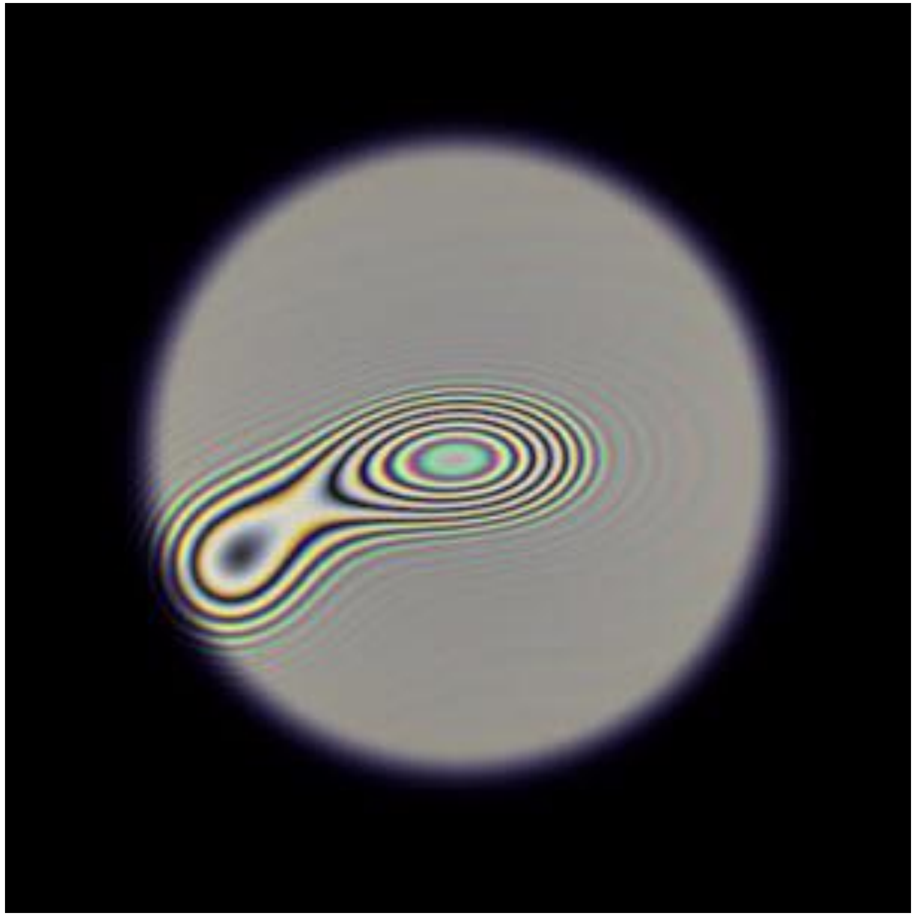
Working Principle of Optical Coherence Tomography

Abstract

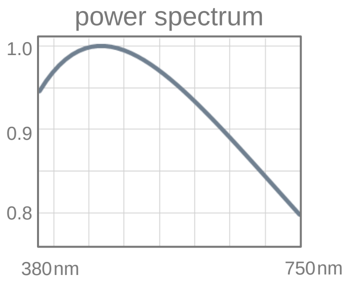


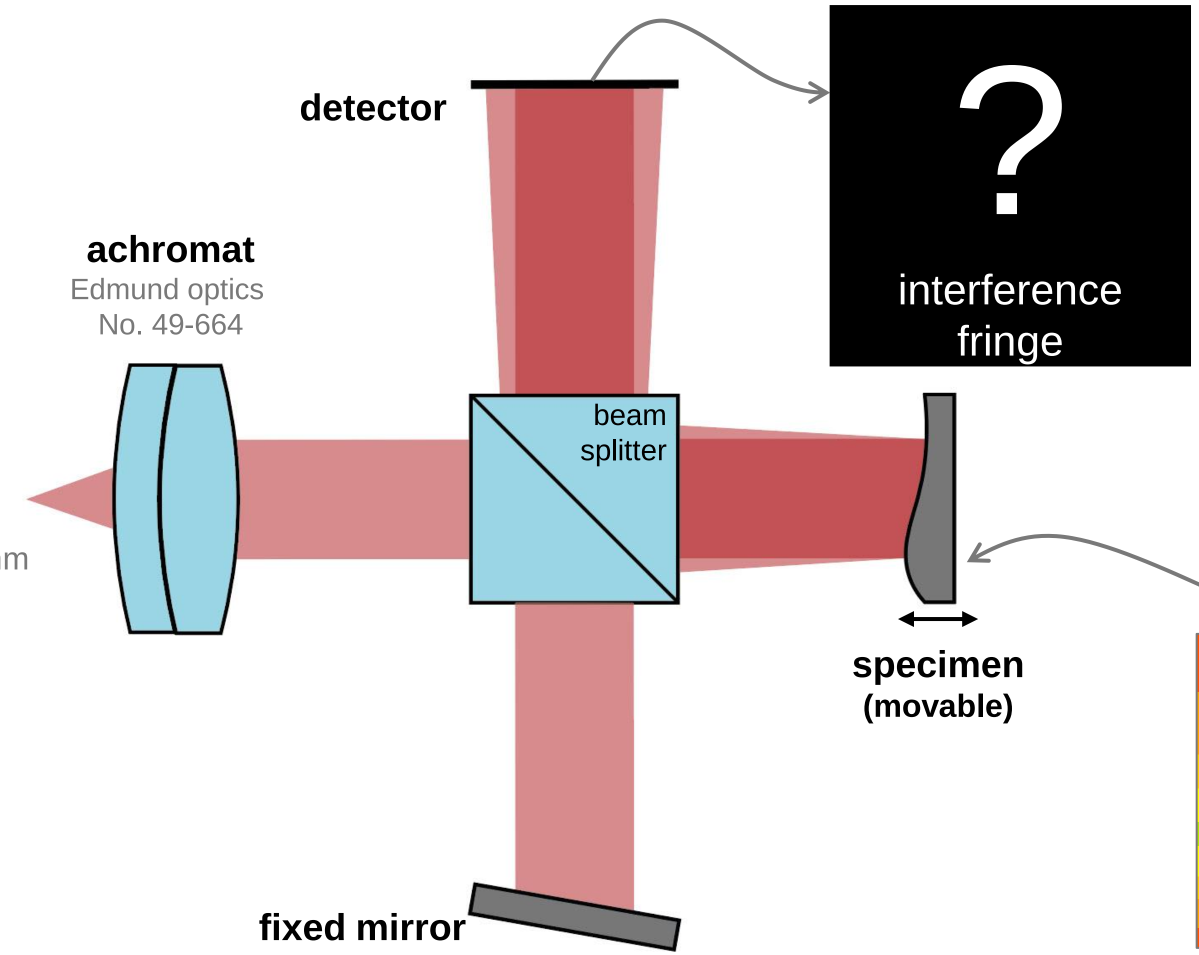
Scanning interferometry is a technique surface height measurement. By exploiting the low coherence of a white light source, an interference pattern appears only when the path length difference falls within the coherence length. Therefore, it enables very precise measurements, a property that is taken advantage of in medical imaging with optical coherence tomography (OCT), which employs precisely this physical principle. VirtualLab Fusion's various interoperable modeling techniques on a single platform facilitate an efficient modeling of coherence effects. In this example a Michelson interferometer with a Xenon lamp is constructed and used to measure a specimen with a smoothly modulated surface.

