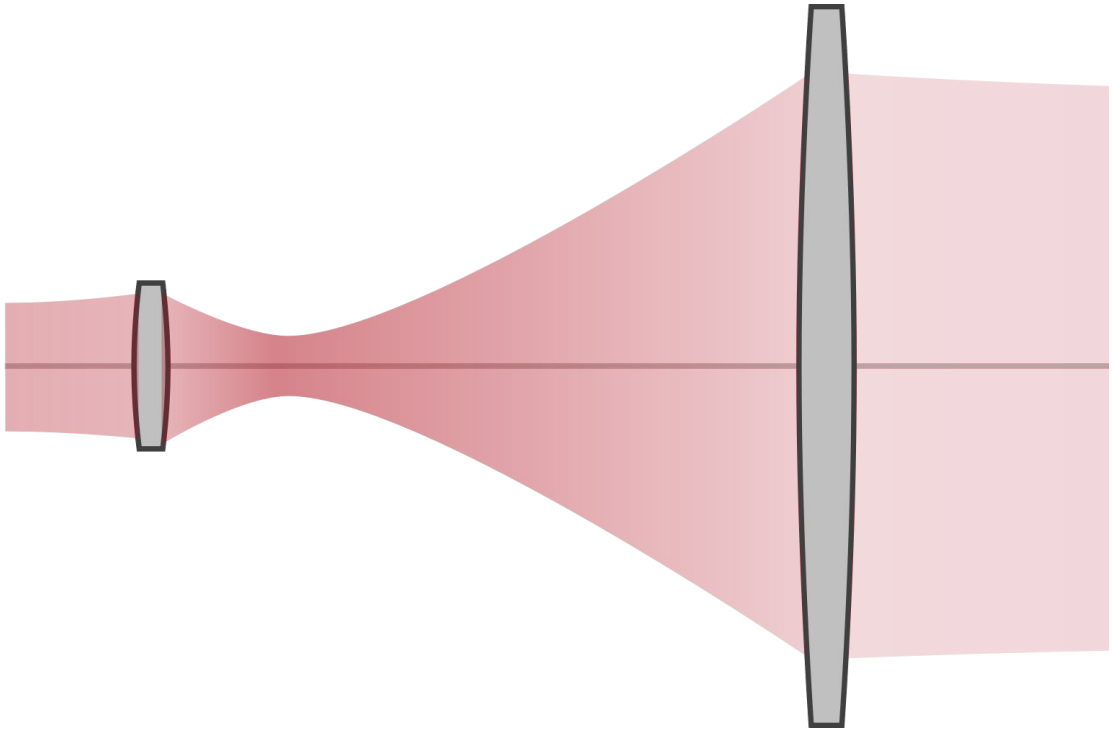
Analysis and Design of Afocal Systems for Laser Guide Stars

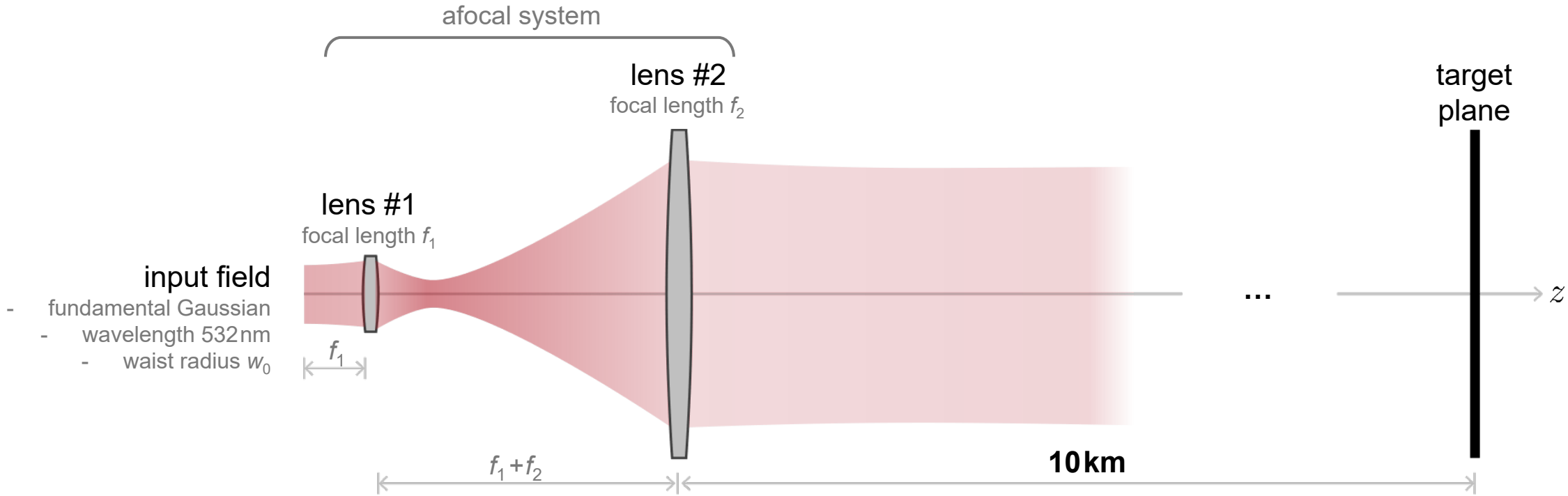
Abstract



For astronomical telescopes, laser guide stars are often used for correction of the atmosphere distortion. Such artificial star images are usually at tens of kilometers away by high-power laser beams. In order to accurately design the optical system to generate and even to control the size of the laser guide star, the diffraction effect of the laser beam must be considered. In this example, we show how to analyze and design afocal systems for laser guide stars.

Design Task #1 – Simple Afocal System

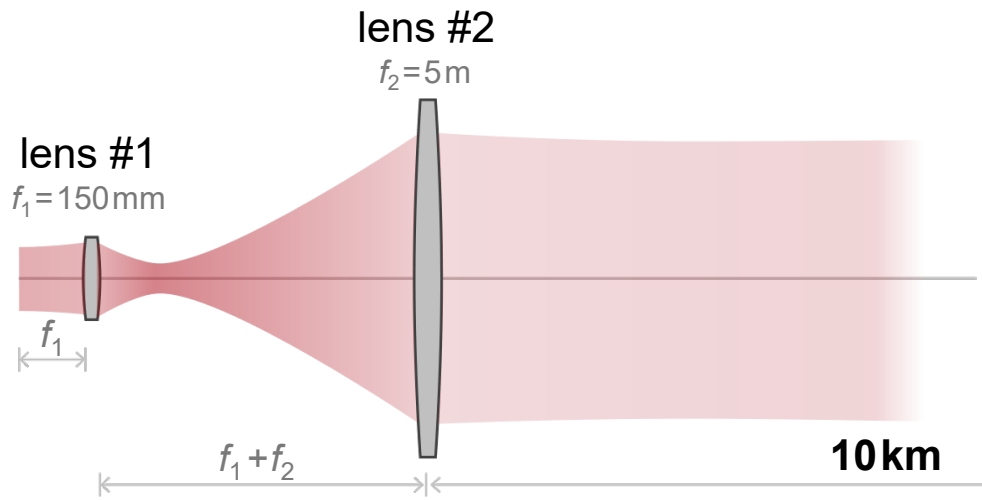
How to accurately calculate the laser beam parameters at the 10 km-away target plane, and how to minimize the spot there by varying the afocal system?



