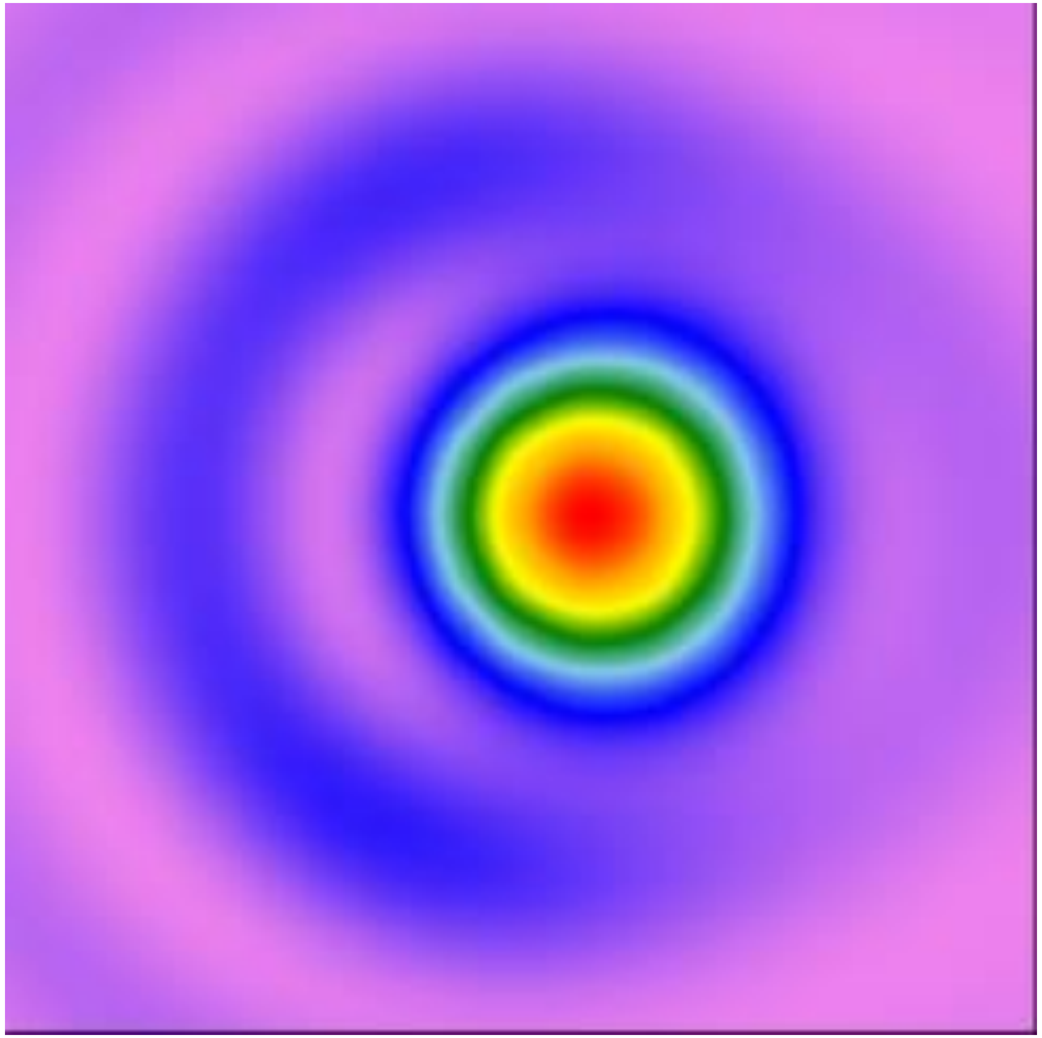
Analysis of Off-Axis Imaging in a High-NA Microscope System

Abstract



The off-axis PSF for imaging systems often suffers from aberrations introduced by the plied optical components (e.g. a microscope system). Hence, the focus is not perfectly invariant to shifts as ideally expected. VirtualLab Fusion provides a fast and convenient way to check the light propagation and PSFs for off-axis imaging with a high-NA microscope. This use case demonstrates the imaging of off-axis object points with different lateral shift distances, to check the influence of the aberrations.

