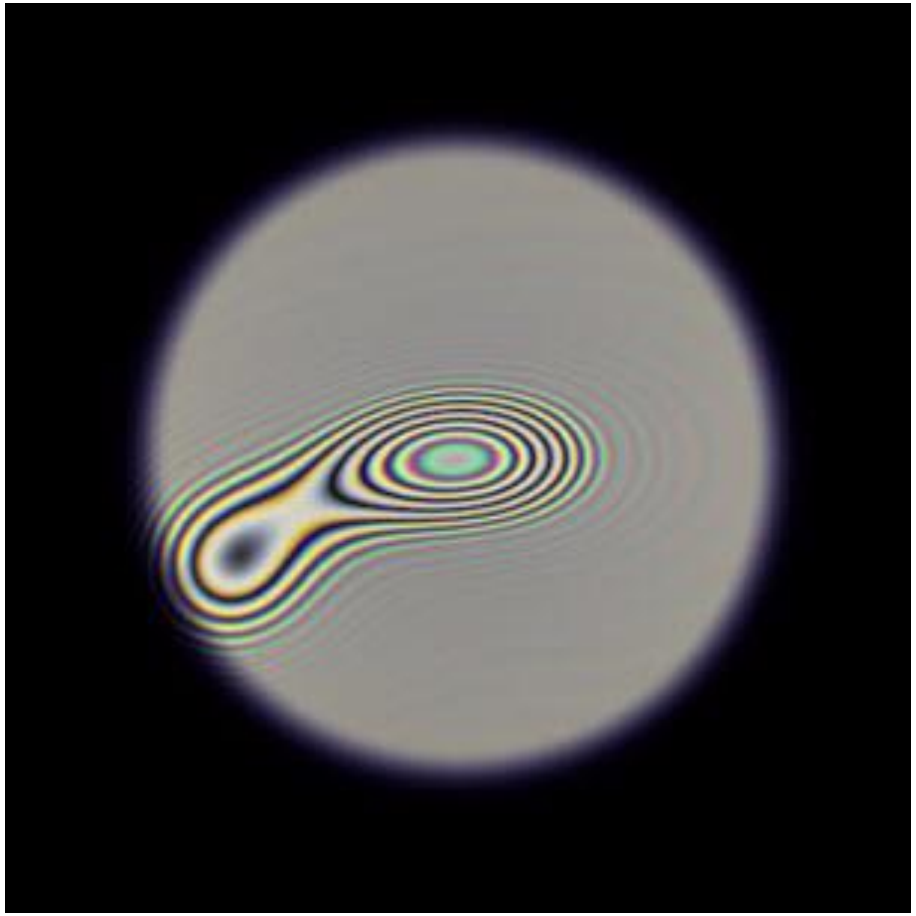
Working Principle of Optical Coherence Tomography

Abstract

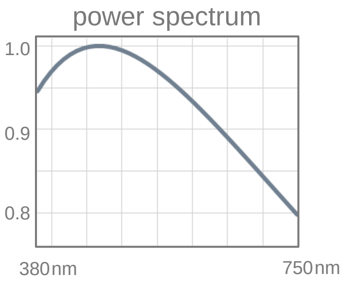


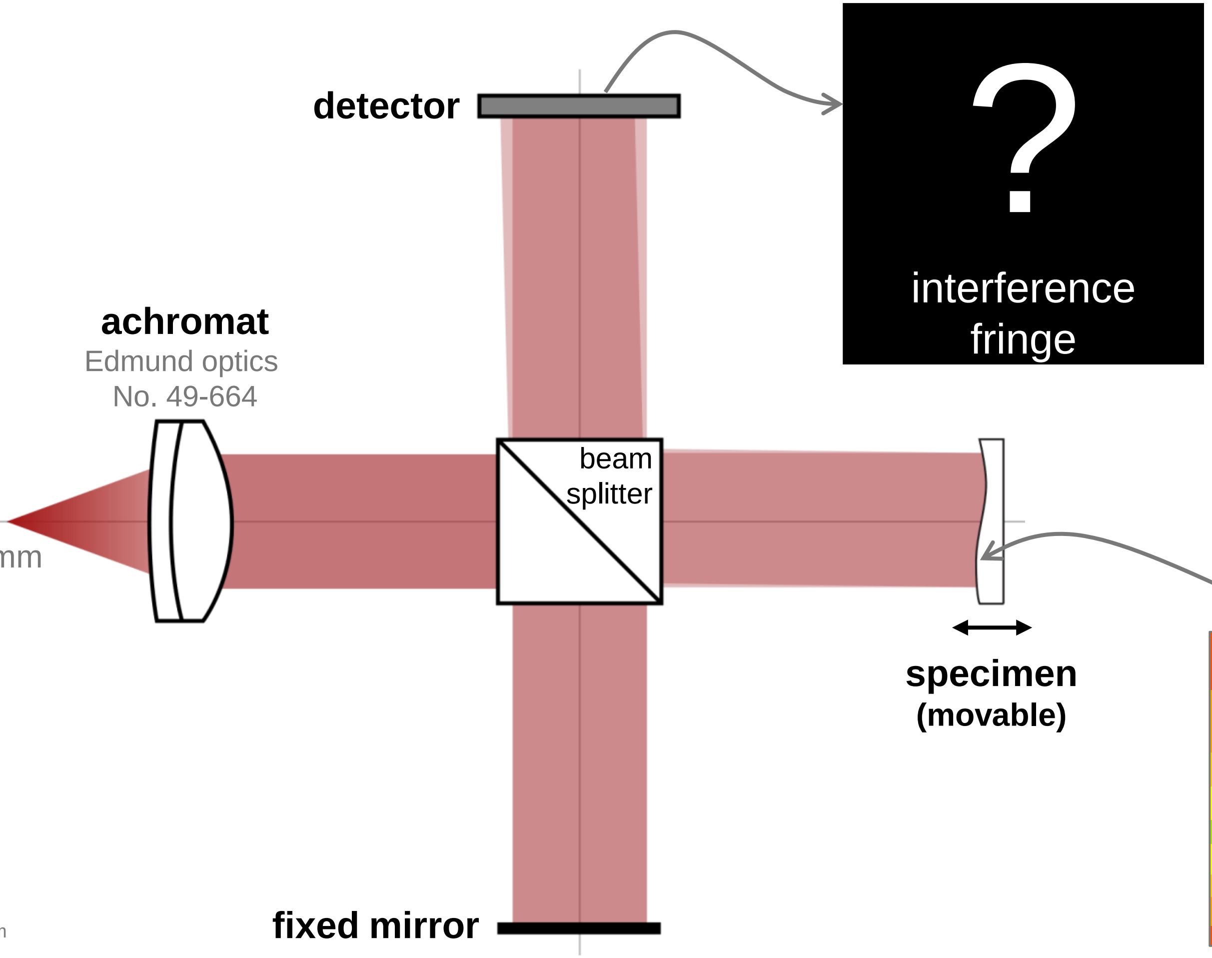
Scanning interferometry is the technique for performing surface height measurement. By exploiting the low coherence of white light source, interference pattern appears only when the path length difference is within the coherent length. Therefore, it enables precise microscopic measurement. Together with a Xenon lamp, a Michelson interferometer is built up and used to measure a specimen with smoothly varying front surface.

Modeling Task

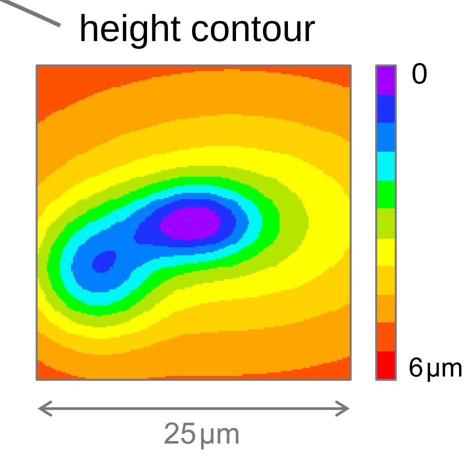
Xenon lamp (Spherical Wave)

- black body spectrum with 6200 K temperature
- spherical wave with 33.48 mm distance to point source





How to calculate the interference pattern and even to derive the height profile of the specimen under test?