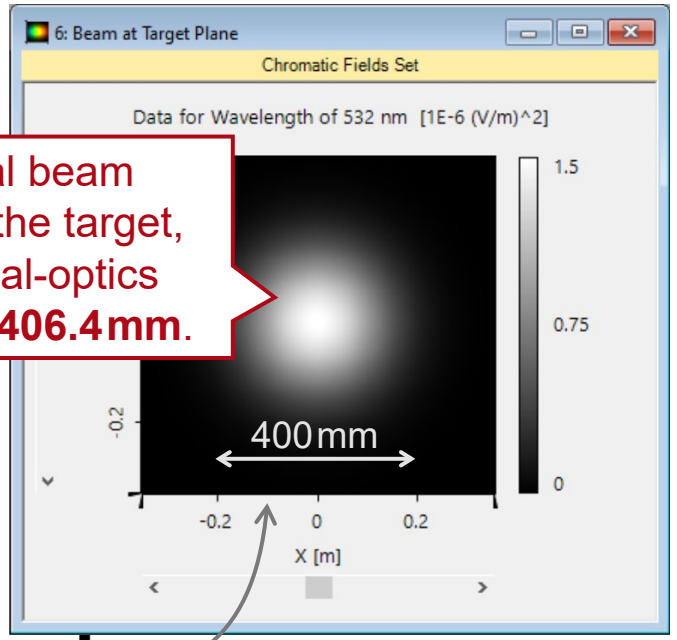
Parameters follow from L. Clermont, *et al.*, "Design of a laser guide star for applications to adaptive optics", Proc. SPIE 11105 (2019)

Analysis of Afocal System for Laser Beams

Using geometrical optics, the afocal system gives a magnification of $f_2/f_1 = 33.33$. That predicts a beam diameter of **16.7 mm** at the target plane.



physical-optics simulation result with diffraction considered



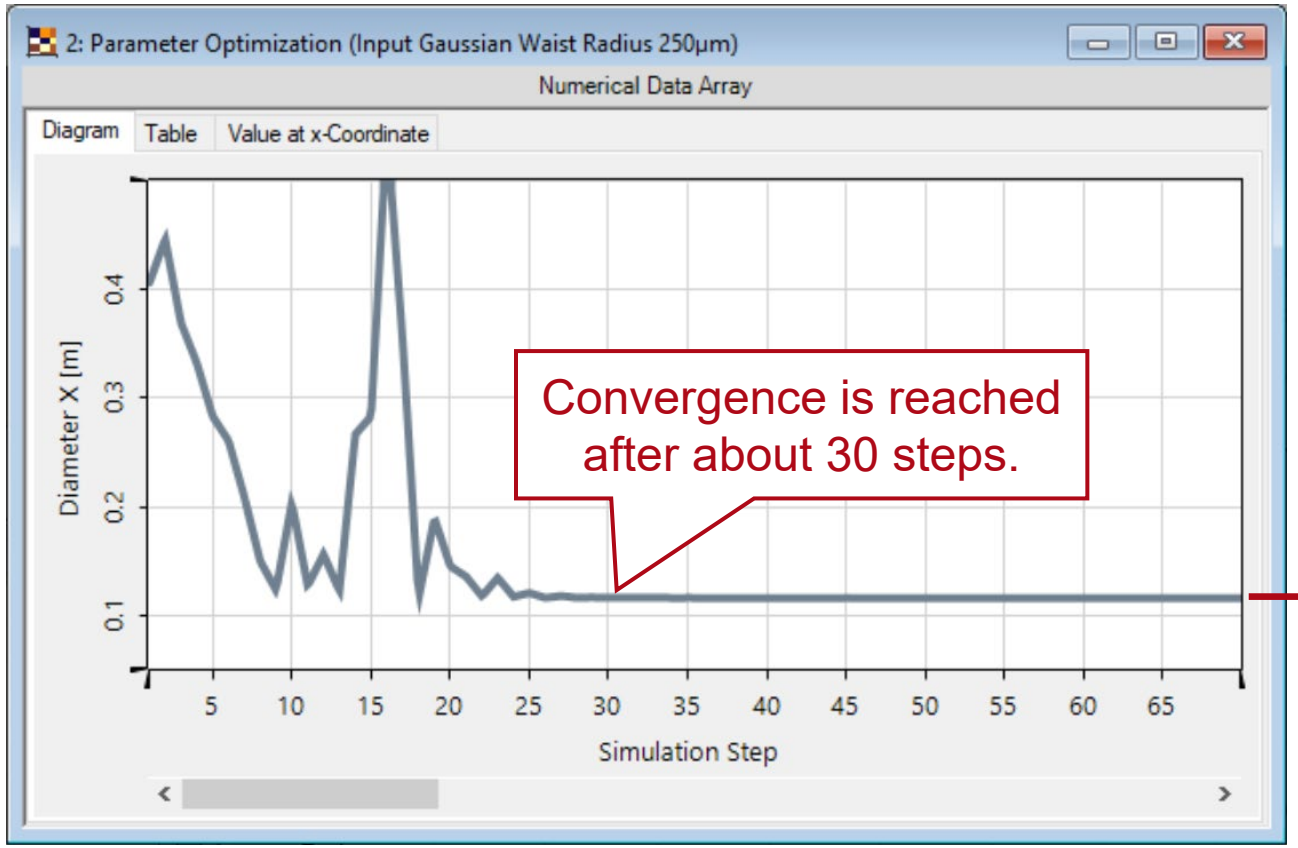
The actual beam diameter at the target, with physical-optics modeling, is **406.4 mm**.

target plane

Design of Simple Afocal System w_0=0.25mm (fixed)