Modeling Task

spherical wave

- wavelength 587.5 nm
- circularly polarized
- lateral shift in *x*-direction 20 µm, 40 µm, 60 µm, 80 µm, 100 µm

How is the PSF influenced by the aberrations in the case of off-axis imaging?

focal spot / PSF

objective lens: Nikon

- NA=1.4, 60X
- US6519092B2

tube lens

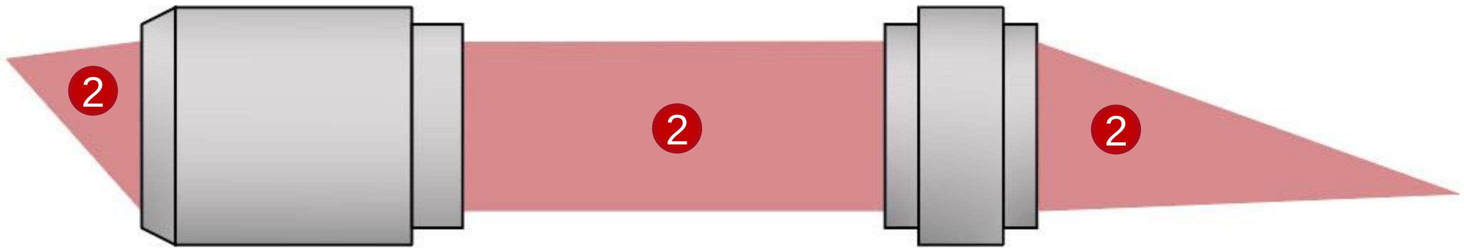
Single-Platform Interoperability of Modeling Techniques

Light will encounter and interact with different components as it propagates through the system. A suitable model that provides a good compromise between accuracy and speed is required for each of these elements of the system:

1. source
2. free-space propagation
3. objective lens
4. tube lens
5. detector

Connected Modeling Techniques: Free-Space Propagation

① source
② free-space propagation
③ objective lens
④ tube lens
⑤ 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	

Significant diffraction effects can be expected near the source and focal region of the system. Therefore, the system is simulated using **Fourier Domain Techniques**.

Connected Modeling Techniques: Objective Lens

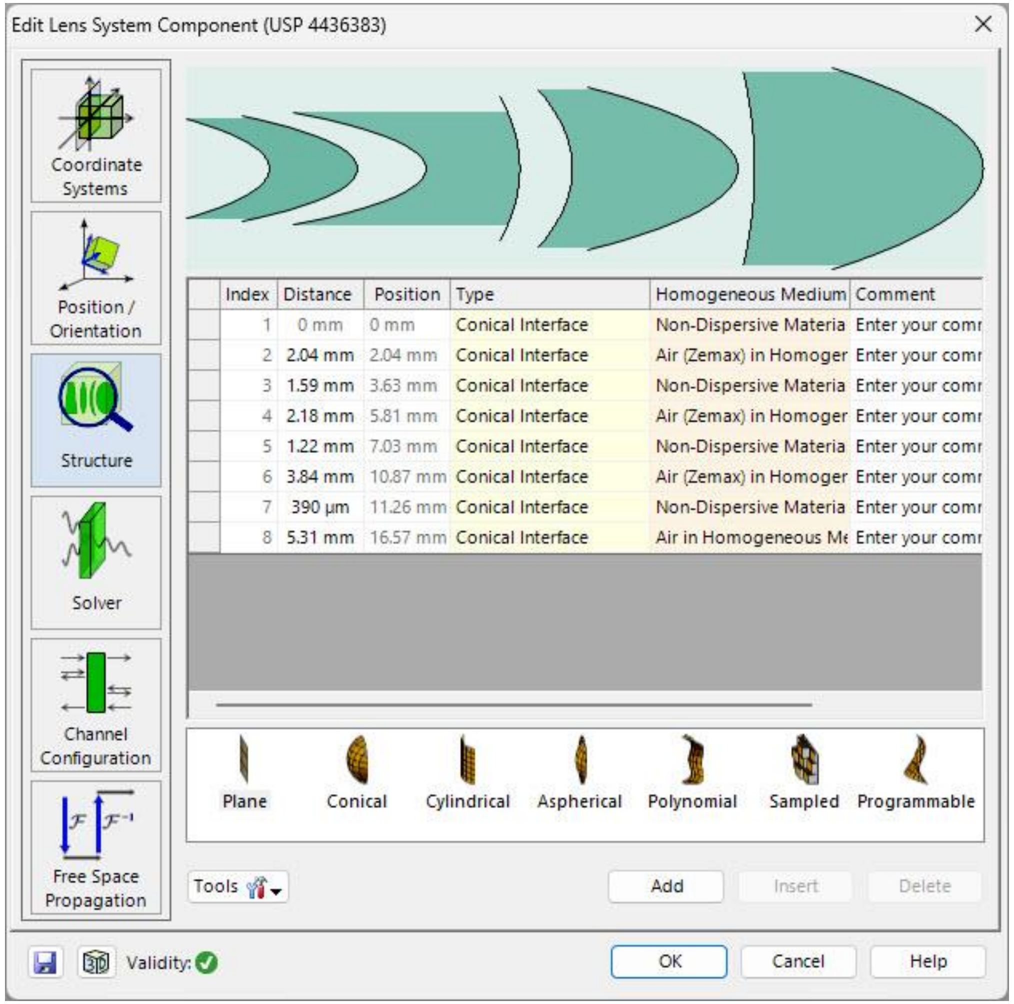
① source
② free-space propagation
③ objective lens
④ tube lens
⑤ detector