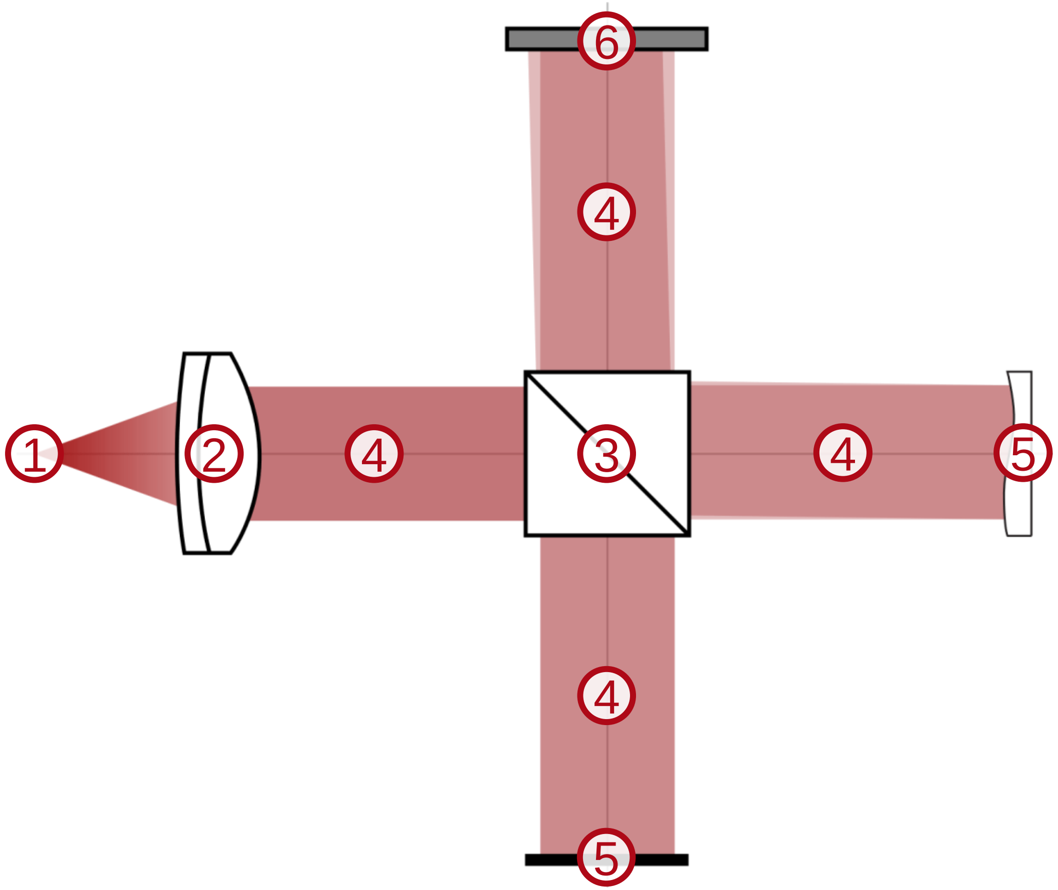


Simulation & Setup: Single Platform Interoperability

Single-Platform Interoperability of Modeling Techniques

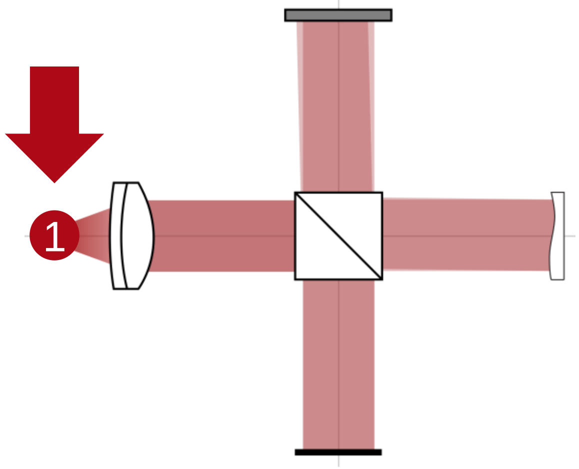
Light will encounter and interact with different components as it propagates through the system. Due to the non-sequential nature of the system, there may be multiple interactions at different points in the propagation. A suitable model that provides a good compromise between accuracy and speed is required for each of these elements of the system:

① Xenon lamp (white-light point source)
② achromat
③ beam splitter
④ free-space propagation
⑤ mirror/specimen
⑥ detector



Connected Modeling Techniques: Source

① Xenon lamp (white-light point source)
② achromat
③ beam splitter
④ free-space propagation
⑤ mirror with specimen
detector



Available modeling techniques for source:

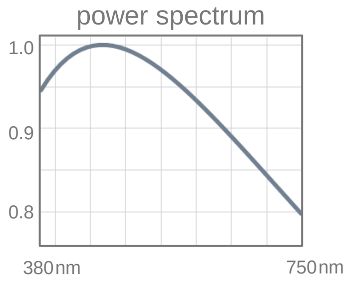
Methods	Preconditions	Accuracy	Speed	Comments
Frequency Domain	None	High	Low	Rigorous; bandwidth sampling; propagation of beams with sampled frequencies through system
Time Domain Approximation	Bandwidth not too large; frequency dispersion & spectrum information not included	Low	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector

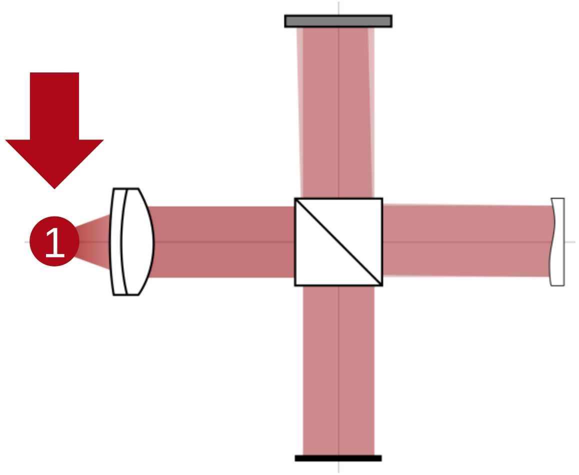
Two different techniques are available to model the temporal coherence of sources; the advantages and disadvantages of each one will be discussed later in the document.

Connected Modeling Techniques: Source

Light Source Model: Spherical Wave

- 33.48 mm distance to point source
- aperture: 16.8 mm × 16.8 mm
- black body spectrum (6200 K)
- spherical wave with 33.48 mm distance to point source





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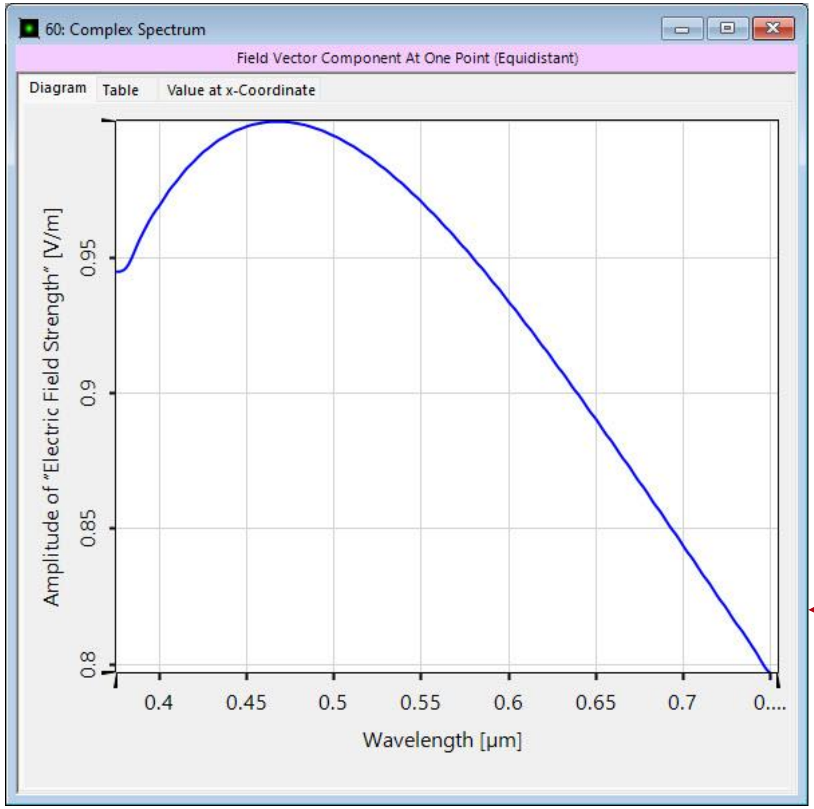
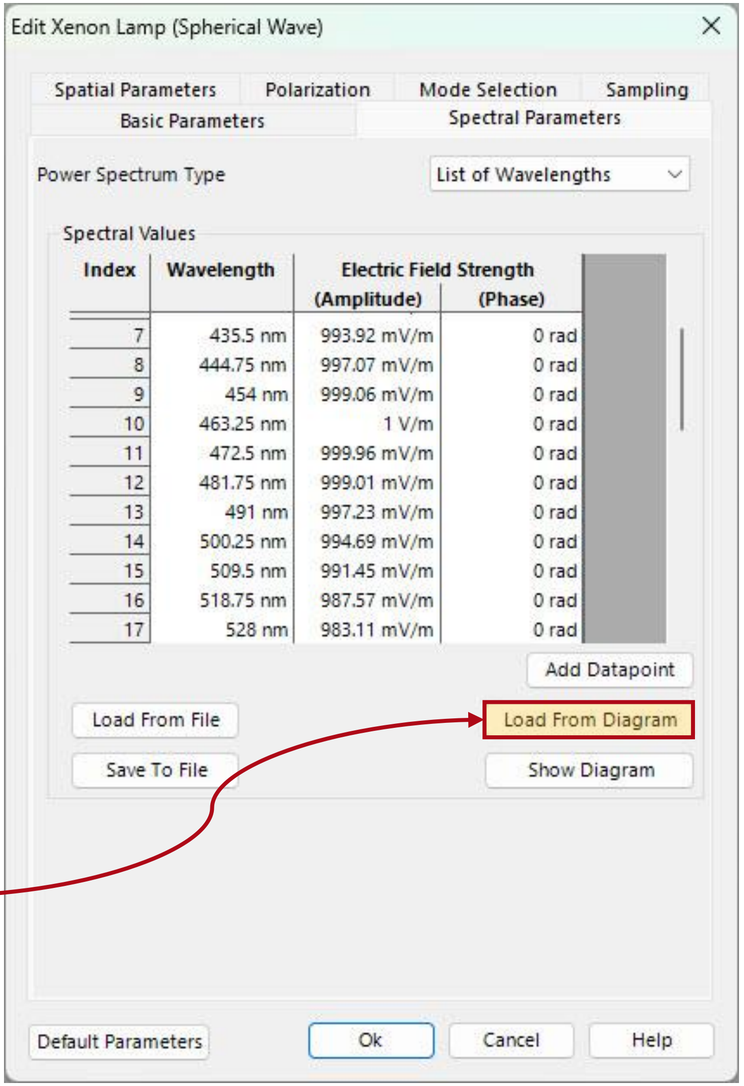
Two different techniques are available to model the temporal coherence of sources; the advantages and disadvantages of each one will be discussed later in the document.