initial variable values	
f_1	150mm
f_2	5m

parametric optimization with downhill simplex method



optimized variable values	
f_1	50.04mm
f_2	8.2416m

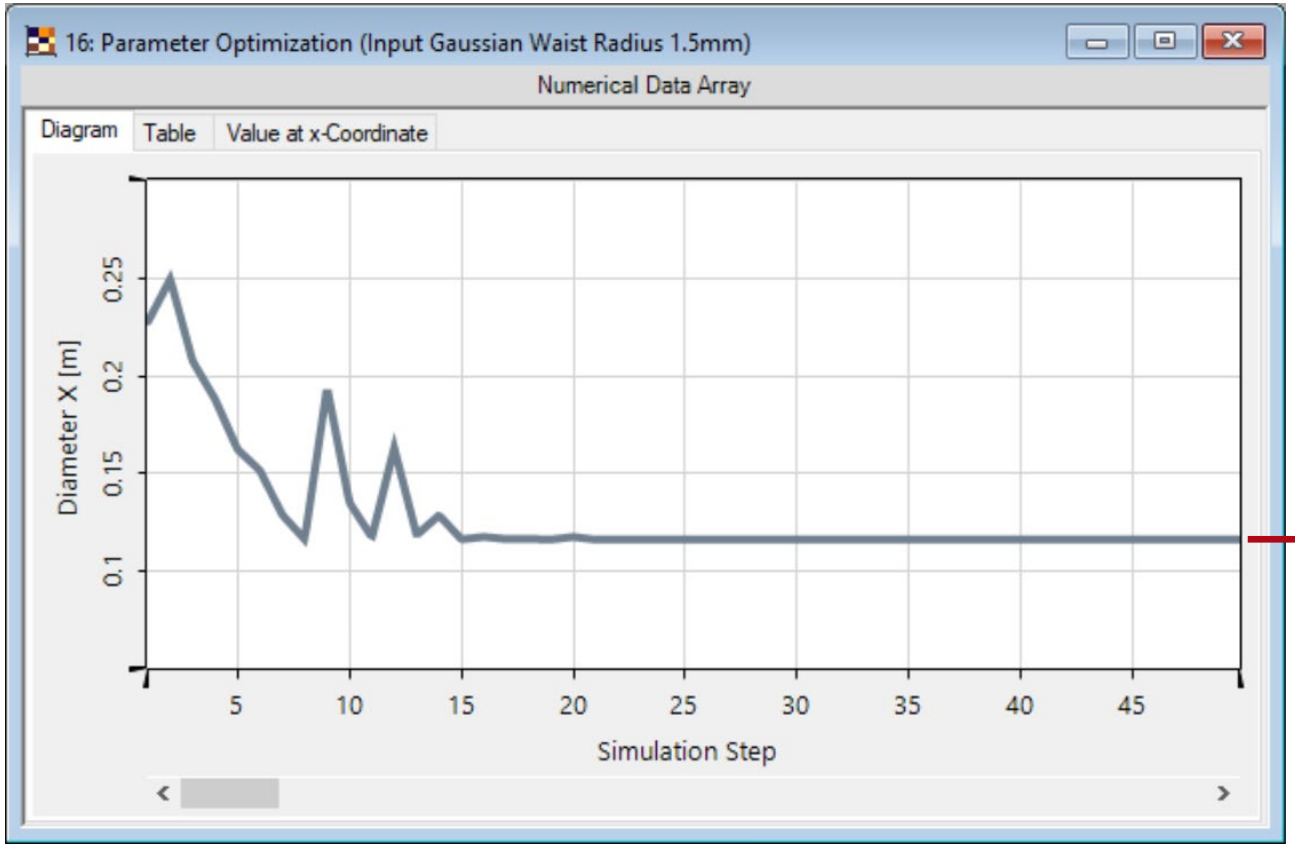
diameter @target
116.4mm

Design of Simple Afocal System w_0=1.5mm (fixed)

Let us try the optimization with another input Gaussian waist radius.

parametric optimization with downhill simplex method

initial variable values	
f_1	250mm
f_2	2.5m



optimized variable values	
f_1	128.6mm
f_2	3.5258m

diameter @target
116.4mm

Design of Simple Afocal System w_0=1.5mm (fixed)