Available modeling techniques for interaction with surfaces :

Methods	Preconditions	Accuracy	Speed	Comments
Functional Approach	-	Low	Very High	No Fresnel Losses
S matrix	Planar surface	High	High	Rigorous model; includes evanescent waves
Local Plane Interface Approximation	Surface not in focal region of beam	High	High	Local application of S matrix

The lens system used for this microscope cannot be considered n objective lens constructed from thin lenses. Hence, **Local Plane Interface Approximation (LPIA)** offers the best compromise between speed and accuracy.

Lens System Component



The *Lens System Component* allows for an easy definition of components consisting of an alternating sequence of smooth surfaces and homogeneous, isotropic media. Both the interfaces and the materials can be chosen as ready-made entries from the in-built catalogs or customizable entries for maximum flexibility.

Connected Modeling Techniques: Tube Lens

1. source
2. free-space propagation
3. objective lens
4. tube lens
5. detector

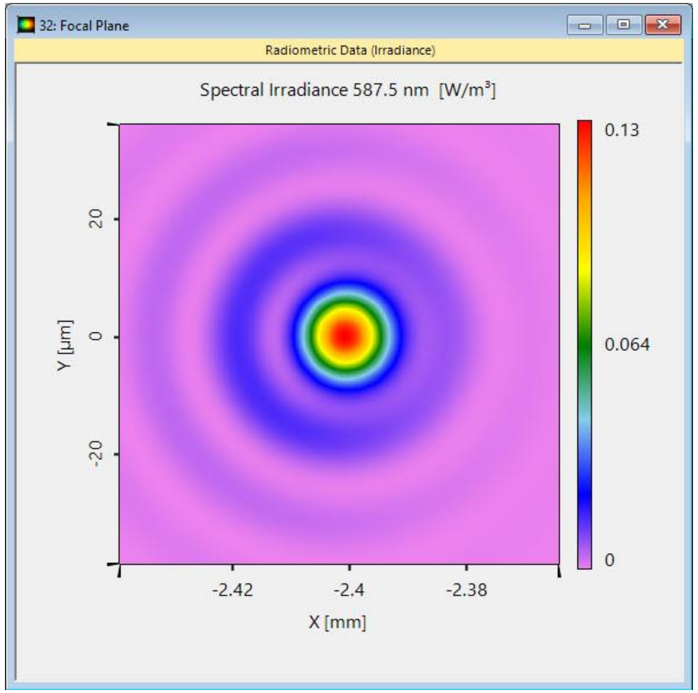
Available modeling techniques for interaction with surfaces :

Methods	Preconditions	Accuracy	Speed	Comments
Functional Approach	-	Low	Very High	No Fresnel Losses
S matrix	Planar surface	High	High	Rigorous model; includes evanescent waves
Local Plane Interface Approximation	Surface not in focal region of beam	High	High	Local application of S matrix

For similar reasons as in the case of the objective lens, we also simulate the tube lens using **Local Plane Interface Approximation (LPIA)**.