Frequency Domain Method

To model a source with a polychromatic spectrum, set the *Power Spectrum Type* to *List of Wavelengths* and include the spectrum of choice via *Load from Diagram* or *Load from File*. VirtualLab Fusion offers multiple tools to quickly construct various types of spectra, such as a *Black Body Spectrum.*

Black Body Spectrum





Power Spectrum Type: List of Wavelengths

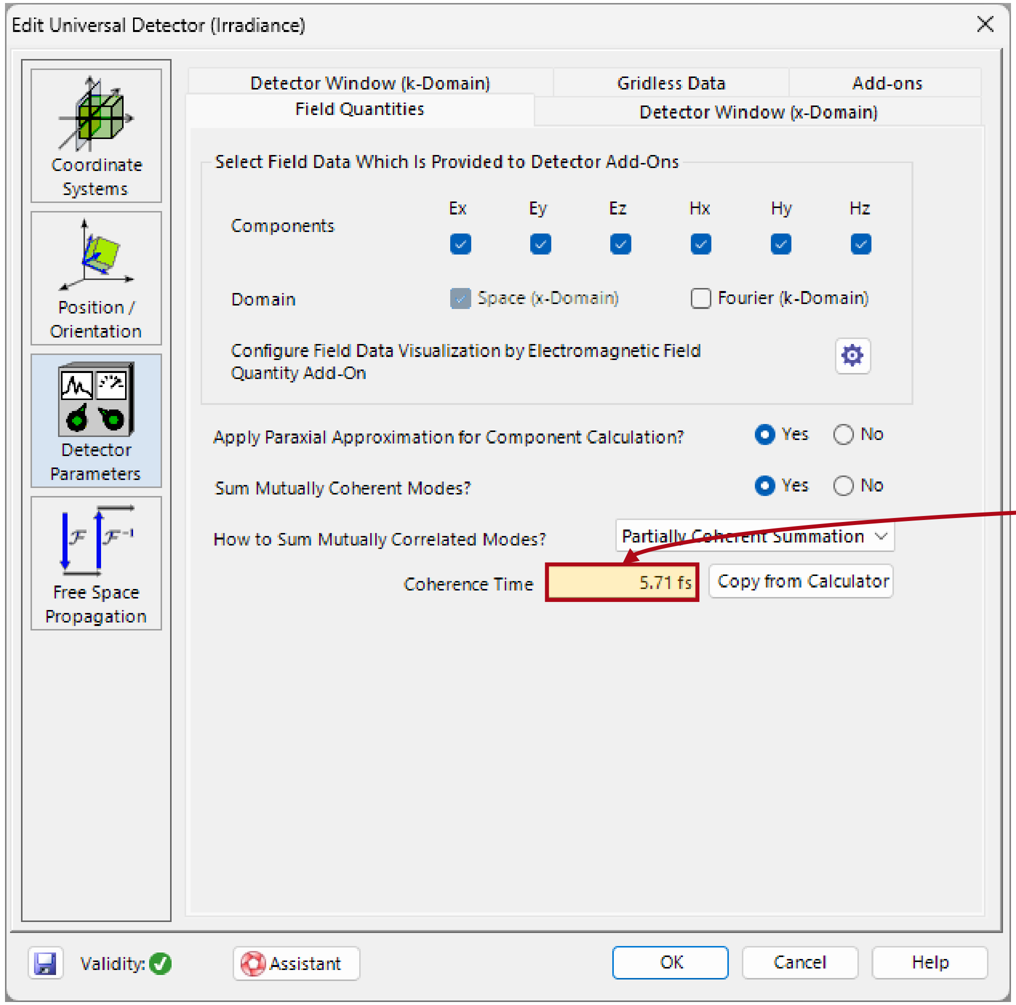
Spectral Values

Index	Wavelength	Electric Field Strength (Amplitude)	(Phase)
7	435.5 nm	993.92 mV/m	0 rad
8	444.75 nm	997.07 mV/m	0 rad
9	454 nm	999.06 mV/m	0 rad
10	463.25 nm	1 V/m	0 rad
11	472.5 nm	999.96 mV/m	0 rad
12	481.75 nm	999.01 mV/m	0 rad
13	491 nm	997.23 mV/m	0 rad
14	500.25 nm	994.69 mV/m	0 rad
15	509.5 nm	991.45 mV/m	0 rad
16	518.75 nm	987.57 mV/m	0 rad
17	528 nm	983.11 mV/m	0 rad

Time Domain Method

The Time Domain Method, on the other hand, is controlled through the *Universal Detector*. The sum of coherent modes in the detector needs to be set *to Partially Coherent* with a *Coherence Time* specified.

The *Coherence Time & Length Calculator* can be used to easily determine the *Coherence Time* of a source with a given bandwidth. Please note, that this method will only use one wavelength for propagation, dispersion effects as well as information about the actual shape of the spectrum are not included.



Edit Universal Detector (Irradiance)

Select Field Data Which Is Provided to Detector Add-Ons

	Ex	Ey	Ez	Hx	Hy	Hz
Components	☑	☑	☑	☑	☑	☑

Domain ☑ Space (x-Domain) ☐ Fourier (k-Domain)

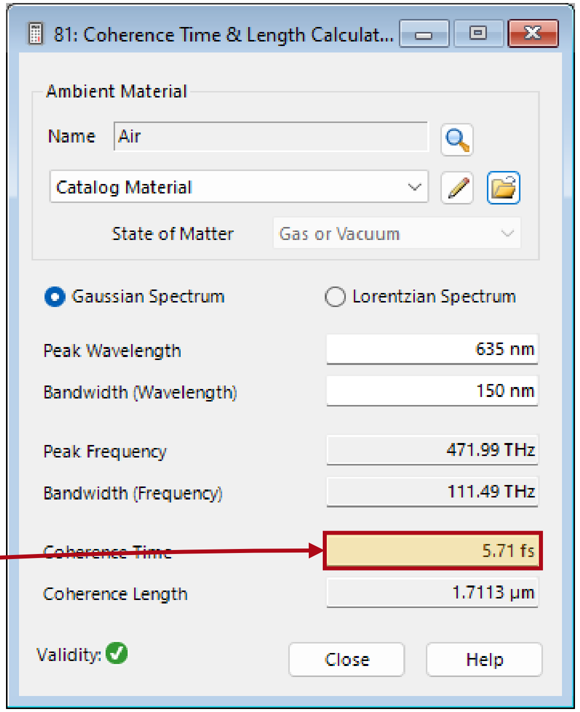
Configure Field Data Visualization by Electromagnetic Field Quantity Add-On

Apply Paraxial Approximation for Component Calculation? ● Yes ○ No

Sum Mutually Coherent Modes? ● Yes ○ No

How to Sum Mutually Correlated Modes? Partially Coherent Summation

Coherence Time 5.71 fs Copy from Calculator



81: Coherence Time & Length Calculat...