Modeling Task

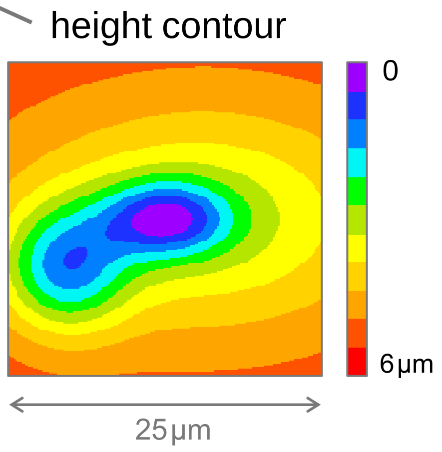
Xenon lamp (Spherical Wave)

- 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?

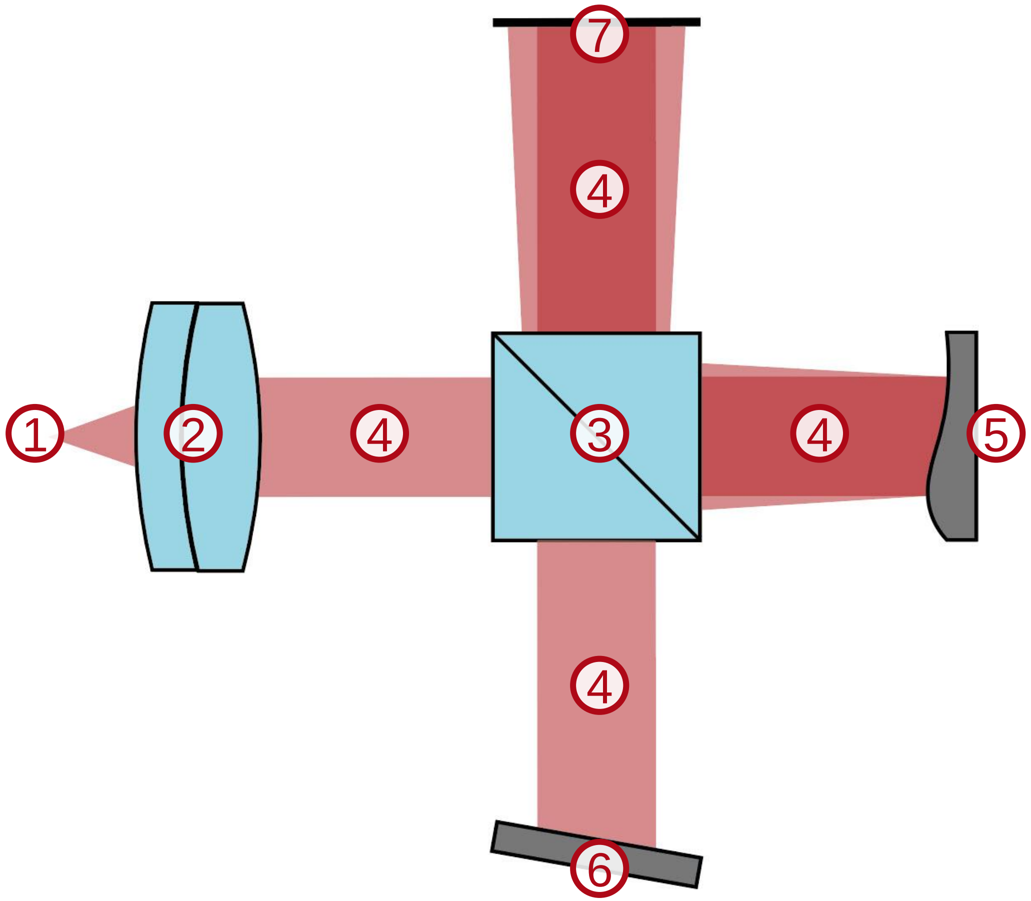


Simulation & Setup: Single Platform Interoperability

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:

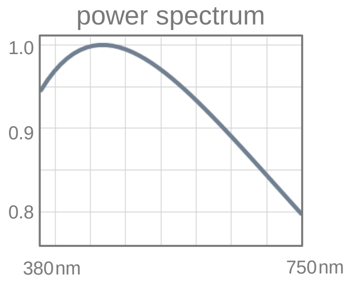
① Xenon lamp (white-light point source)
② achromat
③ beam splitter
④ free-space propagation
⑤ mirror with specimen
⑥ reference mirror
⑦ detector

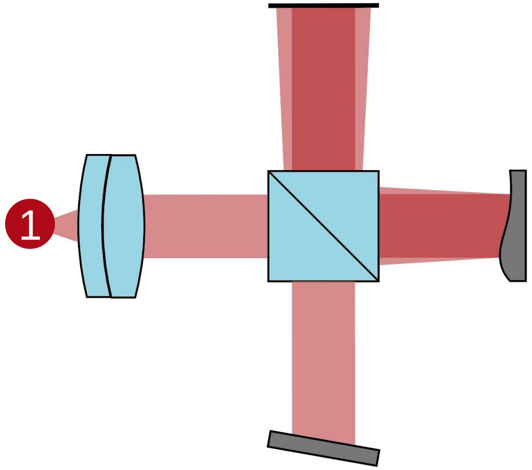


Connected Modeling Techniques: Source

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





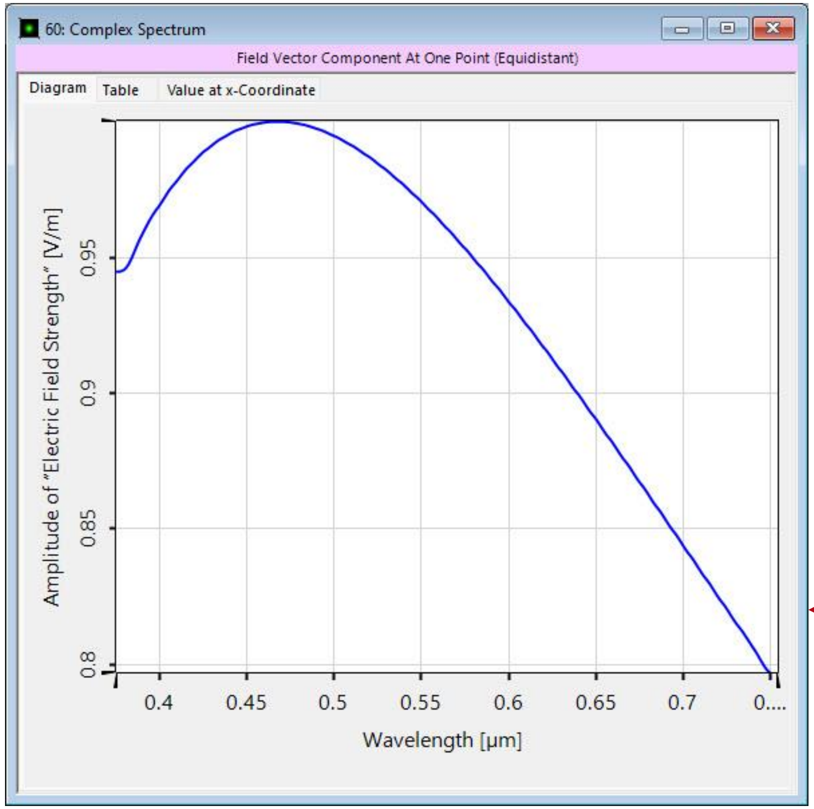
Available modeling techniques for source:

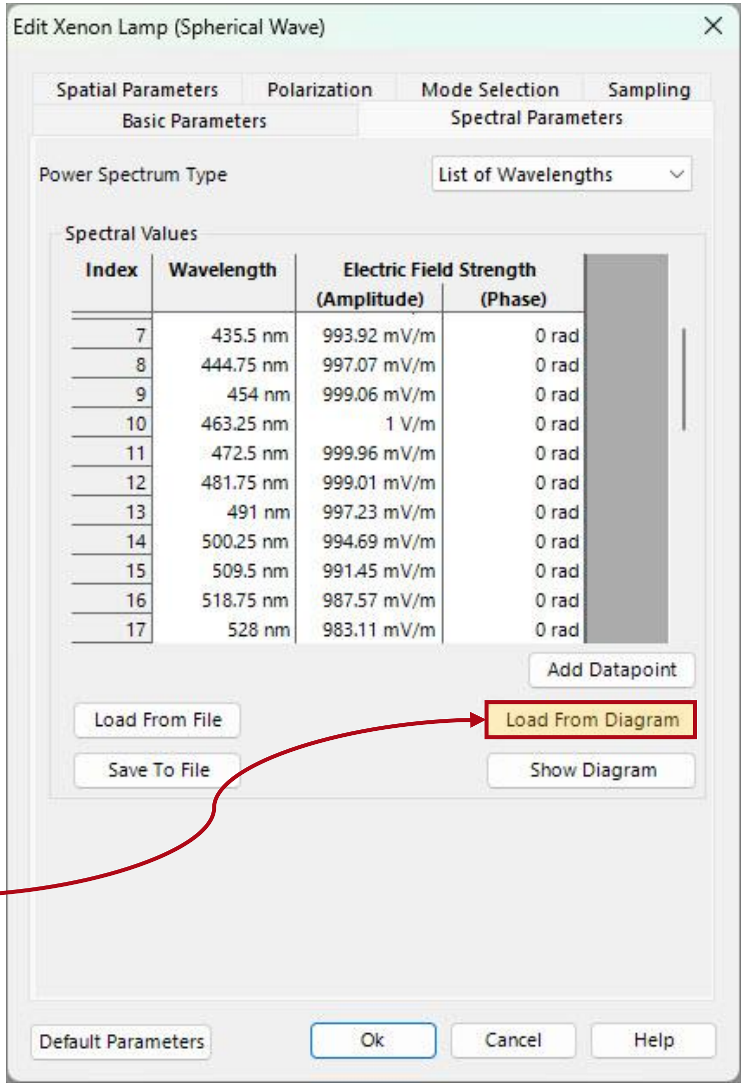
Methods	Preconditions	Accuracy	Speed	Comments
Frequency Domain	None	High	Low	Rigorous; bandwidth sampling; propagation of beams with sampled frequencies through system
Time Domain Approximation	Bandwidth not too large; frequency dispersion & spectrum information not included	Low	Very High	One frequency 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.

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.*

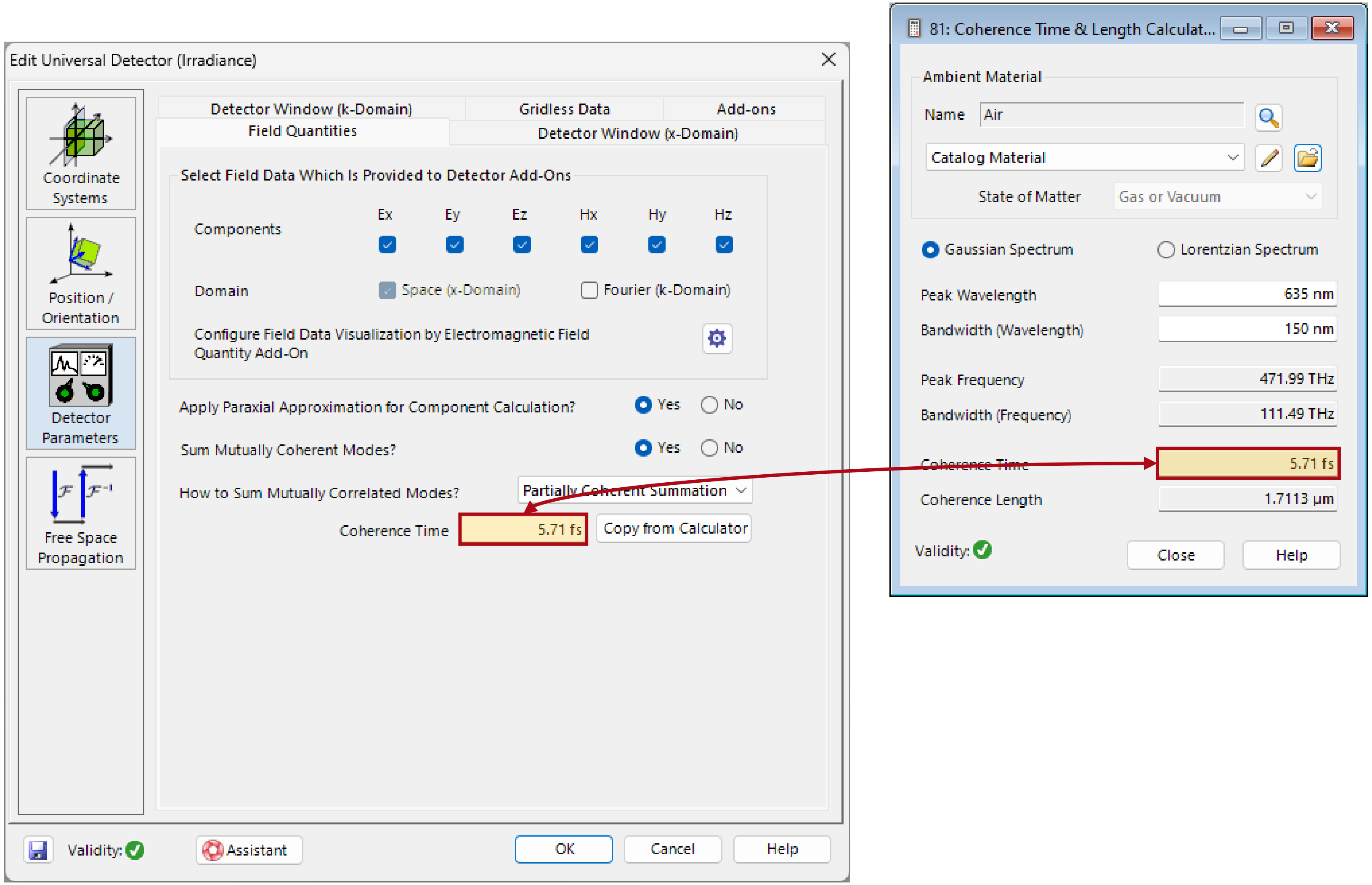




Time Domain Method

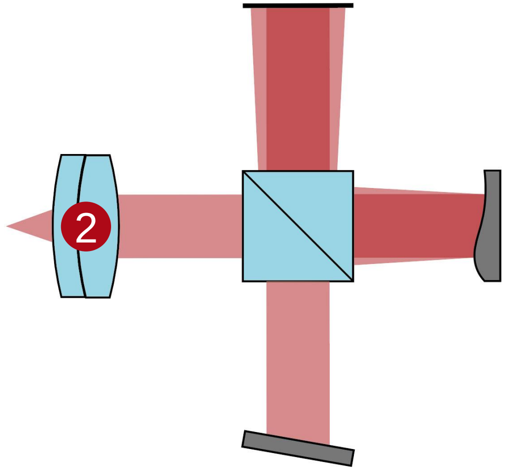
The Time Domain Method, on the other hand, is controlled through the *Universal Detector*. The sum of coherent modes in the detector needs to be set *to Partially Coherent* with a *Coherence Time* specified.