Connected Modeling Techniques: Detector

① source
② free-space propagation
③ objective lens
④ tube lens
⑤ detector

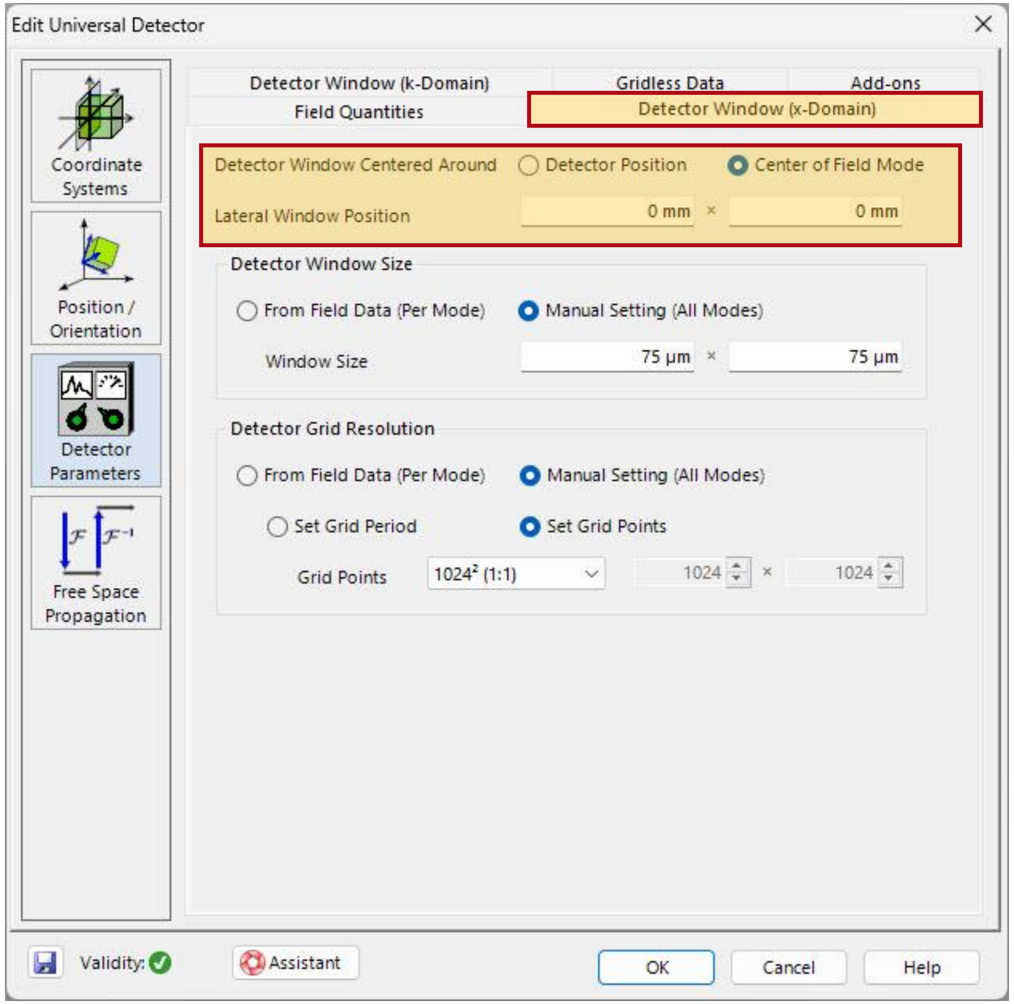


Through the *Universal Detector*, multiple different physical quantities can be calculated, including:

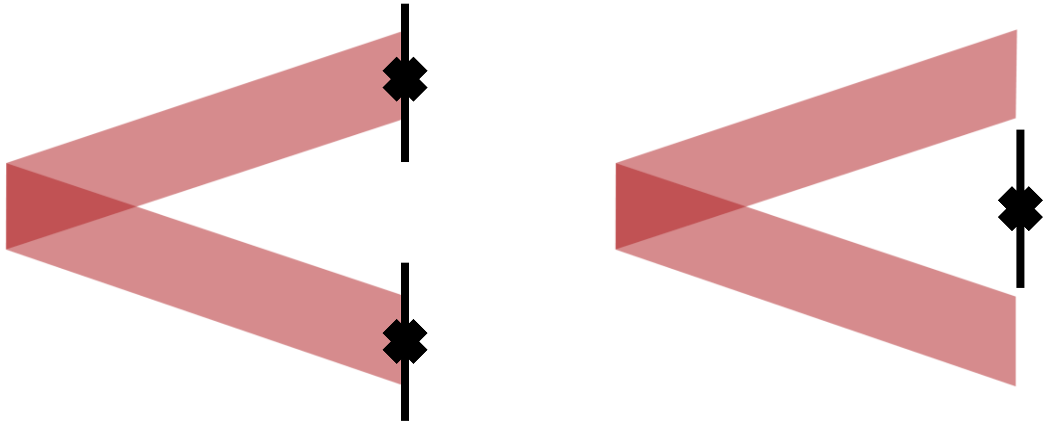
- irradiance/illuminance
- radiant flux
- radiant energy density
- ……