initial variable values	
f_1	250mm
f_2	2.5m

parametric optimization with dov

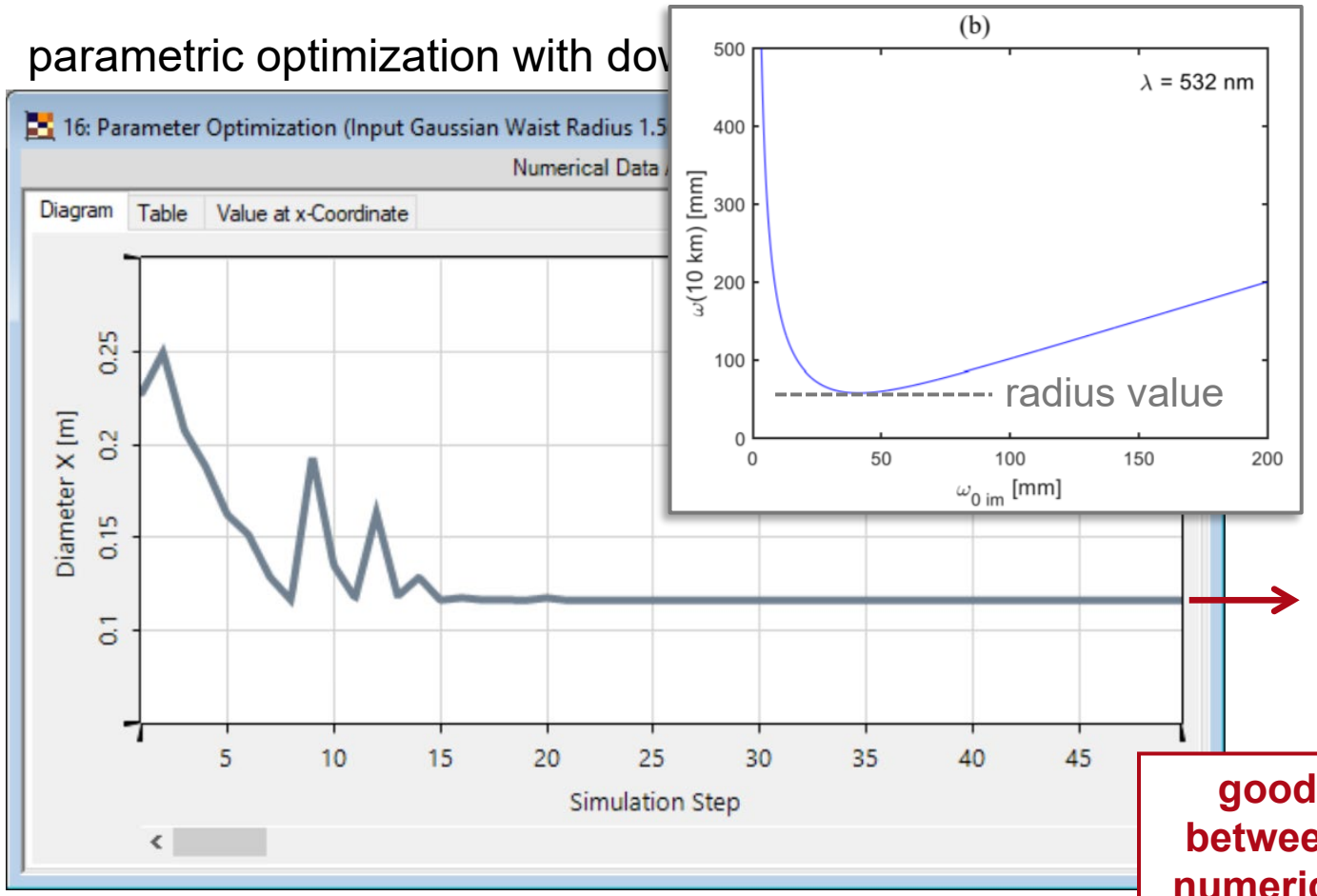


Fig.2(b) from the reference

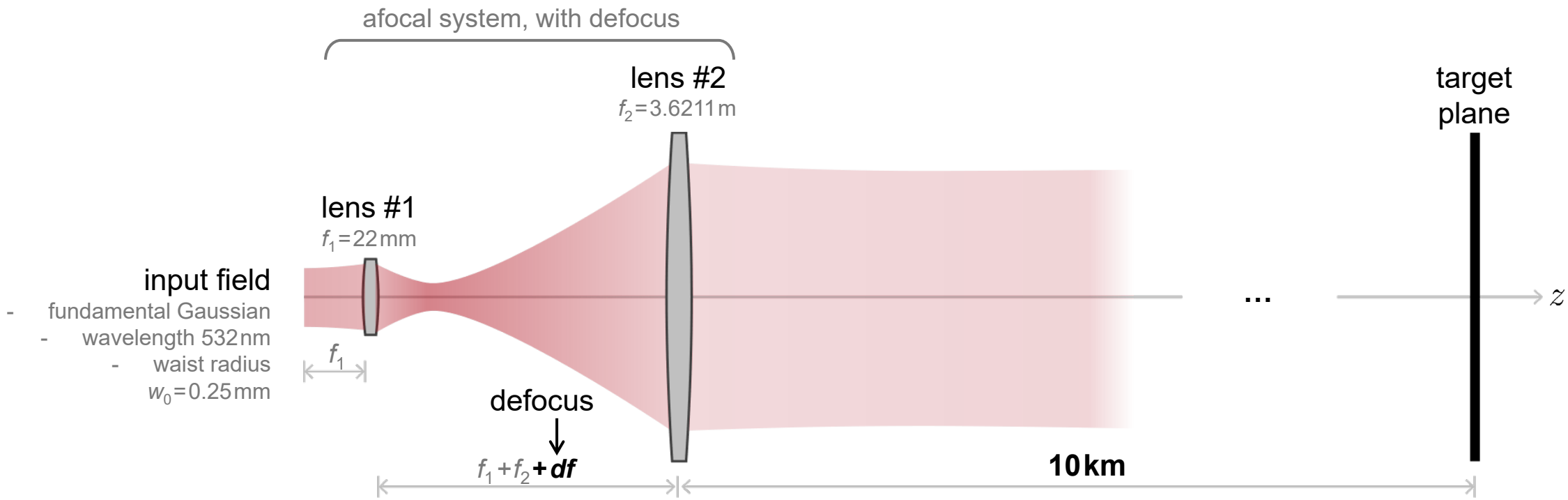
L. Clermont, *et al.*, showed theoretically that the minimum beam *radius* at the target is 58.2mm, for any simple afocal system.

diameter @target
116.4mm

good agreement between theory and numerical simulation

Design Task #2 – Afocal System with Defocus

Is it possible to further reduce the beam size at the target plane if additional freedom is available?
Let us try with the defocus!

