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 10km-away target plane, and how to minimize the spot there by varying the afocal system?

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.

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)

<table>
<thead>
<tr>
<th>initial variable values</th>
<th>optimized variable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>$f_1$</td>
</tr>
<tr>
<td>150mm</td>
<td>50.04mm</td>
</tr>
<tr>
<td>$f_2$</td>
<td>$f_2$</td>
</tr>
<tr>
<td>5m</td>
<td>8.2416m</td>
</tr>
</tbody>
</table>

Convergence is reached after about 30 steps.

Diameter @ target 116.4mm

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

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

<table>
<thead>
<tr>
<th>initial variable values</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$f_1$ 250mm</td>
<td>$f_1$ 128.6mm</td>
</tr>
<tr>
<td>$f_2$ 2.5m</td>
<td>$f_2$ 3.5258m</td>
</tr>
</tbody>
</table>

diameter @target 116.4mm
Design of Simple Afocal System $w_0 = 1.5\text{mm}$ (fixed)

Initial variable values:

<table>
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<tr>
<th>$f_1$</th>
<th>250mm</th>
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<tbody>
<tr>
<td>$f_2$</td>
<td>2.5m</td>
</tr>
</tbody>
</table>

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

Parametric optimization with downhill simplex method.

**Fig. 2(b) from the reference**

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!

afocal system, with defocus

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

lens #1
\( f_1 = 22 \text{ mm} \)

defocus

lens #2
\( f_2 = 3.6211 \text{ m} \)

target plane

\[ f_1 + f_2 + df \]

10 km
Design of Afocal System with Defocus

Parametric optimization with downhill simplex method

<table>
<thead>
<tr>
<th>Initial variable values</th>
<th>Optimized variable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>df 0 mm</td>
<td>df 1.33 mm</td>
</tr>
</tbody>
</table>

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

Diameter @ target: 82.2 mm
Design of Afocal System with Defocus

- Initial variable values:
  - \( df = 0 \text{ mm} \)

- Optimized variable values:
  - \( df = 1.33 \text{ mm} \)

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

- Parametric optimization with downhill simplex method.

  - “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 \( w_{\text{obj}} = 0.25 \text{ mm} \).”

- Simulation output:
  - Diameter at 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

parametric optimization with downhill simplex method

initial variable values

| $dp$ | 0 mm |

optimized variable values

| $dp$ | -13.2 m |

diameter @ target 82.5 mm

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

optimized variable values

| dp  | -13.2 m |

diameter @ target
82.5 mm

good agreement between theory and numerical simulation


parametric optimization with downhill simplex method

- “The optimal value of $dp_*$ is given by . . .
  For example, with $\lambda=532$ nm, $dp_*=-13.3$ mm for $w_{\text{obj}}=1.5$ mm while $dp_*=-370$ mm for $w_{\text{obj}}=0.25$ mm.”

image: Diagram showing simulation steps with values for $dp$ and parameters $w_0$, $f_1$, and $f_2$. The graph shows a comparison between theory and numerical simulation, indicating good agreement.
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)
VirtualLab Fusion Technologies

- Free space prisms, plates, cubes, ...
- Lenses & freeforms
- Gratings
- Diffractive, Fresnel, meta lenses
- HOE, CGH, DOE
- Micro lens & freeform arrays
- SLM & adaptive components
- Waveguides & fibers
- Scatterer
- Diffusers
- Diffractive beam splitters
- Nonlinear components
- Crystals & anisotropic components

Field Solver

# idealized component
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<tr>
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<th>Analysis and Design of Afocal Systems for Laser Guide Stars</th>
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<tbody>
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<td>Application Use Case</td>
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| **further reading** | - [Laser Beam “Clean-Up” with Spatial Filter](#)  
- [Pinhole Modeling in a Low-Fresnel-Number System](#) |