More information under: Universal Detector

Automatic Lateral Positioning of the Detector

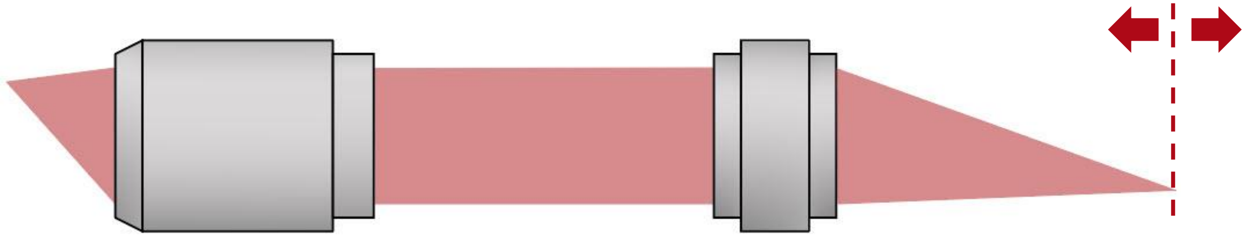


The lateral and longitudinal position of the focal spot is dependent on the lateral shift of the source. The flexible *Universal Detector* has the option to automatically center itself around an incoming field mode. Here, we use the *Center of Field Mode* - feature to automatically reposition detector to match with the lateral position of the focal spot for the different off-axis positions of the source.



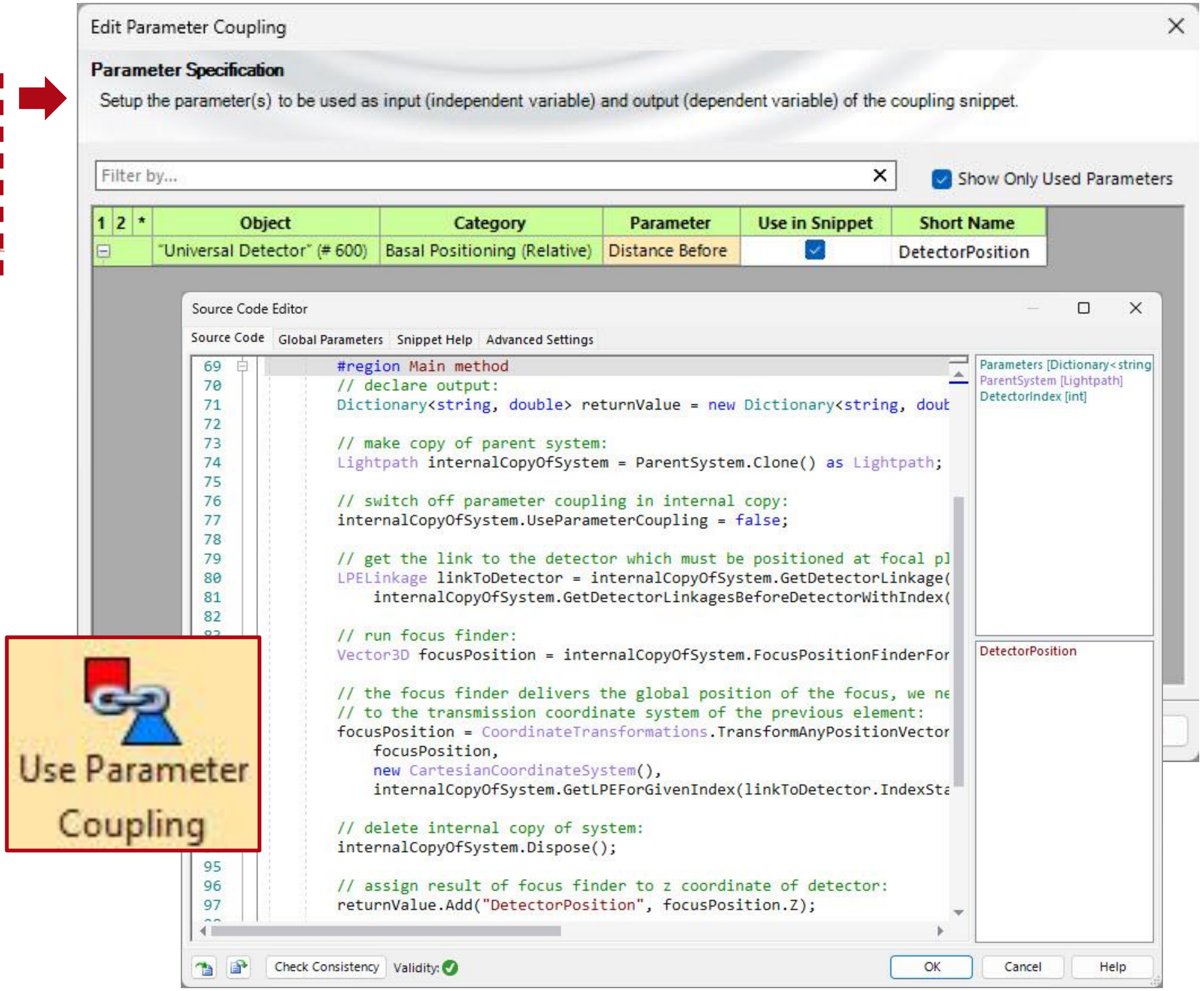
Center of Field Mode *Detector Position*