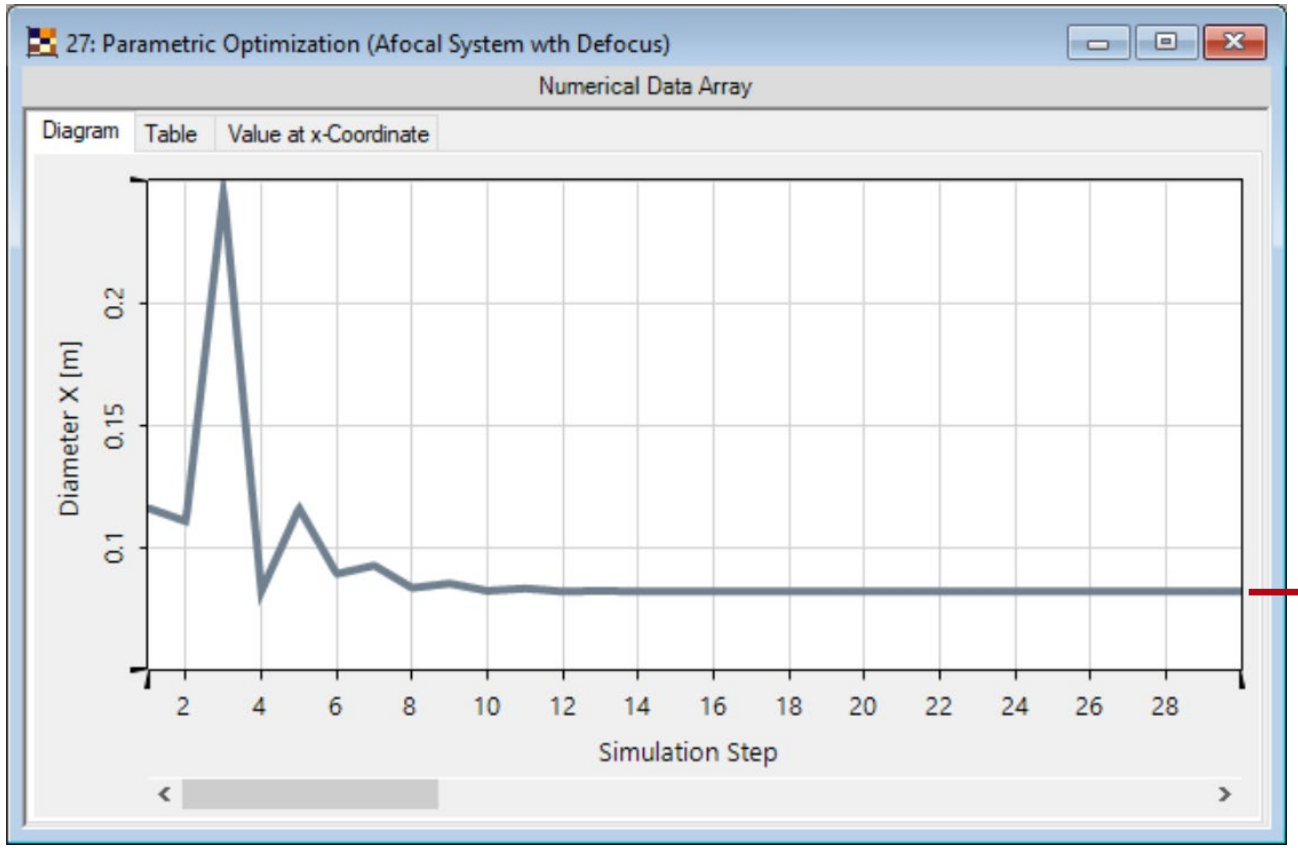


Design of Afocal System with Defocus

parametric optimization with downhill simplex method

initial variable values	
df	0 mm

other parameters
- w_0 = 0.25 mm
- f_1 = 22 mm
- f_2 = 3.6211 m



optimized variable values	
df	1.33 mm

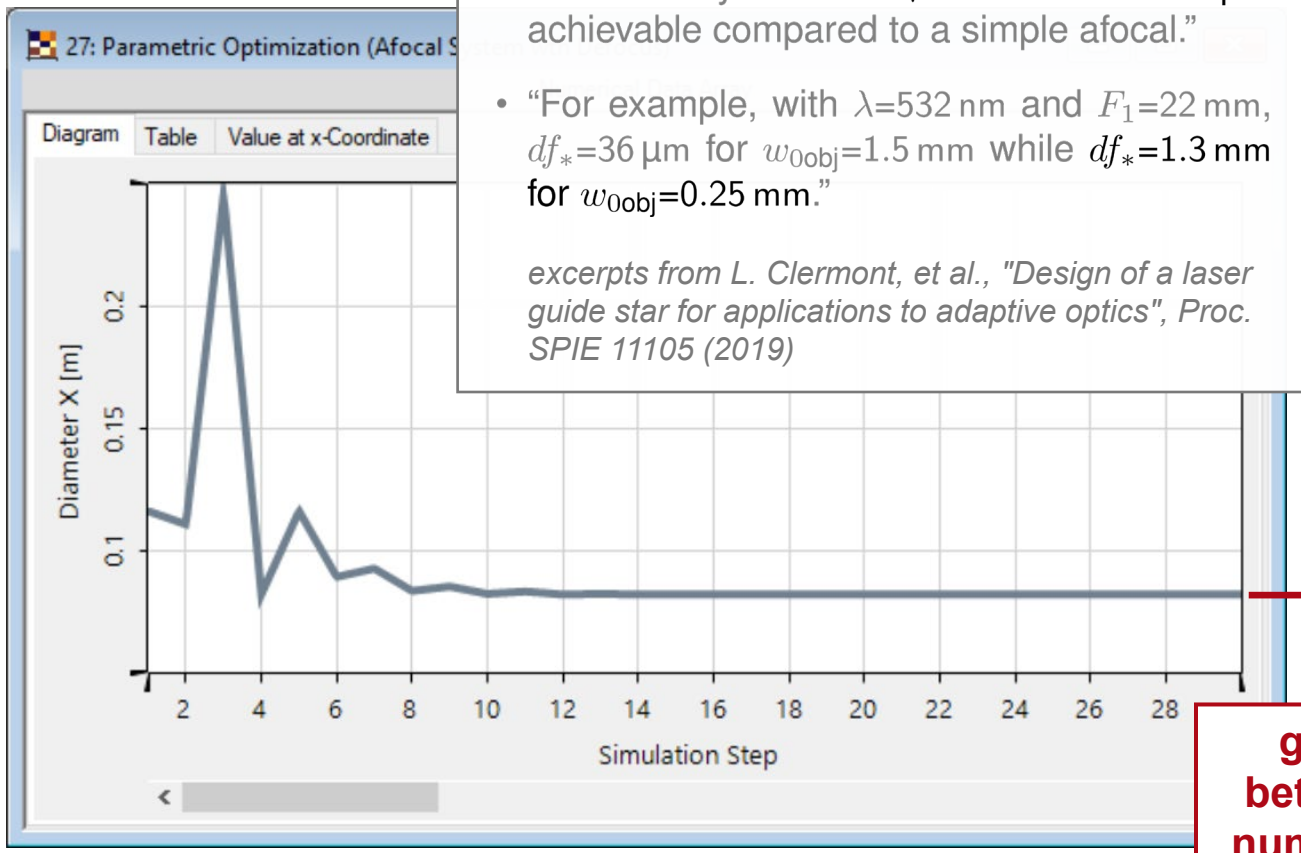
diameter @target
82.2 mm

Design of Afocal System with Defocus

parametric optimizat

- "A controlled defocus of the afocal can thus decrease by a factor $\sqrt{2}$ the minimum spot achievable compared to a simple afocal."
- "For example, with λ=532 nm and F_1=22 mm, df_*=36 µm for w_{0obj}=1.5 mm while df_*=1.3 mm for w_{0obj}=0.25 mm."

excerpts from L. Clermont, et al., "Design of a laser guide star for applications to adaptive optics", Proc. SPIE 11105 (2019)



initial variable values	
df	0 mm

other parameters
- w_0=0.25 mm
- f_1=22 mm
- f_2=3.6211 m

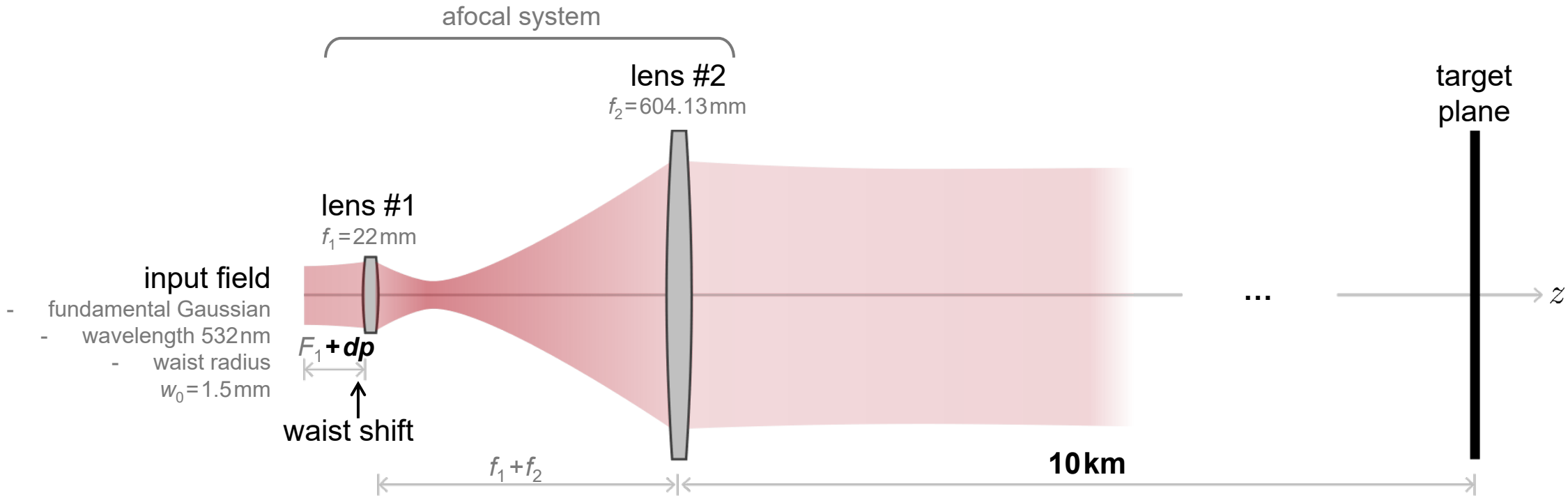
optimized variable values	
df	1.33 mm

diameter @target
82.2 mm

good agreement between theory and numerical simulation

Design Task #3 – Afocal System with Input Beam Waist Shift

Is it possible to further reduce the beam size at the target plane if additional freedom is available?
Next, we will try with input beam waist shift!