Ambient Material

Name Air

Catalog Material

State of Matter Gas or Vacuum

● Gaussian Spectrum ○ Lorentzian Spectrum

Peak Wavelength 635 nm

Bandwidth (Wavelength) 150 nm

Peak Frequency 471.99 THz

Bandwidth (Frequency) 111.49 THz

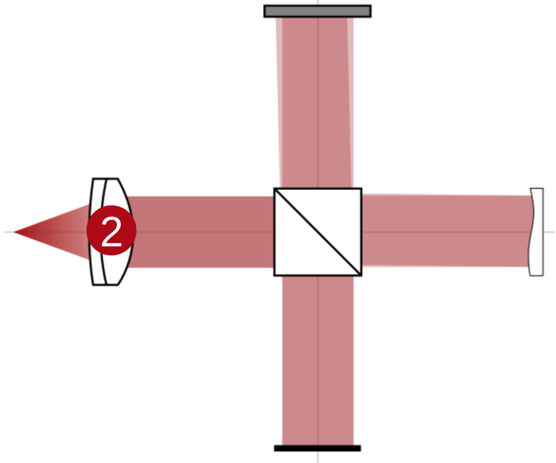
Coherence Time 5.71 fs

Coherence Length 1.7113 µm

Validity: ✓

Connected Modeling Techniques: Achromat

① Xenon lamp (white-light point source)
② achromat
③ beam splitter
④ free-space propagation
⑤ mirror with specimen
detector



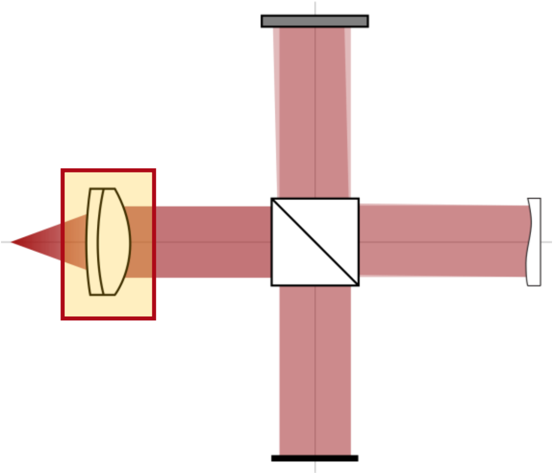
Available modeling techniques interaction with surfaces:

Methods	Preconditions	Accuracy	Speed	Comments
Thin Element Approximation (TEA)	Element not too thick/curvature not to strong	Low	High	Thickness about wavelength
Local Planar Interface Approximation	Surface not in focal region of beam	High	Very High	Local application of S matrix; LPIA; x-domain

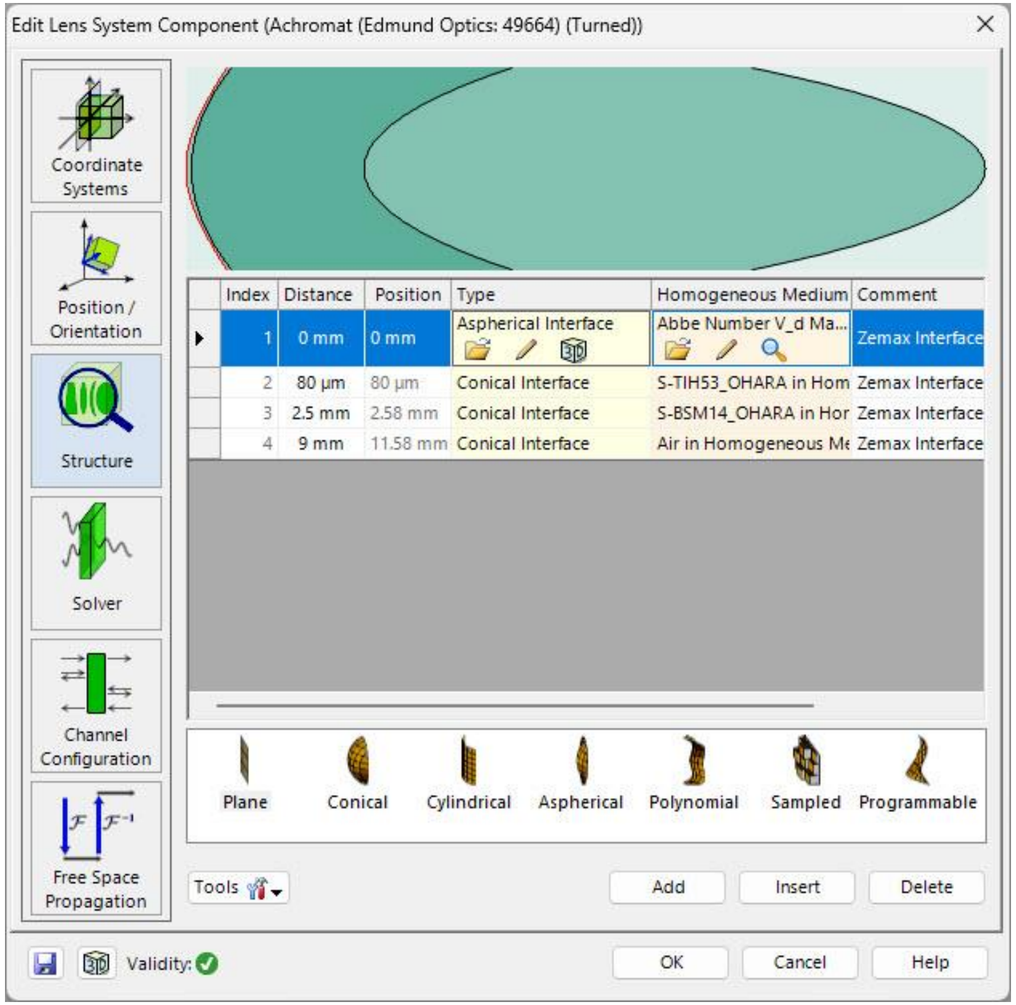
Two modeling techniques are available for calculating the interaction with the surfaces.

As the Thin Element Approximation (TEA) assumes thin components, the **Local Planar Interface Approximation** was chosen instead.

Achromat: Lens System Component



The *Lens System Component* allows the user to easily define a component consisting of an alternating sequence of smooth surfaces and homogeneous, isotropic media. For both interfaces and materials, you can choose ready-made entries from the built-in catalogs or customize your own for maximum flexibility.



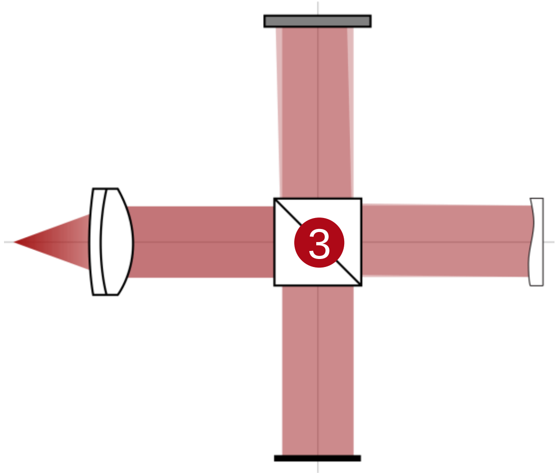
Edit Lens System Component (Achromat (Edmund Optics: 49664) (Turned))

Index	Distance	Position	Type	Homogeneous Medium	Comment
1	0 mm	0 mm	Aspherical Interface	Abbe Number V_d Ma...	Zemax Interface
2	80 µm	80 µm	Conical Interface	S-TIH53_OHARA in Hom	Zemax Interface
3	2.5 mm	2.58 mm	Conical Interface	S-BSM14_OHARA in Hor	Zemax Interface
4	9 mm	11.58 mm	Conical Interface	Air in Homogeneous Me	Zemax Interface

Validity: ✓

Connected Modeling Techniques: Beam Splitter

① Xenon lamp (white-light point source)
② achromat
③ beam splitter
④ free-space propagation
⑤ mirror with specimen
⑥ detector



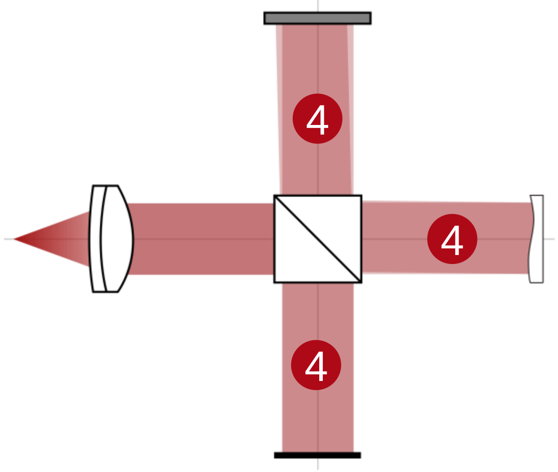
Available modeling techniques for beam splitter:

Methods	Preconditions	Accuracy	Speed	Comments
Functional Approach	idealized splitting of incident energy	Low	Very High	Idealized version of a beam splitter
S matrix	Planar surface	High	High	Rigorous model; includes evanescent waves (for e.g. FTIR effect modeling)
Local Planar Interface Approximation	Surface not in focal region of beam	High	High	Local application of S matrix; LPIA; x-domain

The choice of an appropriate modeling technique for a beam splitter heavily depends on which kind of beam splitter is used. In this use case we employ an idealized beam splitter model since we do not want to investigate e.g. the Fresnel losses that appear in the beam splitter, hence a **Functional Approach** is sufficient.

