Afocal Systems for Laser Guide Stars
Abstract

For astronomical telescopes, laser guide stars are often used for correction of the atmospheric distortion. Such artificial star images are usually generated tens of kilometers away by high-power laser beams. In order to accurately design the optical system to generate and control the size of the laser guide star, the diffraction effects of the laser beam must be considered. In this example, a classical design of such a system is analyzed. The minimum spot size given by geometrical optics optimization can then be further reduced by considering diffractive effects and including a defocus or waist shift into the system.
Design Task #1 – Simple Afocal System

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

input field
- fundamental Gaussian
- wavelength 532 nm
- waist radius $w_0$

Using geometrical optics, the afocal system gives a magnification of $\frac{f_2}{f_1} = 33.33$. That predicts a beam diameter of **16.7 mm** at the target plane, but this does not include the divergence of the actual Gaussian source.

The actual beam diameter at the target, with physical-optics modeling, is **406.4 mm**.
Design of Simple Afocal System $w_0=0.25\text{mm}$ (fixed)

Initial variable values

<table>
<thead>
<tr>
<th>$f_1$</th>
<th>150 mm</th>
</tr>
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<tbody>
<tr>
<td>$f_2$</td>
<td>5 m</td>
</tr>
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</table>

Optimized variable values

<table>
<thead>
<tr>
<th>$f_1$</th>
<th>51.404 mm</th>
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<tbody>
<tr>
<td>$f_2$</td>
<td>8.463 m</td>
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</table>

Diameter @ target: 116.4 mm

Convergence is reached after about 50 steps.

Parametric optimization with downhill simplex method.
Design of Simple Afocal System $w_0=1.5\text{mm} \ (\text{fixed})$

<table>
<thead>
<tr>
<th>initial variable values</th>
<th>optimized variable values</th>
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<tbody>
<tr>
<td>$f_1$ 250\text{mm}</td>
<td>$f_1$ 133.24\text{mm}</td>
</tr>
<tr>
<td>$f_2$ 2.5\text{m}</td>
<td>$f_2$ 3.66\text{m}</td>
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diameter @ target 116.4\text{mm}

Let us try the optimization with another input Gaussian waist radius.
Design of Simple Afocal System $w_0=1.5\text{mm}$ (fixed)

initial variable values

\begin{align*}
  f_1 & \quad 250\text{mm} \\
  f_2 & \quad 2.5\text{m}
\end{align*}

parametric optimization with downhill simplex method

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

Fig. 2(b) from the reference

\begin{itemize}
  \item [radius value] Good agreement between theory and numerical simulation
  \item [diameter @ target] 116.4 mm
\end{itemize}
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 defocus!

afocal system, with defocus

input field
- fundamental Gaussian
- wavelength 532 nm
- waist radius \( w_0 = 0.25 \text{mm} \)

lens #1
\[ f_1 = 22 \text{mm} \]

lens #2
\[ f_2 = 3.6211 \text{m} \]

defocus
\[ f_1 + f_2 + df \]

10 km

\( \ldots \)
Design of Afocal System with Defocus

Parametric optimization with downhill simplex method

Initial variable values

| df | 0 mm |

Other parameters

- \( w_0 = 0.25 \text{ mm} \)
- \( f_1 = 22 \text{ mm} \)
- \( f_2 = 3.6211 \text{ m} \)

Optimized variable values

| df | 1.30 mm |

diameter @ target 82.4 mm
Design of Afocal System with Defocus

- "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 $\lambda=532\,\text{nm}$ and $F_1=22\,\text{mm}$, $df_s=36\,\mu\text{m}$ for $w_{\text{obj}}=1.5\,\text{mm}$ while $df_s=1.3\,\text{mm}$ for $w_{\text{obj}}=0.25\,\text{mm}".


**initial variable values**

| $df$ | 0 mm |

**other parameters**

- $w_0=0.25\,\text{mm}$
- $f_1=22\,\text{mm}$
- $f_2=3.6211\,\text{m}$

**optimized variable values**

| $df$ | 1.30 mm |

**diameter @ target**

- 82.4 mm

Good agreement between theory and numerical simulation.
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

parametric optimization with downhill simplex method

initial variable values
\[ dp = 0 \text{ mm} \]

optimized variable values
\[ dp = -13.2 \text{ m} \]

diameter @ target
\[ 82.3 \text{ mm} \]

other parameters
- \( w_0 = 1.5 \text{ mm} \)
- \( f_1 = 22 \text{ mm} \)
- \( f_2 = 604.13 \text{ mm} \)
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

"The optimal value of $dp_*$ is given by ... For example, with $\lambda = 532$ nm, $dp_* = -13.3$ m for $\omega_{0\text{Obj}} = 1.5$ mm while $dp_* = -370$ mm for $\omega_{0\text{Obj}} = 0.25$ mm"


optimized variable values

diameter @ target

$dp$ -13.2 m

82.3 mm

good agreement between theory and numerical simulation
VirtualLab Fusion Technologies

- Prisms, plates, cubes, ...
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- Apertures & boundaries
- Gratings
- Diffractive, Fresnel, meta lenses
- HOE, CGH, DOE
- Micro lens & freeform arrays
- SLM & adaptive components
- Diffractive beam splitters
- Scatterer
- Diffusers
- Waveguides & fibers
- Nonlinear components
- Anisotropic components
- Crystals & anisotropic components
- Free space
- Idealized component
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| further reading       | • Laser Beam “Clean-Up” with Spatial Filter  
                          • Pinhole Modeling in a Low-Fresnel-Number System |