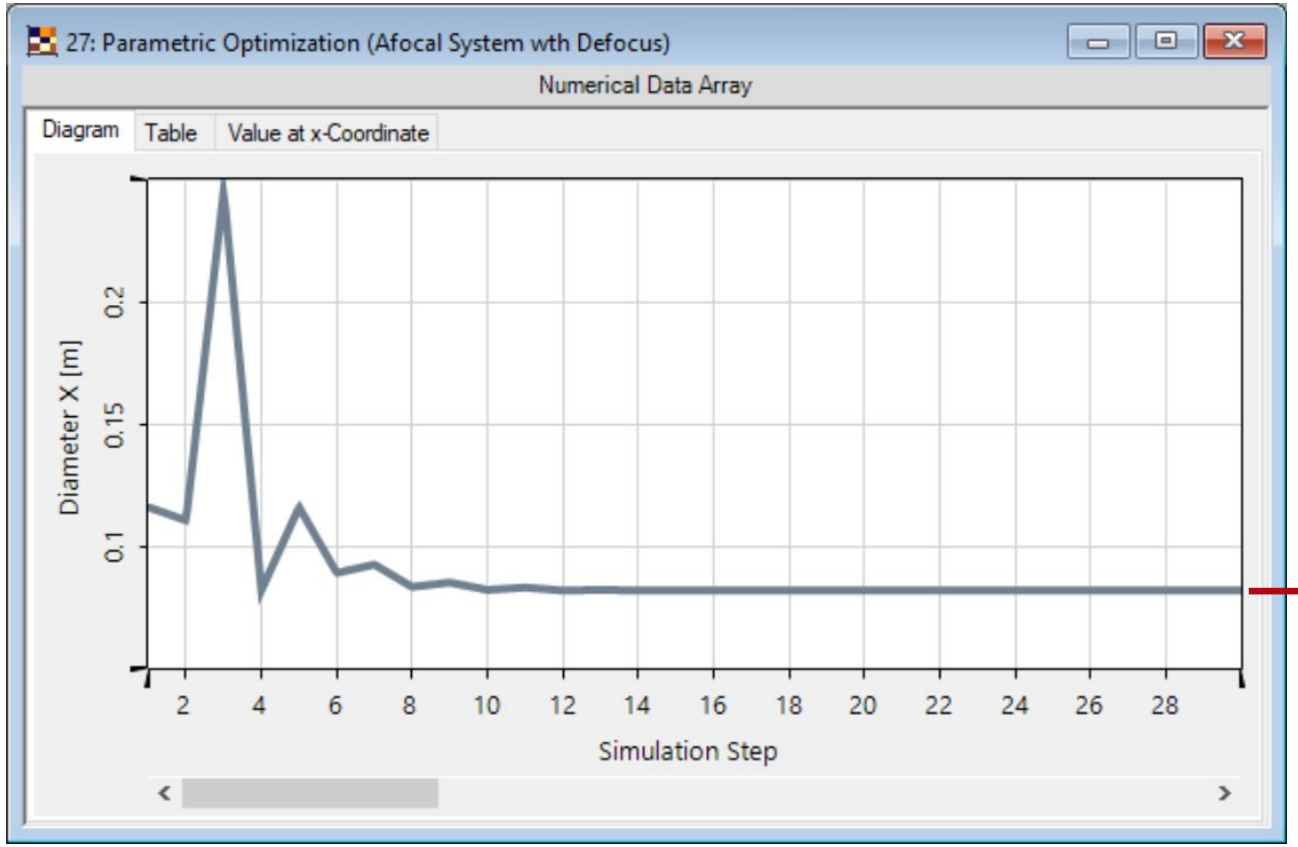


Design of Afocal System with Input Beam Waist Shift

initial variable values	
dp	0 mm

other parameters
- w_0 = 1.5 mm
- f_1 = 22 mm
- f_2 = 604.13 mm

parametric optimization with downhill simplex method



optimized variable values	
dp	-13.2 m

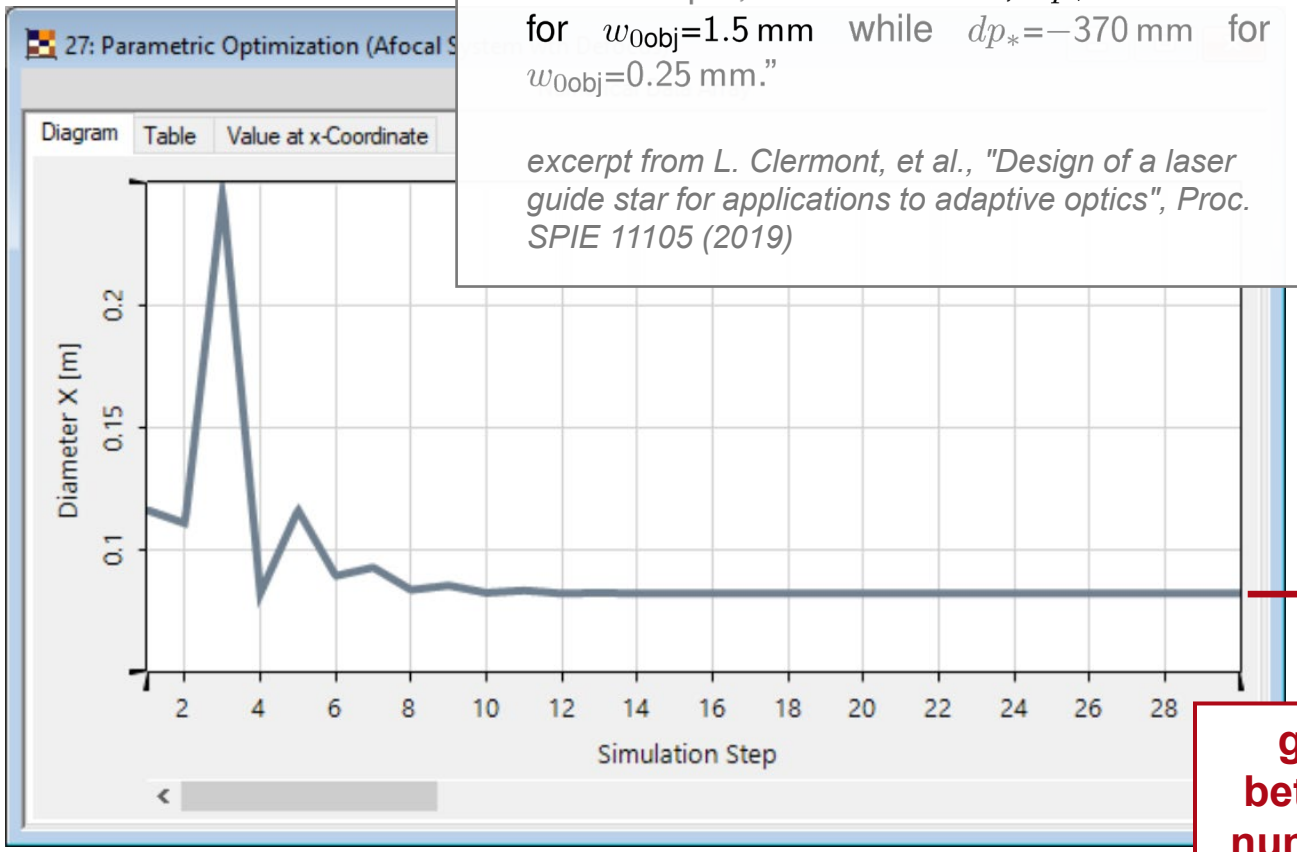
diameter @target
82.5 mm

Design of Afocal System with Input Beam Waist Shift

parametric optimizat

- "The optimal value of dp_* is given by … For example, with λ=532 nm, dp_*=−13.3 mm for w_{0obj}=1.5 mm while dp_*=−370 mm for w_{0obj}=0.25 mm."