Connected Modeling Techniques: Free-Space Propagation

① Xenon lamp (white-light point source)
② achromat
③ beam splitter
④ free-space propagation
⑤ mirror with specimen
⑥ detector



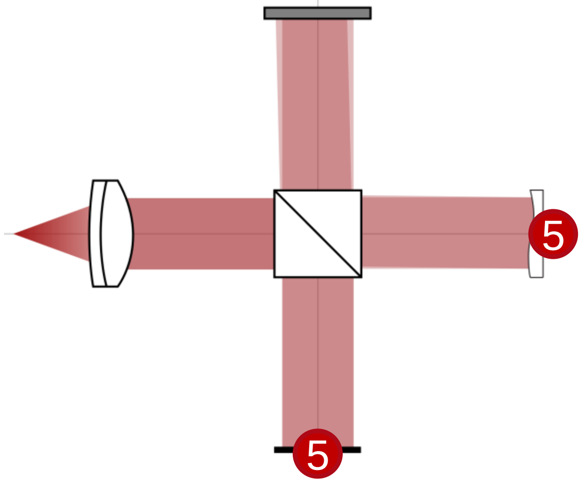
Available modeling techniques for free-space propagation:

Methods	Preconditions	Accuracy	Speed	Comments
Rayleigh Sommerfeld Integral	None	High	Low	Rigorous solution
Fourier Domain Techniques	None	High	High	Rigorous mathematical reformulation of RS integral
Fresnel Integral	**Paraxial**	High	High	Assumes paraxial light; moderate speed for very short distances
	Non-paraxial	Low	High	
Geometric Propagation	**Low diffraction**	High	Very high	Neglects diffraction effects
	Otherwise	Low	Very high	

In this particular case diffraction effects can be neglected as there are no hard edges or strong aperture effects. For this purpose **Geometric Propagation** was chosen for a fast simulation of the system

Connected Modeling Techniques: Mirror with Specimen

① Xenon lamp (white-light point source)
② achromat
③ beam splitter
④ free-space propagation
⑤ mirror with specimen
⑥ detector



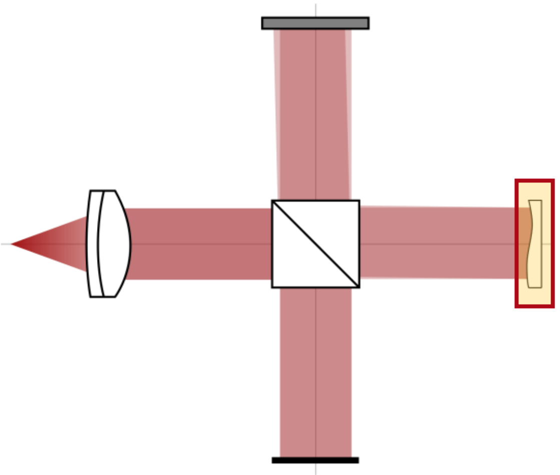
Available modeling techniques interaction with surfaces:

Methods	Preconditions	Accuracy	Speed	Comments
Thin Element Approximation	Thin element, large feature sizes	High	Very High	Thickness about wavelength; period & features larger than about ten wavelengths
Local Planar Interface Approximation	Surface not in focal region of beam	High	Very High	Local application of S matrix; LPIA; x-domain

Two modeling techniques are available for calculating the interaction with the surfaces.

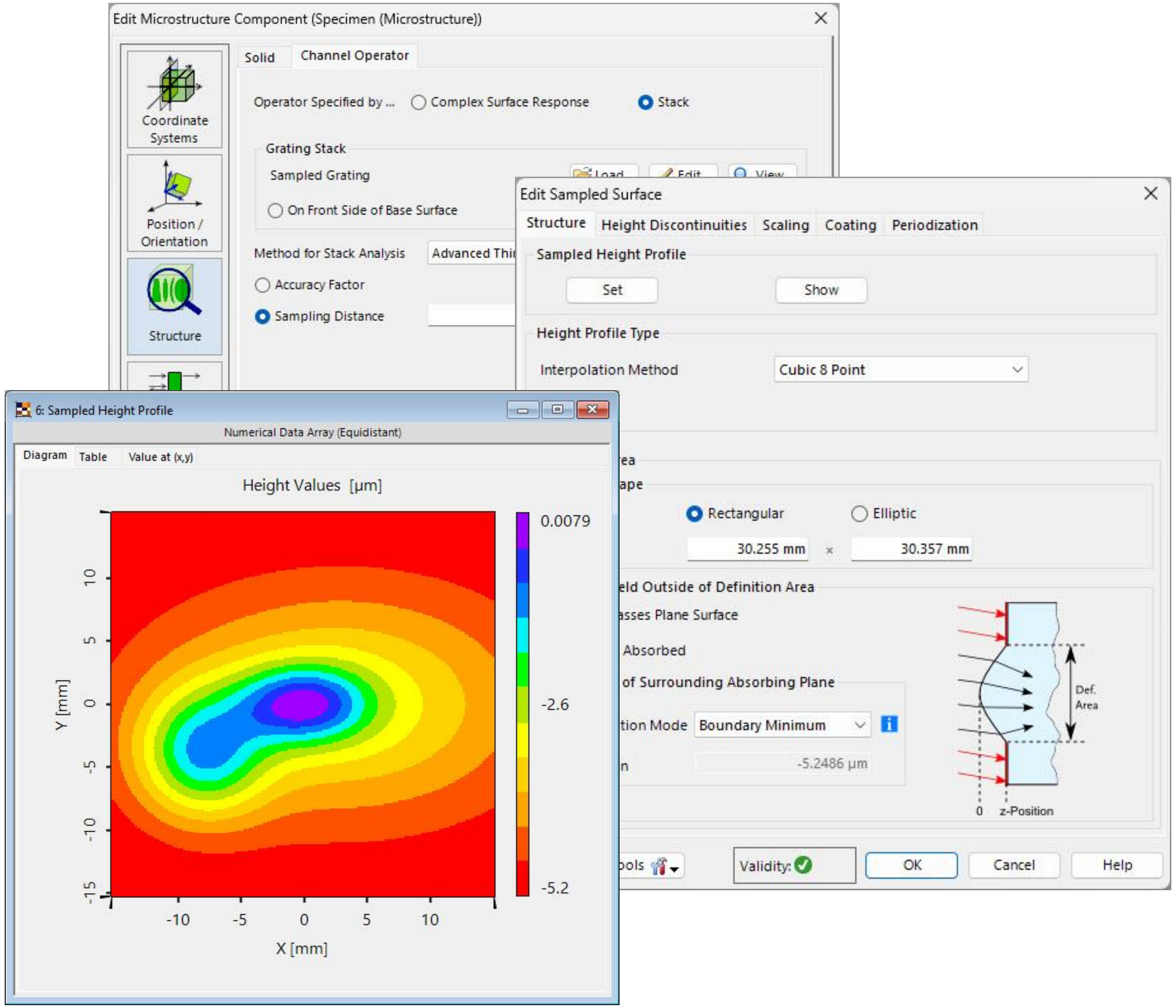
As both their preconditions are met and they both have very high speed, we expect them to provide similar results. We test both for the sample, and use LPIA for the reference mirror.

Mirror with Specimen: Sampled Interface



To incorporate the specimen with a custom height profile, VirtualLab offers the *Sampled Surface*, which can import arbitrary structures per as long as their height information is given in a *Data Array.*

This surface then can be loaded into a *Microstructure Component* or a *Curved Surface/Lens System Component* to be used in the system.