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.



Connected Modeling Techniques: Achromat

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

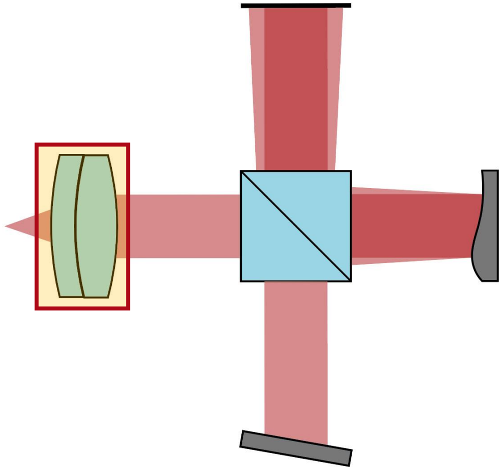


Available modeling techniques interaction with surfaces:

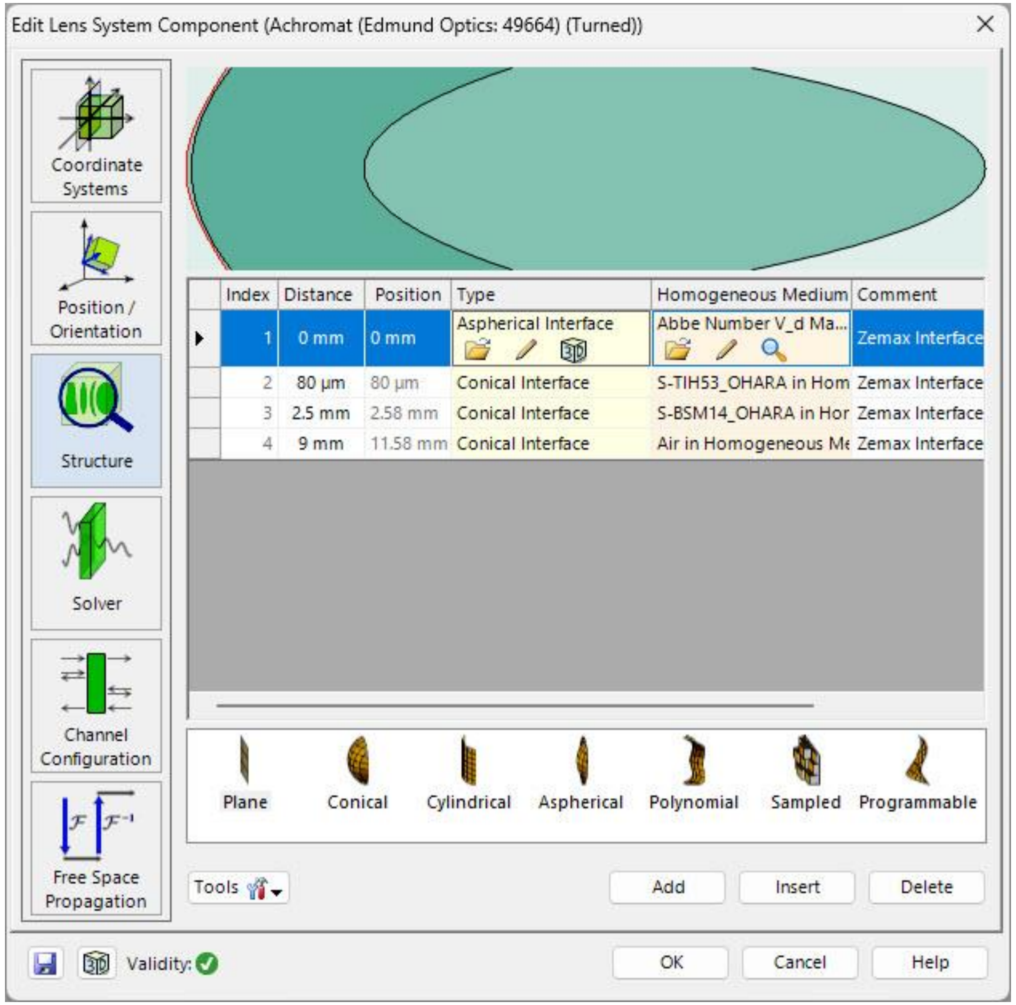
Methods	Preconditions	Accuracy	Speed	Comments
Thin Element Approximation (TEA)	Element not too thick/curvature not to strong	Low	High	Thickness about wavelength
Local Planar Interface Approximation	Surface not in focal region of beam	High	Very High	Local application of S matrix; LPIA; x-domain

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** offers the best compromise between speed and accuracy.

Achromat: Lens System Component

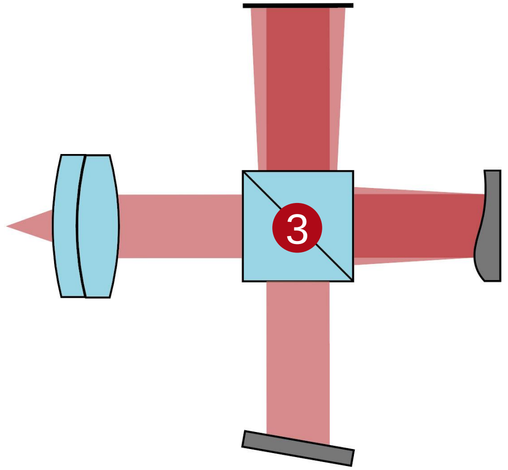


The *Lens System Component* allows the user to easily define a component consisting of an alternating sequence of smooth surfaces and homogeneous, isotropic media. For both interfaces and materials, you can choose ready-made entries from the built-in catalogs or customize your own for maximum flexibility.



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. reference mirror
7. detector



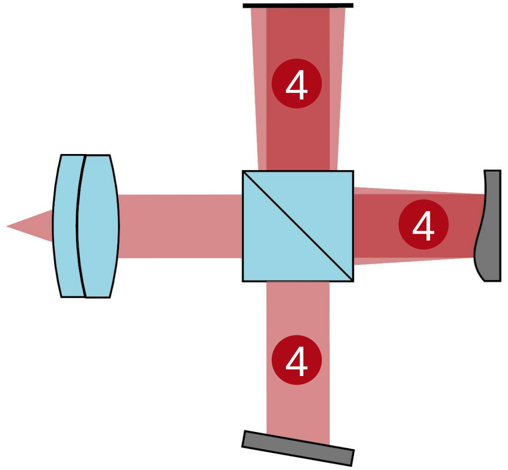
Available modeling techniques for beam splitter:

Methods	Preconditions	Accuracy	Speed	Comments
Functional Approach	No Fresnel losses	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 in principle have no interest in investigating 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. reference mirror
7. detector



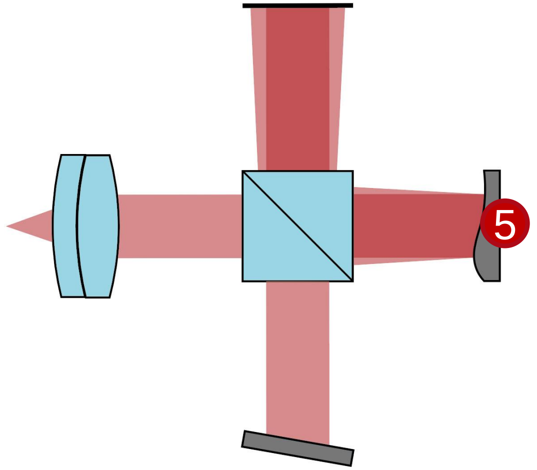
Available modeling techniques for free-space propagation:

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. With this in mind, **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. reference mirror
7. detector



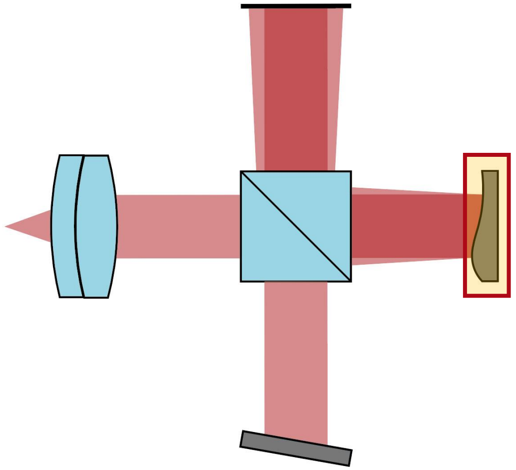
Available modeling techniques interaction with surfaces:

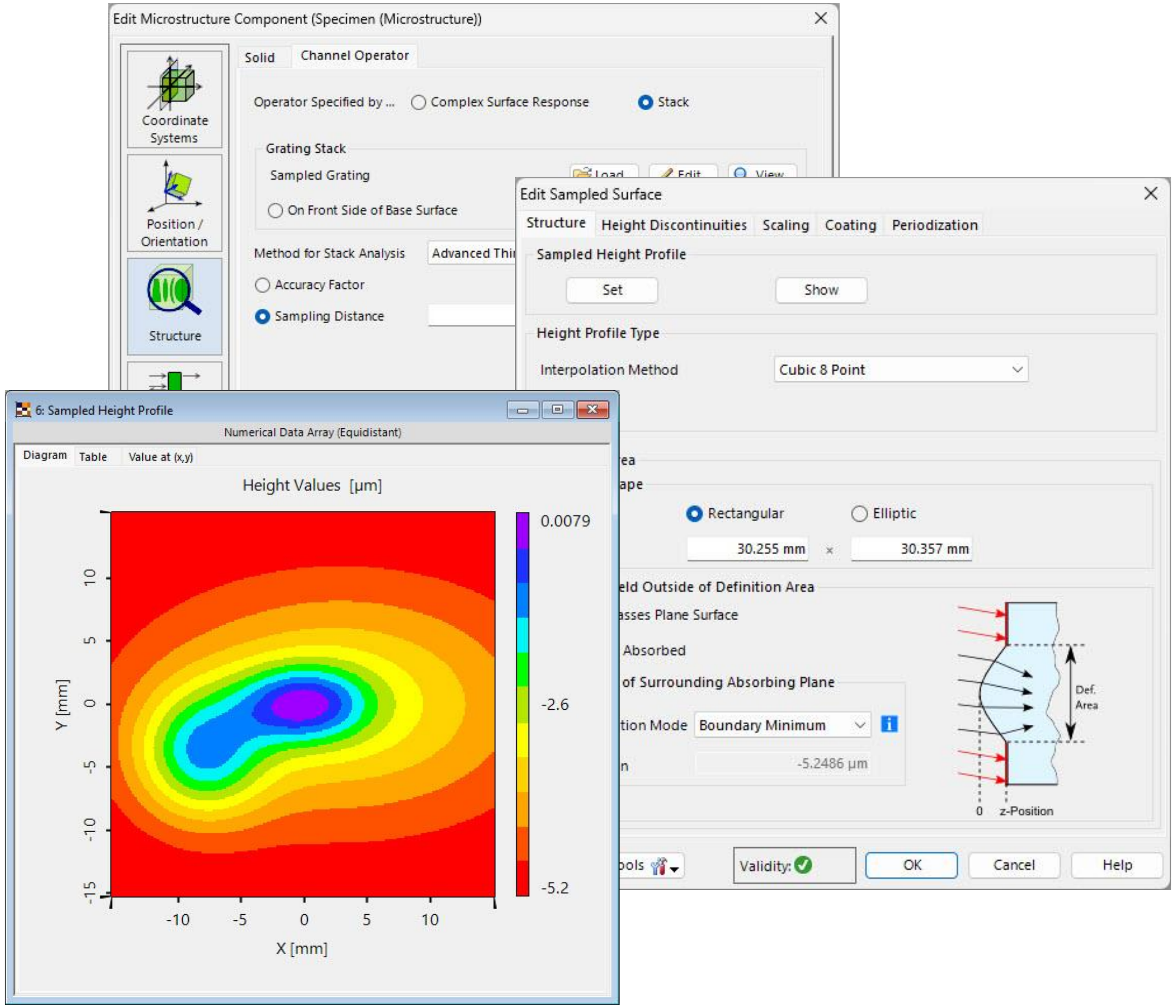
Methods	Preconditions	Accuracy	Speed	Comments
Thin Element Approximation	Thin element, large feature sizes	High	Very High	Thickness about wavelength; period & features larger than about ten wavelengths
Local Planar Interface Approximation	Surface not in focal region of beam	High	Very High	Local application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

Mirror with Specimen: Sampled Interface



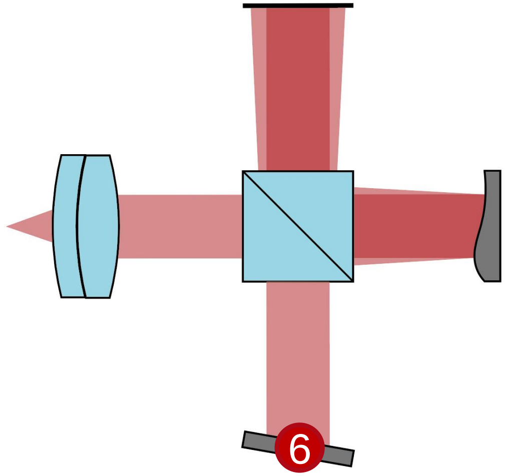


To incorporate the specimen with a custom height profile, VirtualLab offers the *Sampled Surface*, which can import arbitrary structures as long as their height information is given in a *Data Array.*

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

Connected Modeling Techniques: Reference Mirror

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



Available modeling techniques for beam splitter:

Methods	Preconditions	Accuracy	Speed	Comments
Functional Approach	No Fresnel losses	Low	Very High	Idealized version of a mirror
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

In this use case we investigate the effects of the specimen. Hence, for the other mirror of the interferometer we employ an idealized beam splitter model since we do not want to investigate e.g. the Fresnel losses that appear there. Therefore, a **Functional Approach** is sufficient.