Automatic Longitudinal Positioning of the Detector

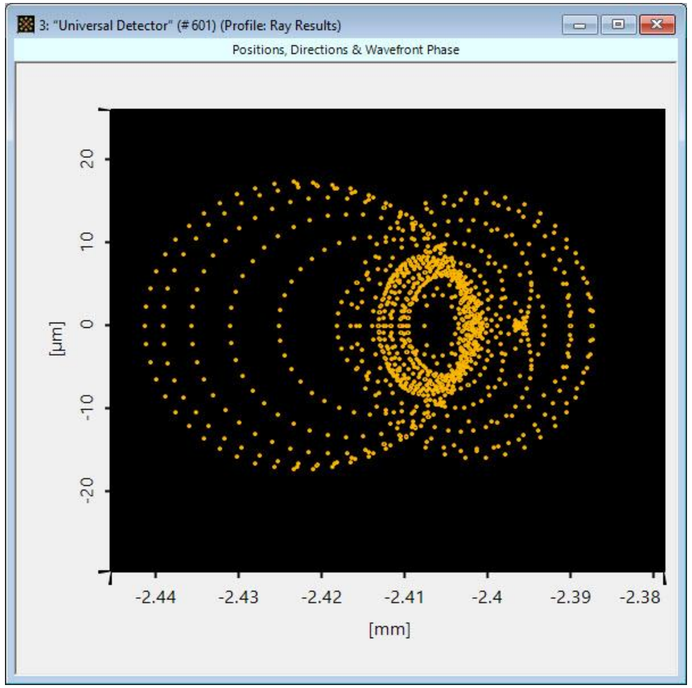


While the lateral positioning of the detector is handled by the detector itself, the longitudinal positioning needs an adjustment of the system. For this reasons we employ *Parameter Coupling* to calculate the expected longitudinal position of the focal point (of each off-axis shift of the source) and automatically adjust the z-position of the detector to match that value.

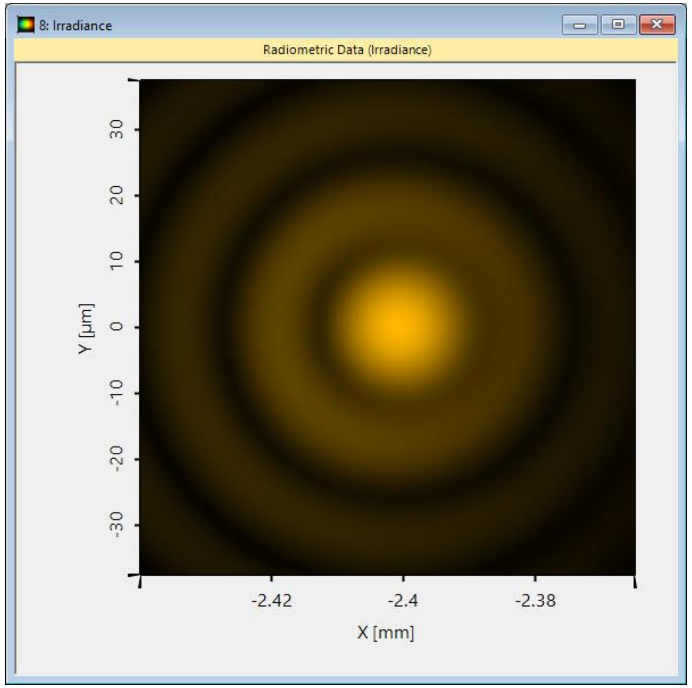
More information on this specific *Parameter Coupling* snippet can be found under:
[Focus Position as Function of NA]()