Edit Microstructure Component (Specimen (Microstructure))

Operator Specified by ... ○ Complex Surface Response ● Stack

Grating Stack

Sampled Grating

○ On Front Side of Base Surface

Method for Stack Analysis: Advanced Thi

○ Accuracy Factor

● Sampling Distance

Edit Sampled Surface

Sampled Height Profile

Height Profile Type

Interpolation Method: Cubic 8 Point

● Rectangular ○ Elliptic

30.255 mm × 30.357 mm

eld Outside of Definition Area

asses Plane Surface

Absorbed

of Surrounding Absorbing Plane

tion Mode: Boundary Minimum

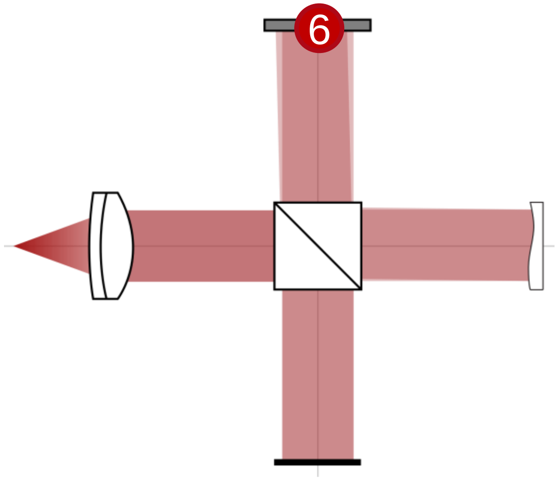
n: -5.2486 µm

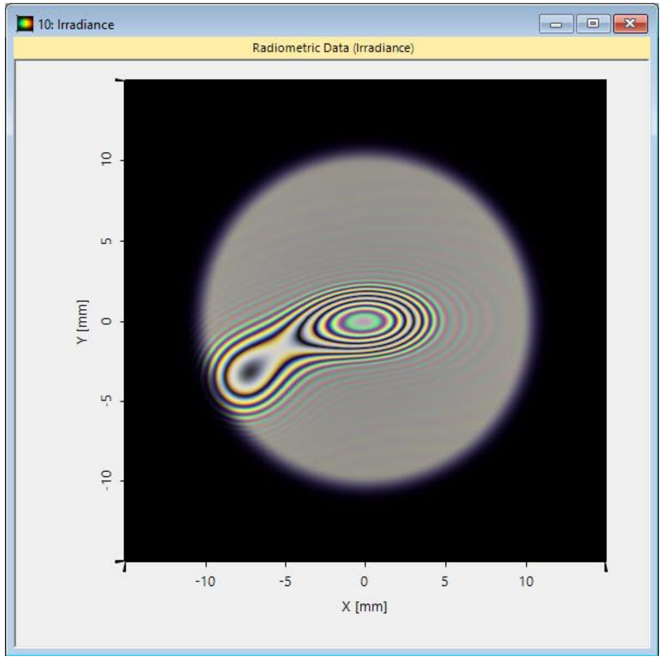
6: Sampled Height Profile

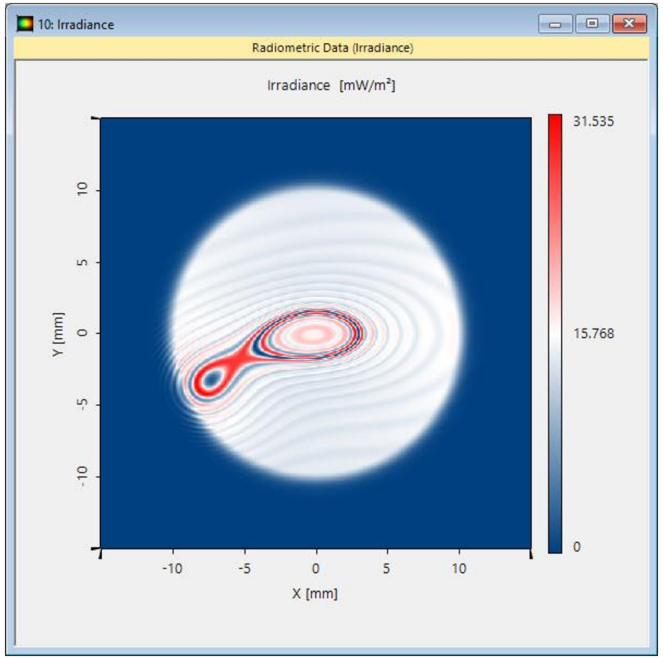
Numerical Data Array (Equidistant)

Connected Modeling Techniques: Detector

① Xenon lamp (white-light point source)
② achromat
③ beam splitter
④ free space propagation
⑤ mirror with specimen
⑥ detector





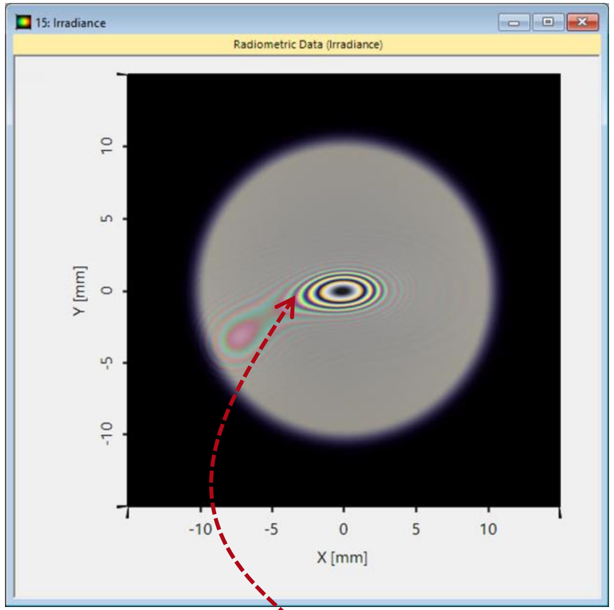


Full flexibility in detector modeling of different physical values, including irradiance, which can be given out in a predefined color-scheme or in the *Real-Color View*, which simulates how the human eye would see the result.