excerpt from L. Clermont, et al., "Design of a laser guide star for applications to adaptive optics", Proc. SPIE 11105 (2019)



initial variable values	
dp	0 mm

other parameters
- w_0=1.5 mm
- f_1=22 mm
- f_2=604.13 mm

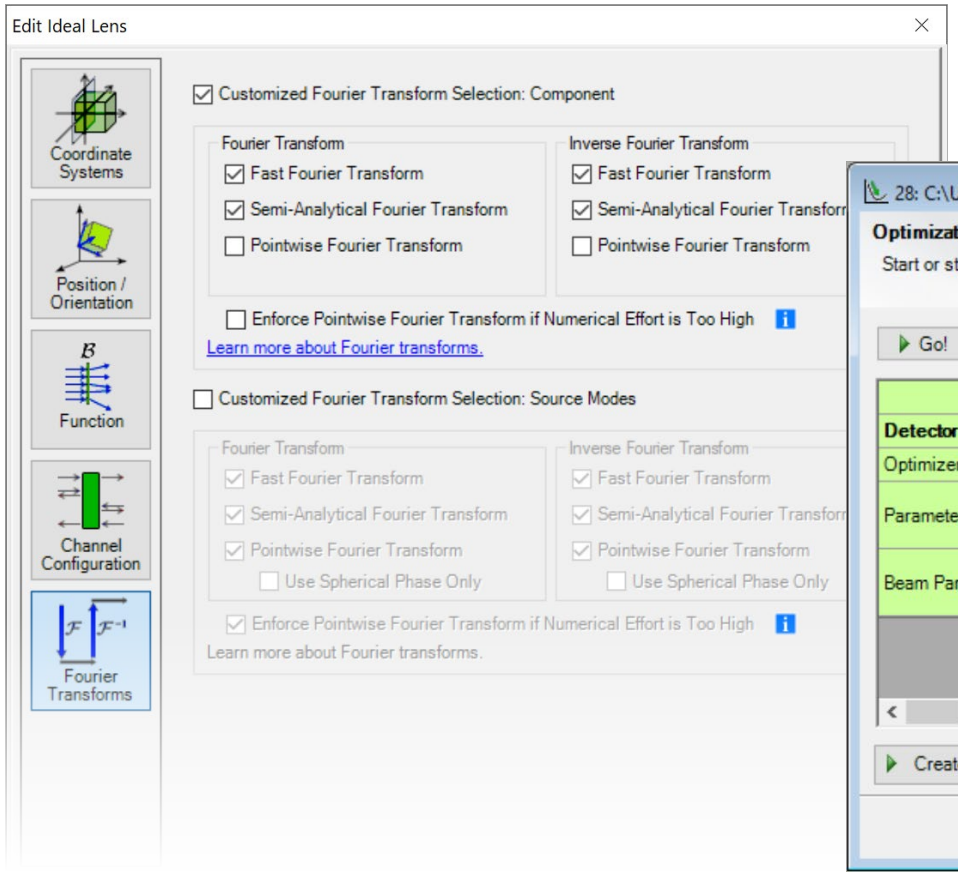
optimized variable values	
dp	-13.2 m

diameter @target
82.5 mm

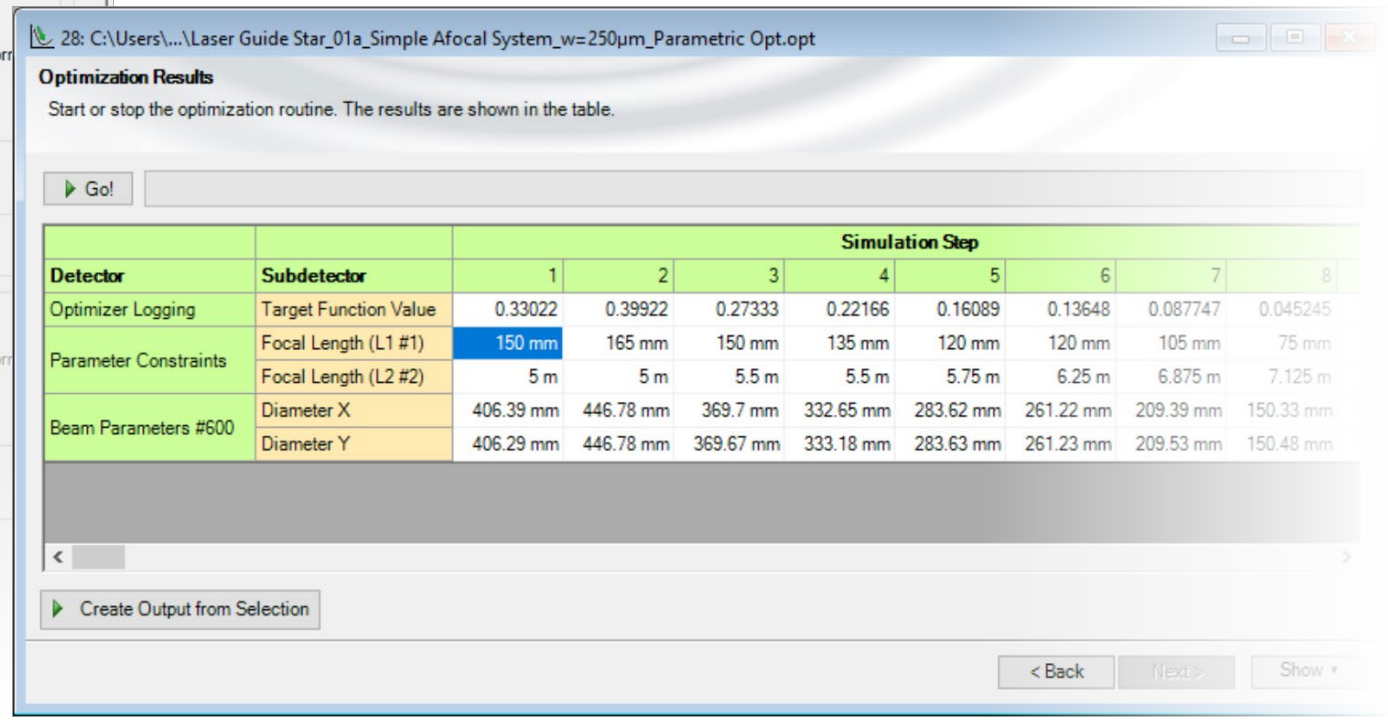
good agreement between theory and numerical simulation