Connected Modeling Techniques: Detector

1. Xenon lamp (white-light point source)
2. achromat
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4. free-space propagation
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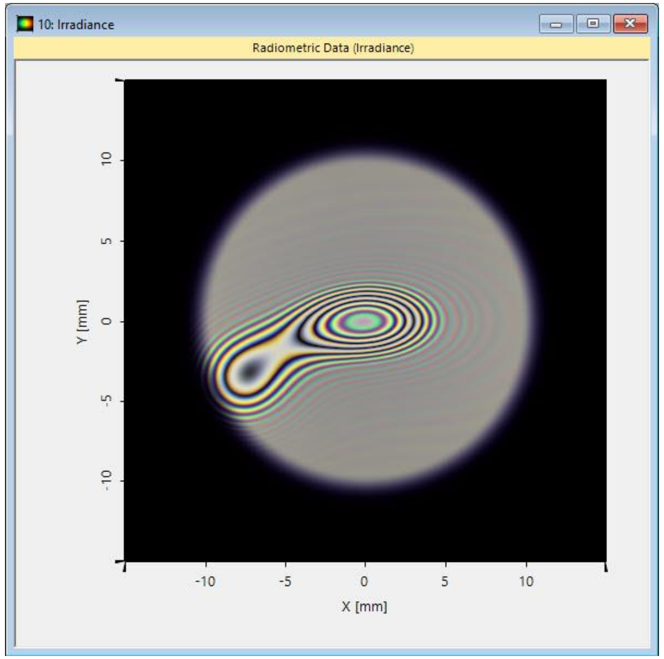
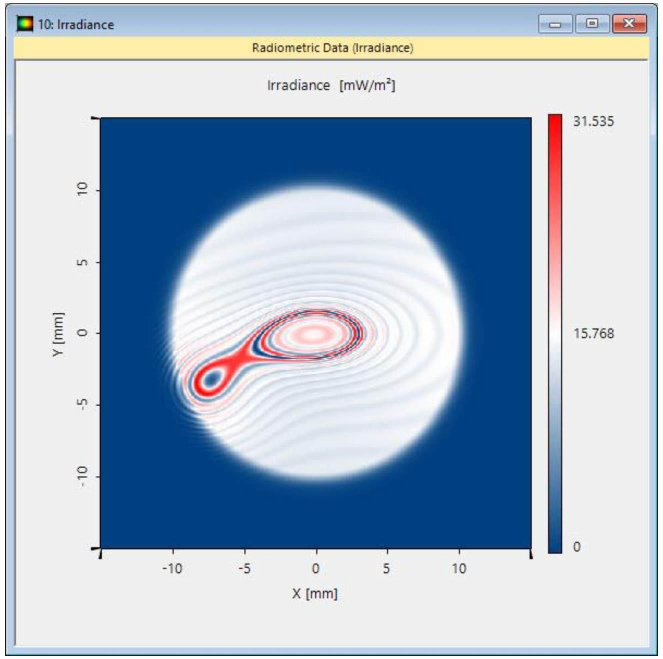
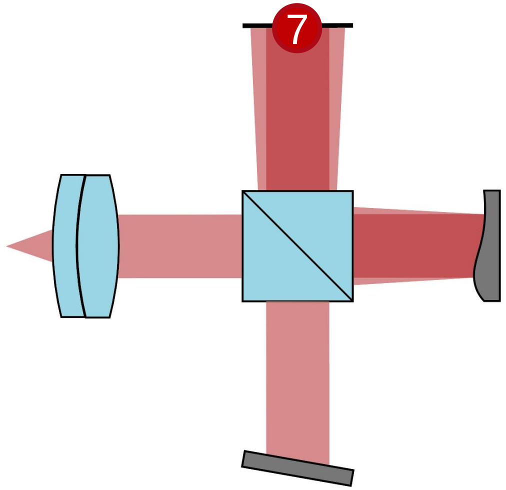
7. detector



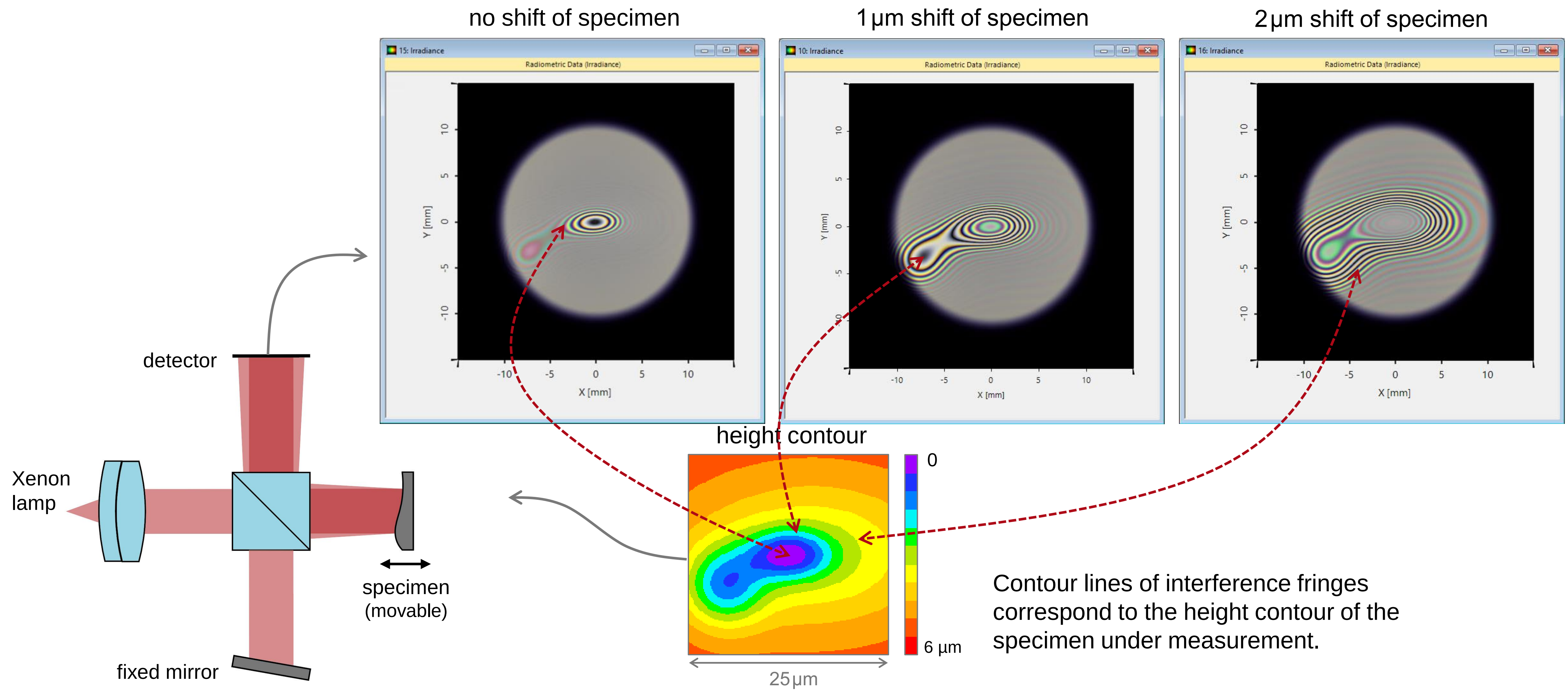




Full flexibility in detector modeling of different physical values, including irradiance, which can be given out in a predefined color-scheme or in the *Real-Color View,* which simulates how the human eye would see the result.