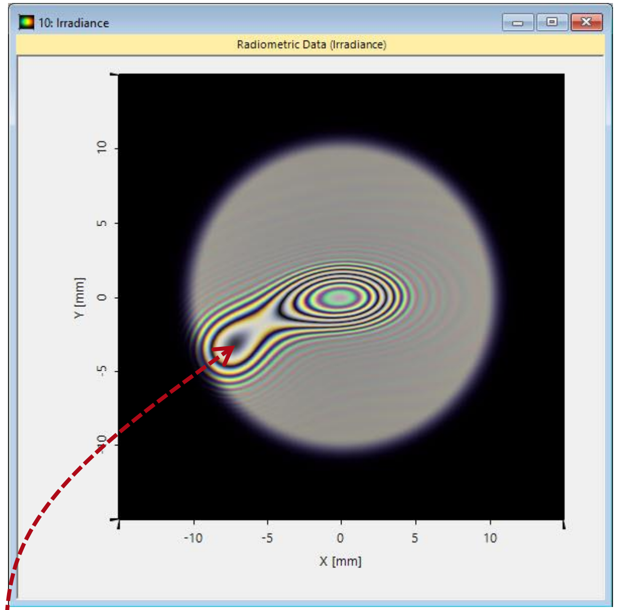
Simulation Results

Simulated Interference Fringes

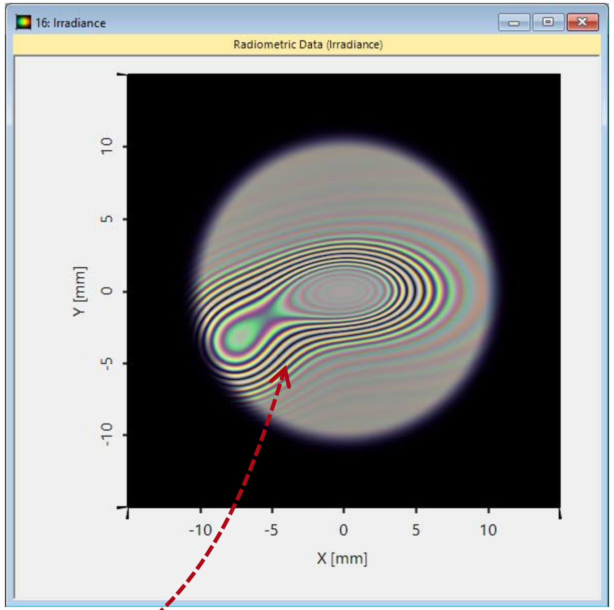
no shift of specimen

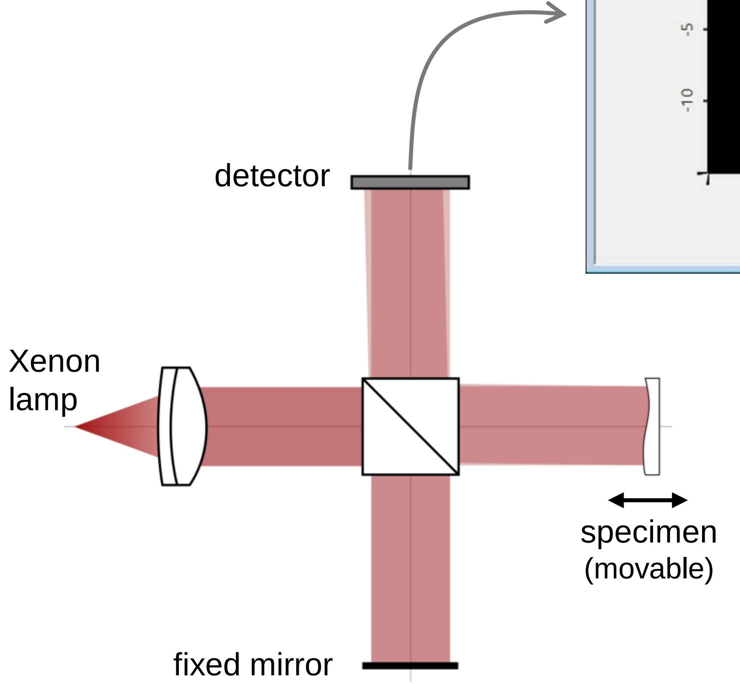


1 µm shift of specimen

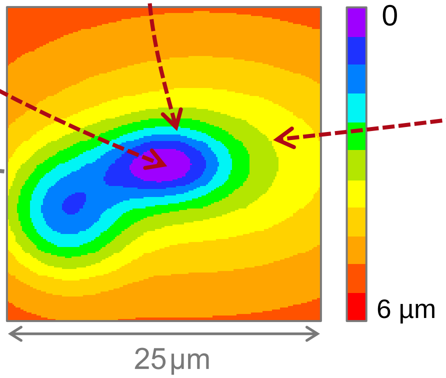


2 µm shift of specimen



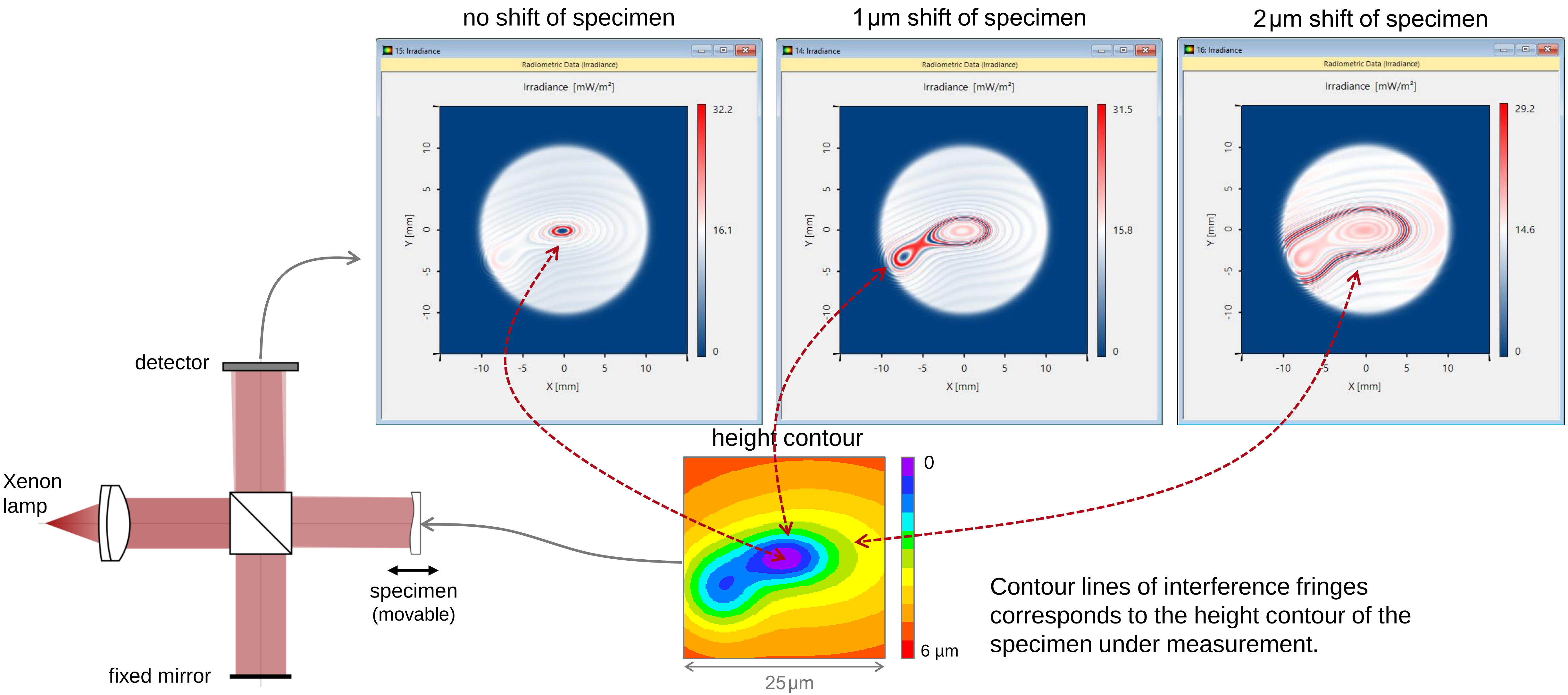


height contour



Contour lines of interference fringes corresponds to the height contour of the specimen under measurement.

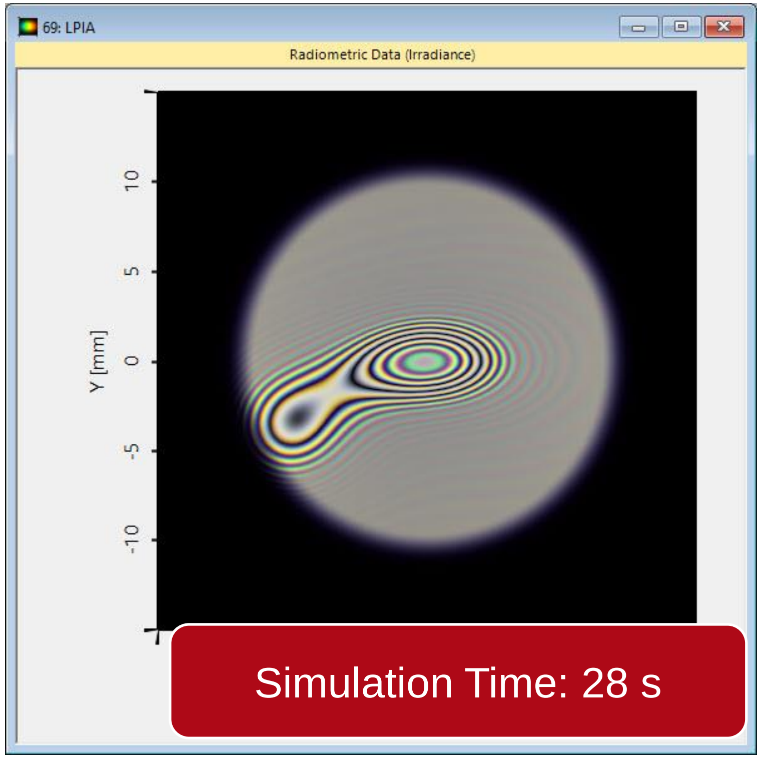
Simulated Interference Fringes – False Color



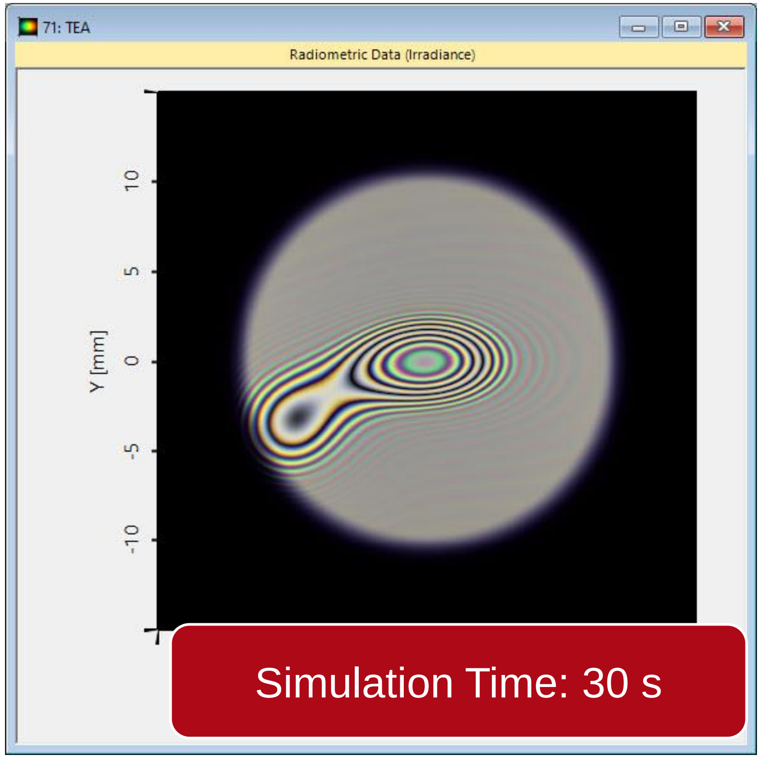
Contour lines of interference fringes corresponds to the height contour of the specimen under measurement.

Method Comparison: LPIA vs TEA

As mentioned previously the LPIA and TEA algorithm provide indistinguishable results, with the TEA algorithm being marginally slower than LPIA.