Peek into VirtualLab Fusion

flexible Fourier transform settings

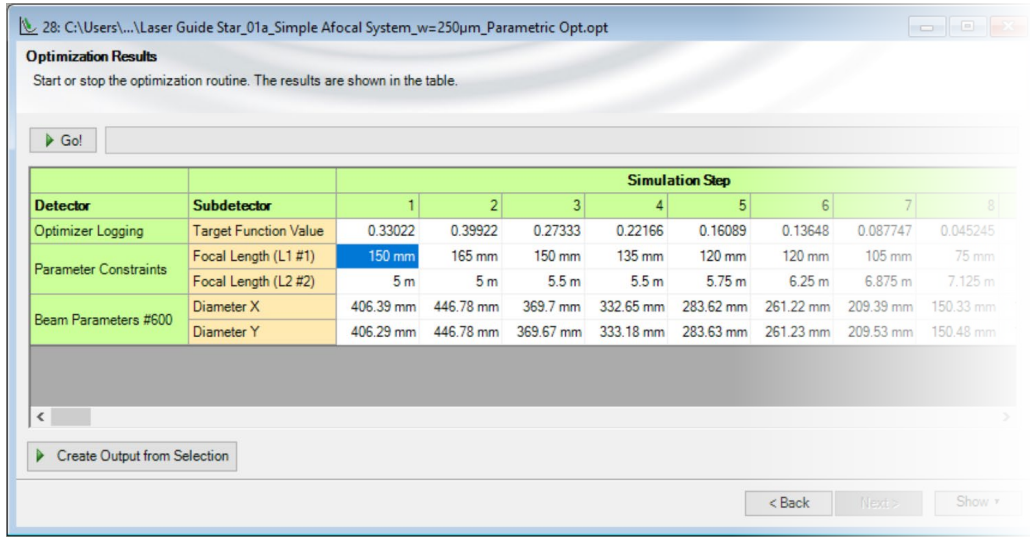


parametric optimization



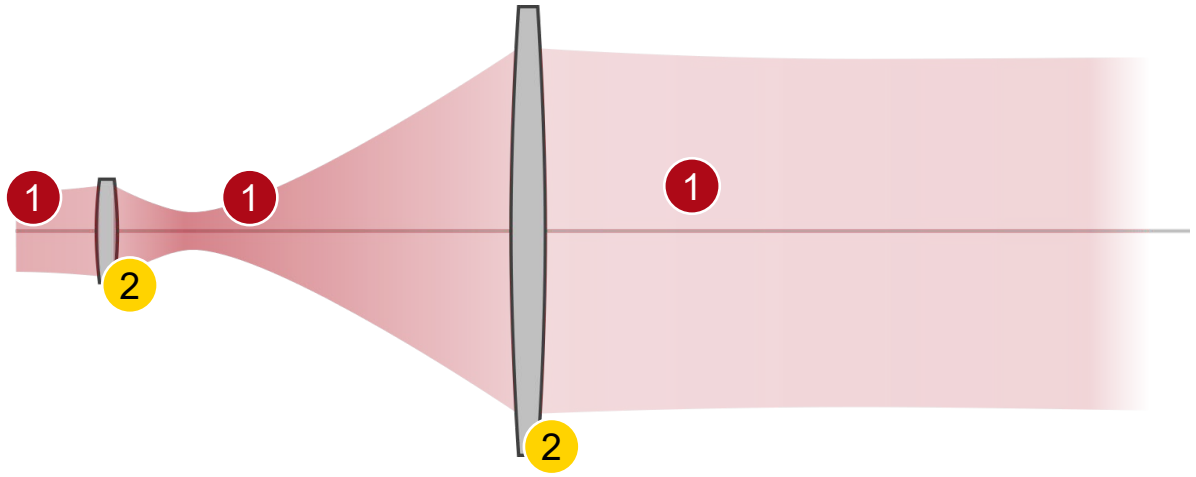
Workflow in VirtualLab Fusion

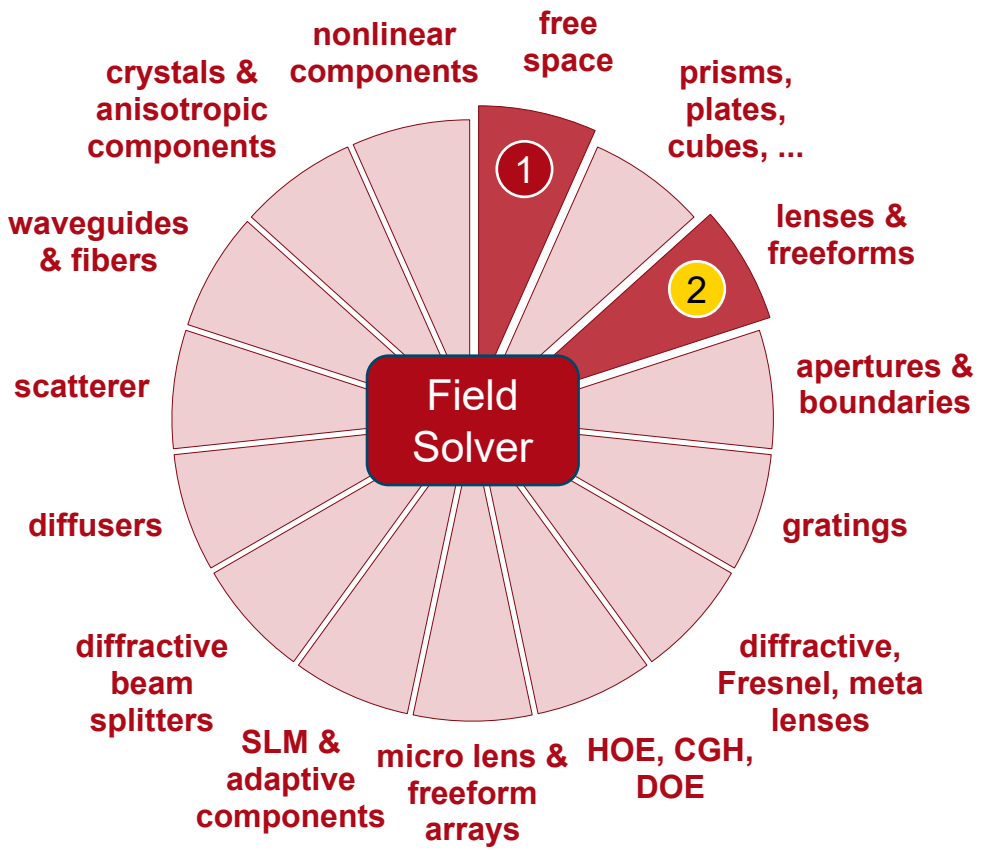
- Set up input Gaussian field
  - Basic Source Models [Tutorial Video]
- Set the position and orientation of components
  - LPD II: Position and Orientation [Tutorial Video]
- Set the Fourier transforms properly
- Parametric optimization of optical system
  - Parametric Optimization [Tutorial Video]



Detector	Subdetector	Simulation Step 1	2	3	4	5	6	7	8
Optimizer Logging	Target Function Value	0.33022	0.39922	0.27333	0.22166	0.16089	0.13648	0.087747	0.045245
Parameter Constraints	Focal Length (L1 #1)	150 mm	165 mm	150 mm	135 mm	120 mm	120 mm	105 mm	75 mm
	Focal Length (L2 #2)	5 m	5 m	5.5 m	5.5 m	5.75 m	6.25 m	6.875 m	7.125 m
Beam Parameters #600	Diameter X	406.39 mm	446.78 mm	369.7 mm	332.65 mm	283.62 mm	261.22 mm	209.39 mm	150.33 mm
	Diameter Y	406.29 mm	446.78 mm	369.67 mm	333.18 mm	283.63 mm	261.23 mm	209.53 mm	150.48 mm

VirtualLab Fusion Technologies





Document Information

title	Analysis and Design of Afocal Systems for Laser Guide Stars
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further reading	- Laser Beam “Clean-Up” with Spatial Filter - Pinhole Modeling in a Low-Fresnel-Number System