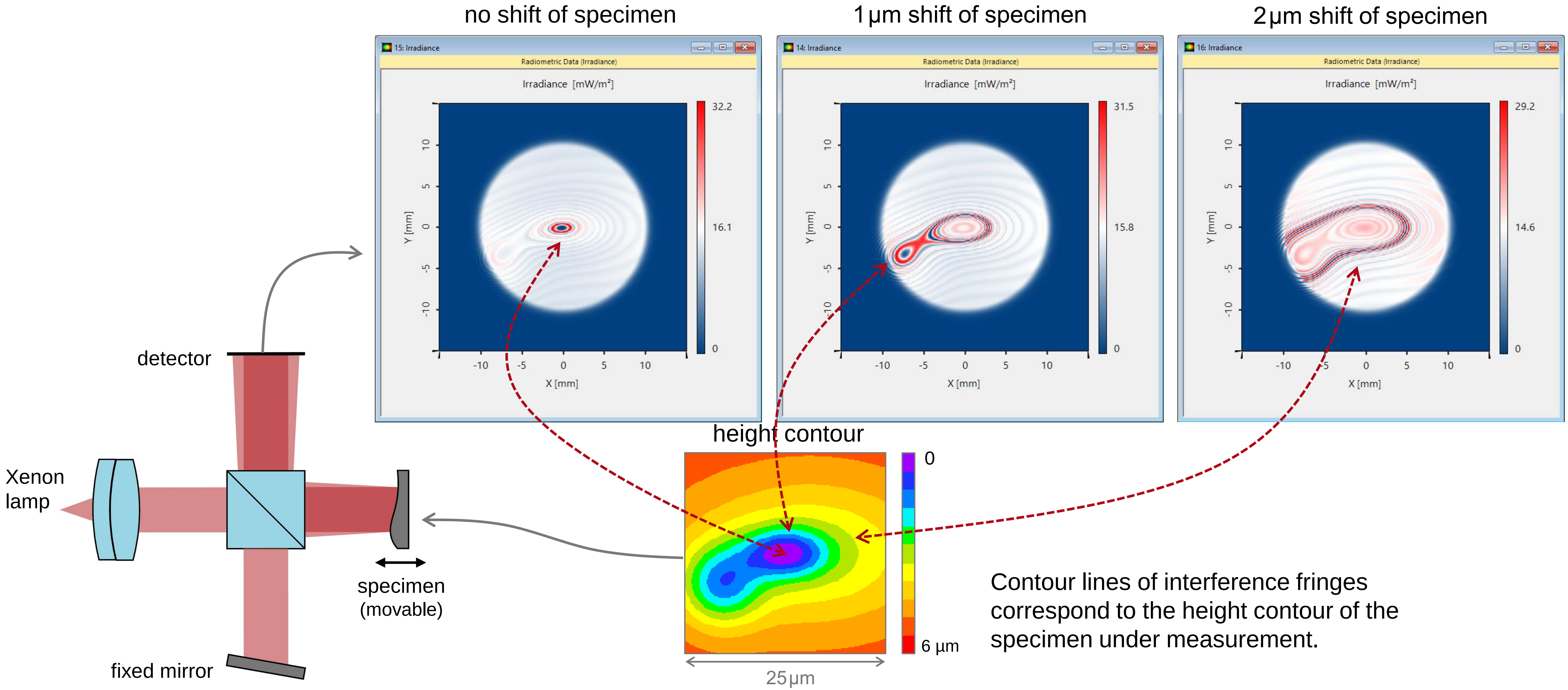
Simulation Results

Simulated Interference Fringes



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

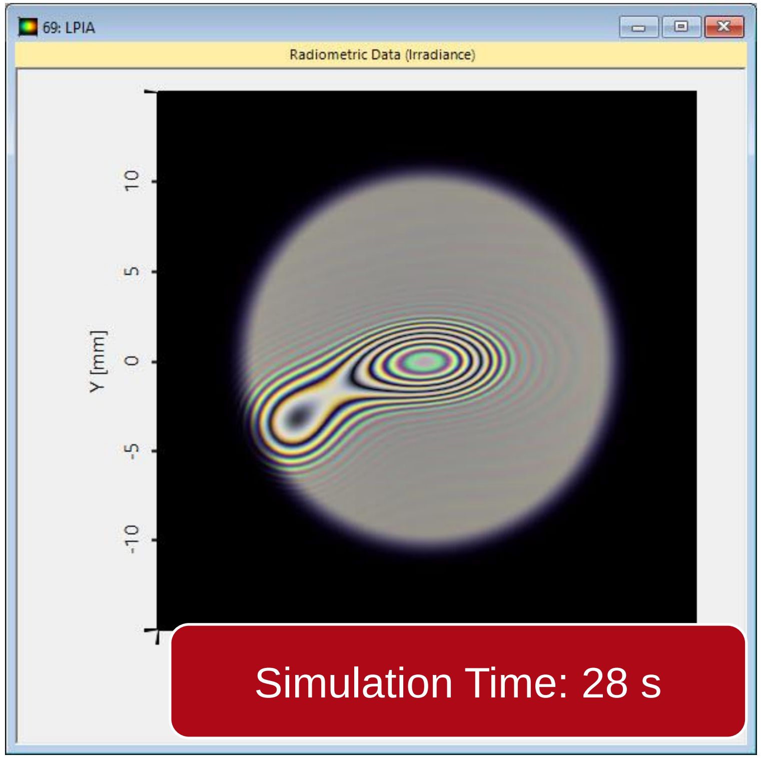
Simulated Interference Fringes – False Color

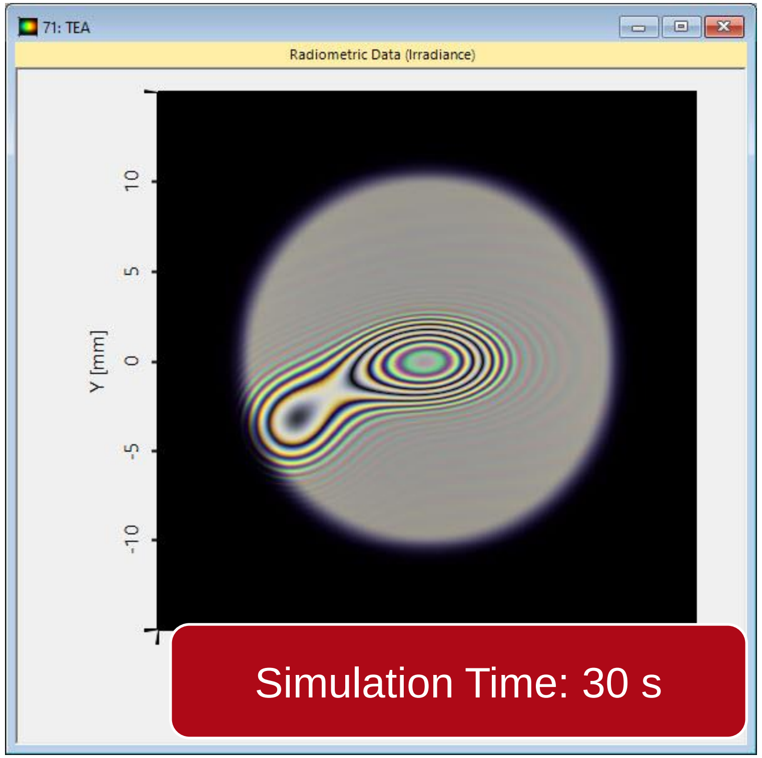


Contour lines of interference fringes correspond to the height contour of the specimen under measurement.

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.