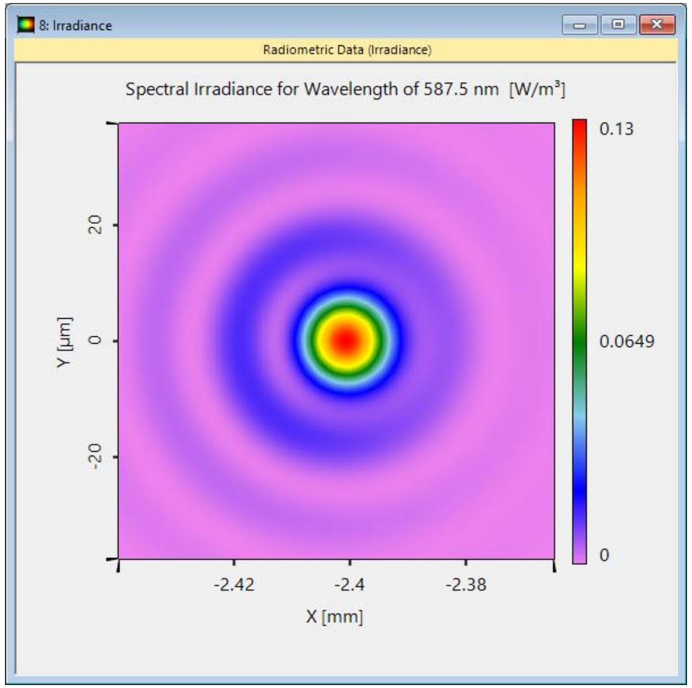
System Overview



ray distribution

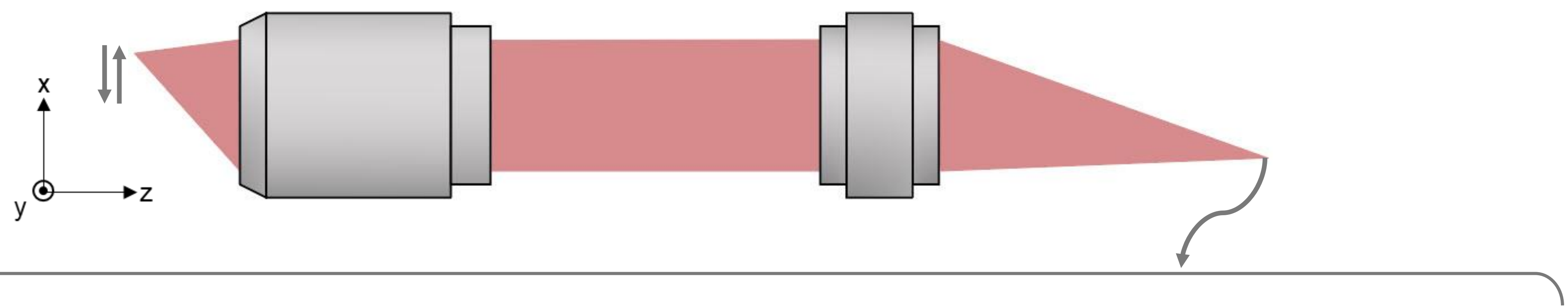


irradiance

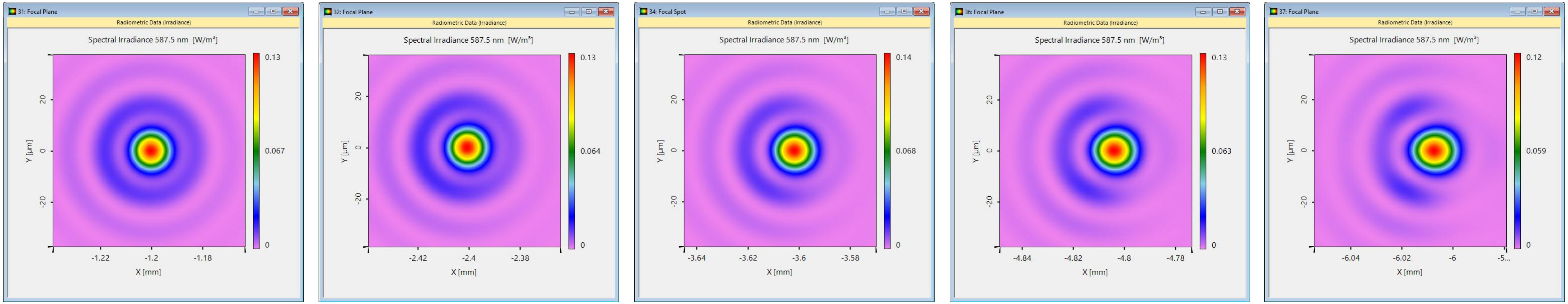


irradiance (false color)