Simulation Time: 28 s



Simulation Time: 30 s

Methods	Preconditions	Accuracy	Speed	Comments
Thin Element Approximation	Thin element, large feature sizes	High	Very High	Thickness about wavelength; period & features larger than about ten wavelengths
Local Planar Interface Approximation	Surface not in focal region of beam	High	Very High	Local application of S matrix; LPIA; x-domain

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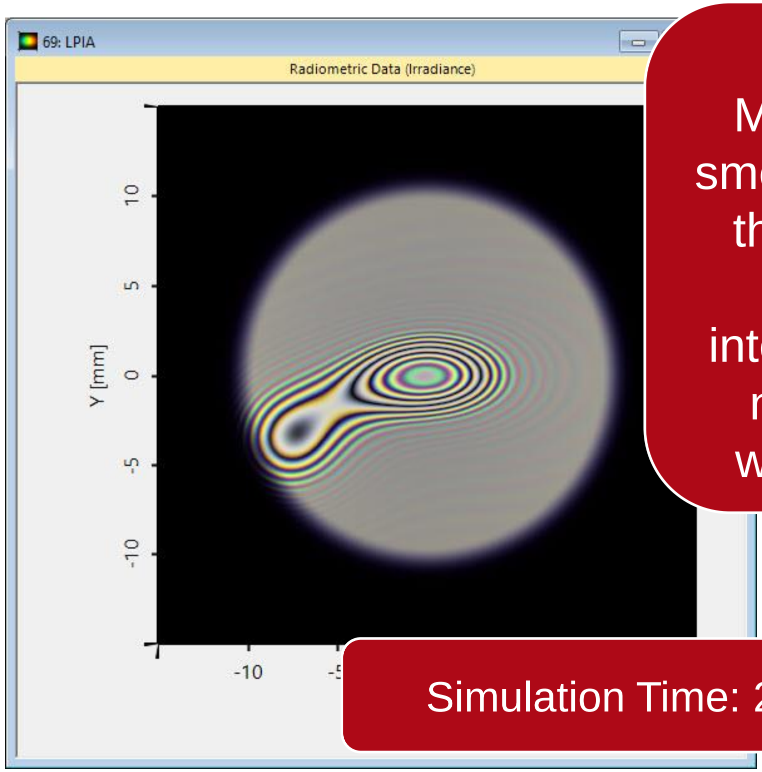
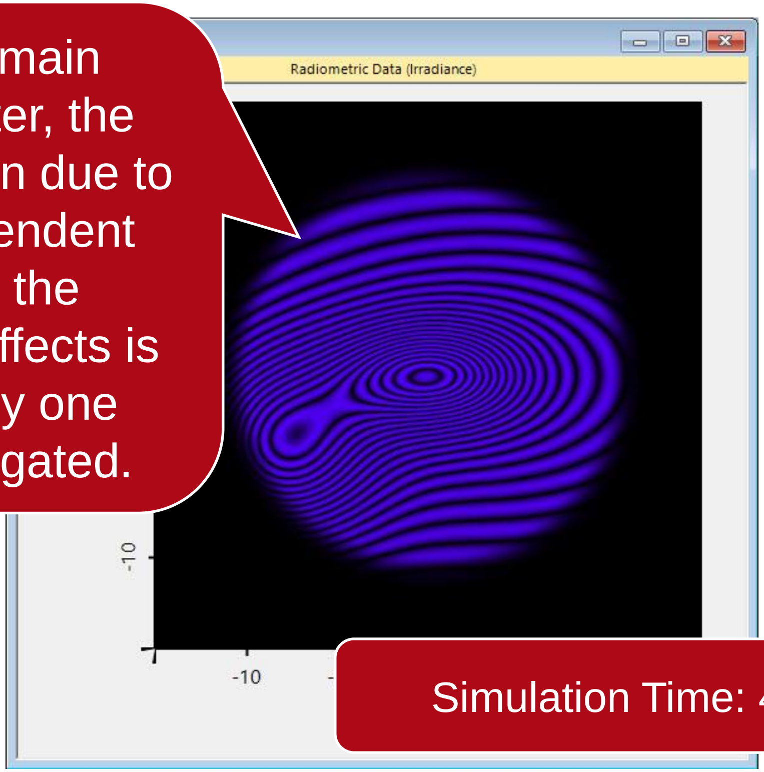
Method Comparison: Frequency vs Time Domain Method



Simulation Time: 28 s

While the Time Domain Method is much faster, the smearing of the pattern due to the wavelength-dependent distance between the interference fringes effects is not included, as only one wavelength is propagated.



Simulation Time: 4 s

Methods	Preconditions	Accuracy	Speed	Comments
Frequency Domain	None	High	Low	Rigorous; bandwidth sampling; propagation of beams with sampled frequencies through system
Time Domain	Bandwidth not too large; frequency dispersion & spectrum information not included	High	Very High	One frequency only; use of different travel time per beam to distinguish type of addition of beams in detector

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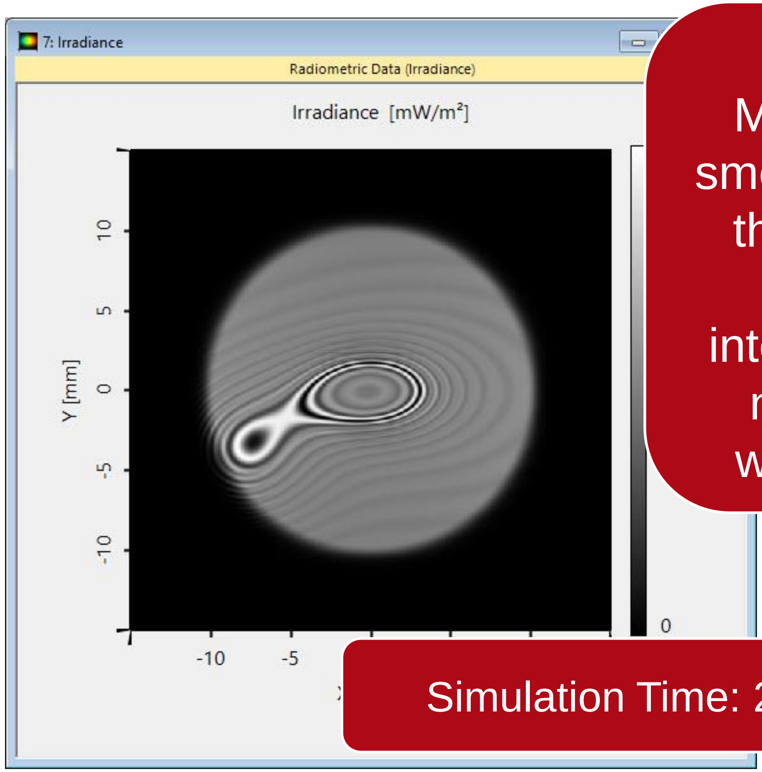
Method Comparison: Frequency vs Time Domain Method



Simulation Time: 28 s

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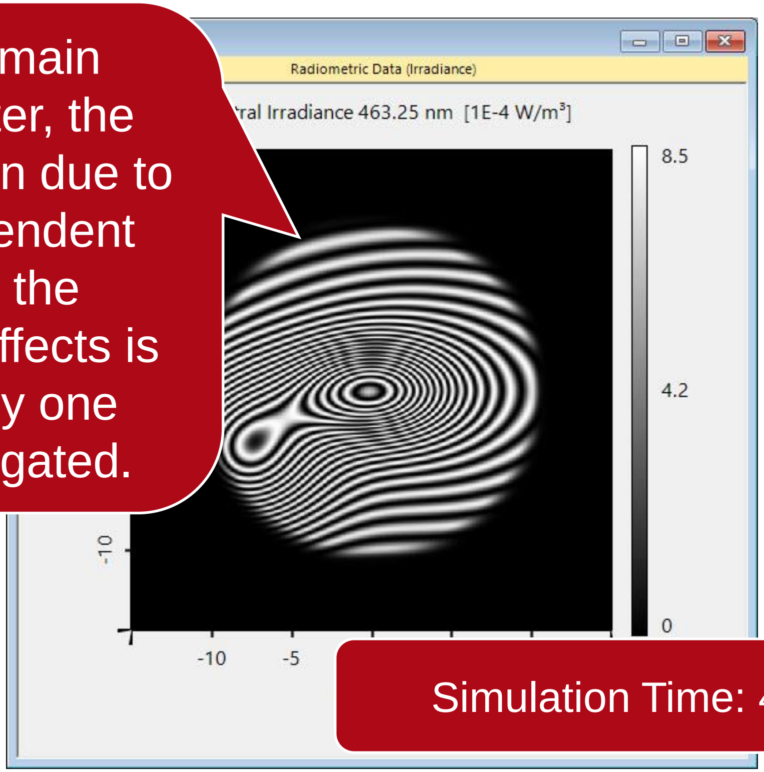

Simulation Time: 4 s

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Document Information

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