Methods	Preconditions	Accuracy	Speed	Comments
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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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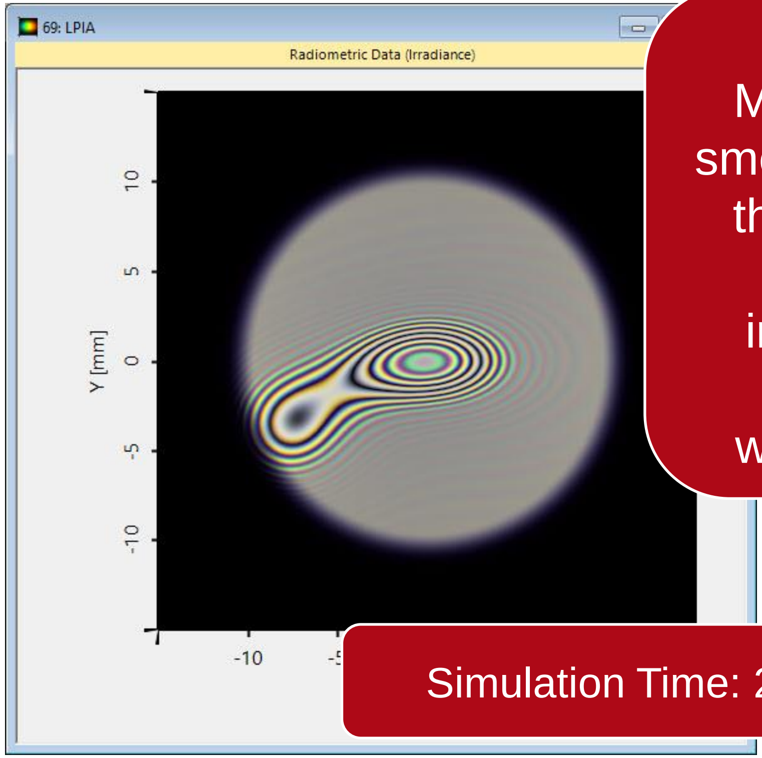
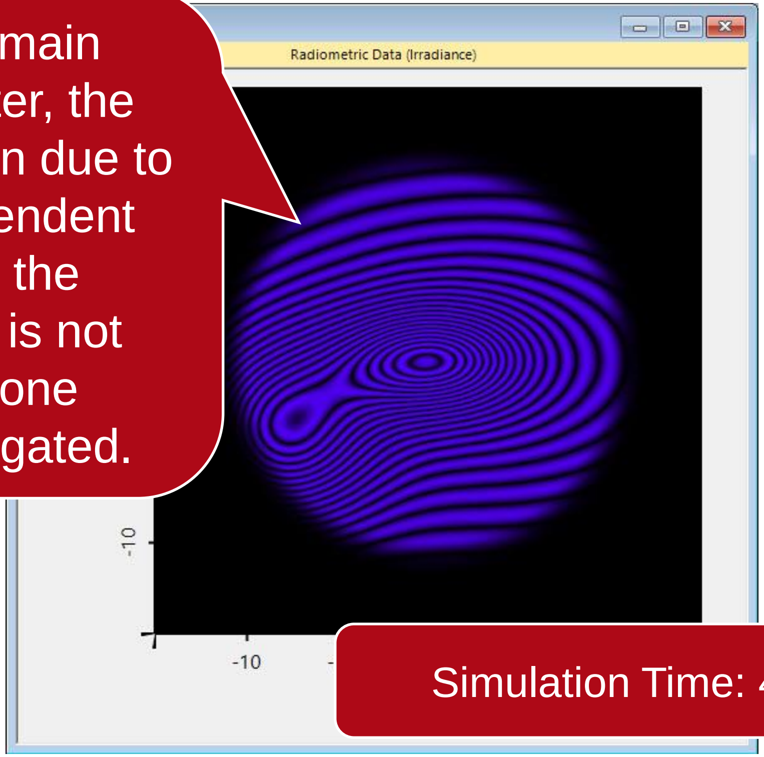
Method Comparison: Frequency vs Time Domain Method



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 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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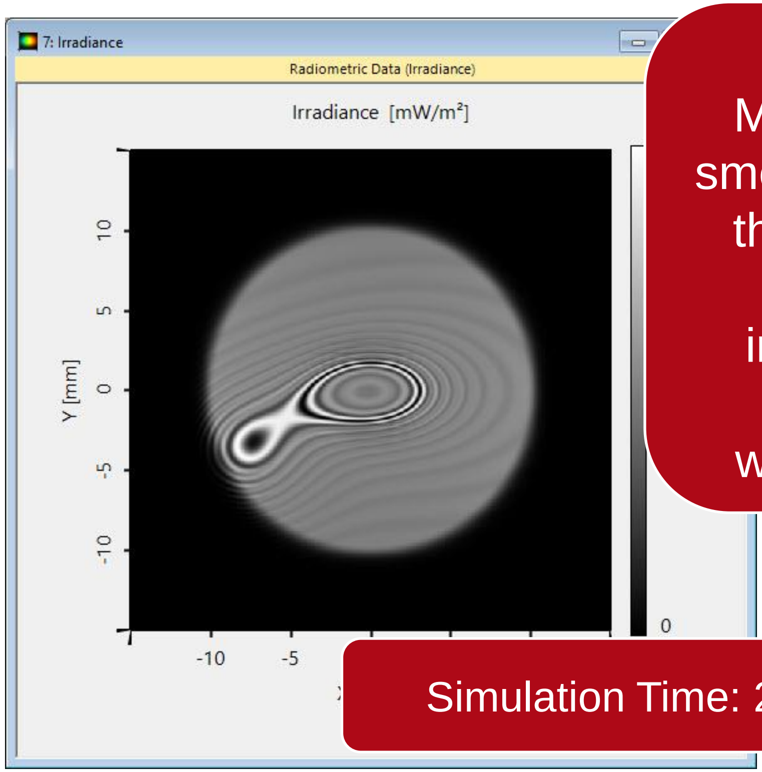
Method Comparison – False Color



Simulation Time: 28 s

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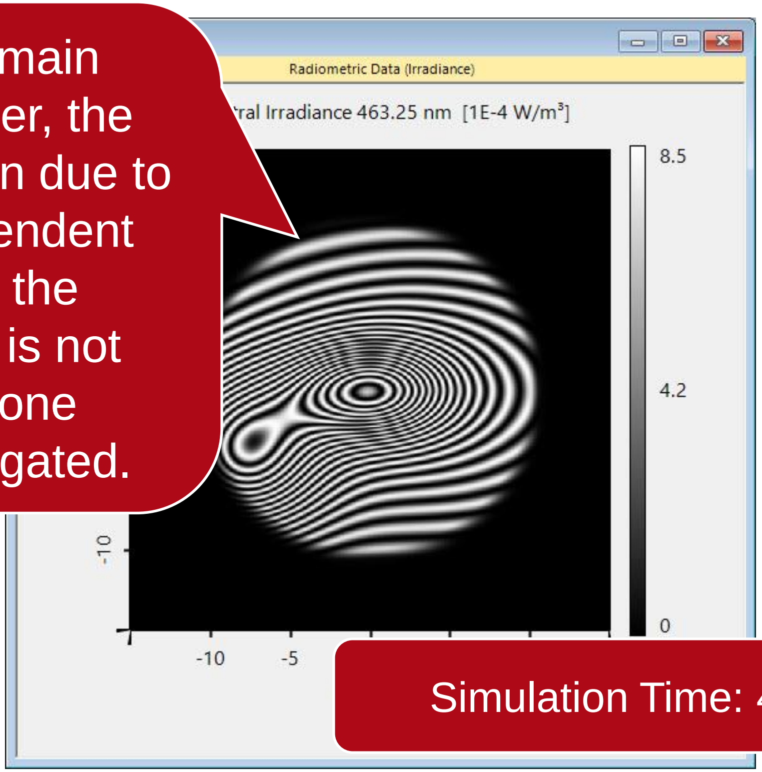

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