Irradiance at Focal Plane with Lateral Shifts



x=20µm x=40µm x=60µm x=80µm x=100µm



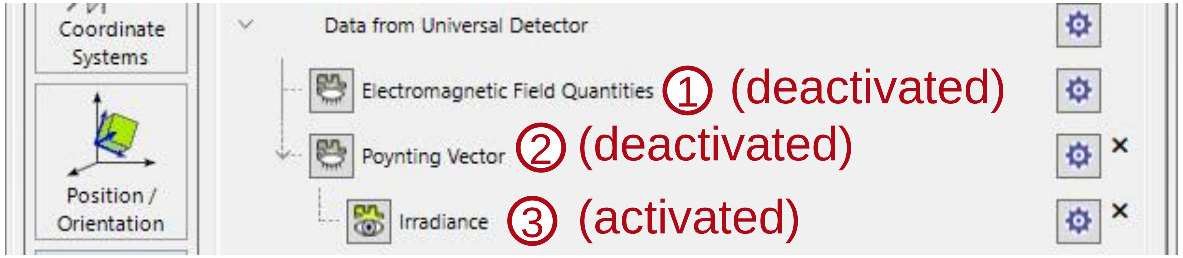
Technical Insight: Additional Detected Quantities

For this use case we only measure the irradiance of the focal spot. Though it is possible to calculate additional physical quantities, such as illuminance, radiant flux and many more – by simply adding more *Detector Add-ons*.

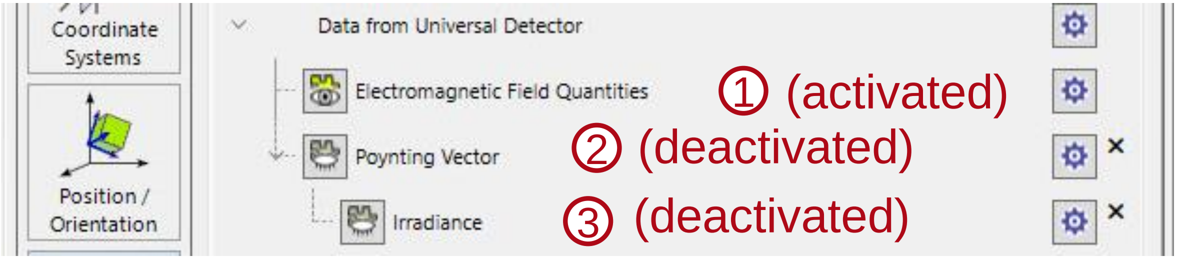
In this specific use case however – in order to avoid error messages – it is necessary to adjust the programmable snippet of the *Parameter Coupling* slightly, as depicted below. The reason behind it is, that the algorithm used to calculate the focal plane is based on the *Ray Result Profile* engine, which in incompatible with most *Detector Add-ons* that calculate physical quantities, hence they need to be deactivated for *Parameter Coupling* algorithm.

```
// make copy of parent system:
Lightpath internalCopyOfSystem = ParentSystem.Clone() as Lightpath;
(internalCopyOfSystem.GetLPEForGivenIndex(DetectorIndex) as ElectromagneticFieldDetectorLPE).AddonContainer.Addons[1].UseAddon = true;
(internalCopyOfSystem.GetLPEForGivenIndex(DetectorIndex) as ElectromagneticFieldDetectorLPE).AddonContainer.Addons[2].UseAddon = false;
(internalCopyOfSystem.GetLPEForGivenIndex(DetectorIndex) as ElectromagneticFieldDetectorLPE).AddonContainer.Addons[3].UseAddon = false;
```

① ② ③



settings to detect fields (irradiance)



settings to detect ray distributions

Document Information

title	Analysis of Off-Axis Imaging by a High-NA Microscope
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software version	2023.2 (Build 2.30)
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further reading	• Debye-Wolf Integral Calculator • Analyzing High-NA Objective Lens • Resolution Investigation for Microscope Objective Lenses by Rayleigh Criterion • Focus Position as Function of NA