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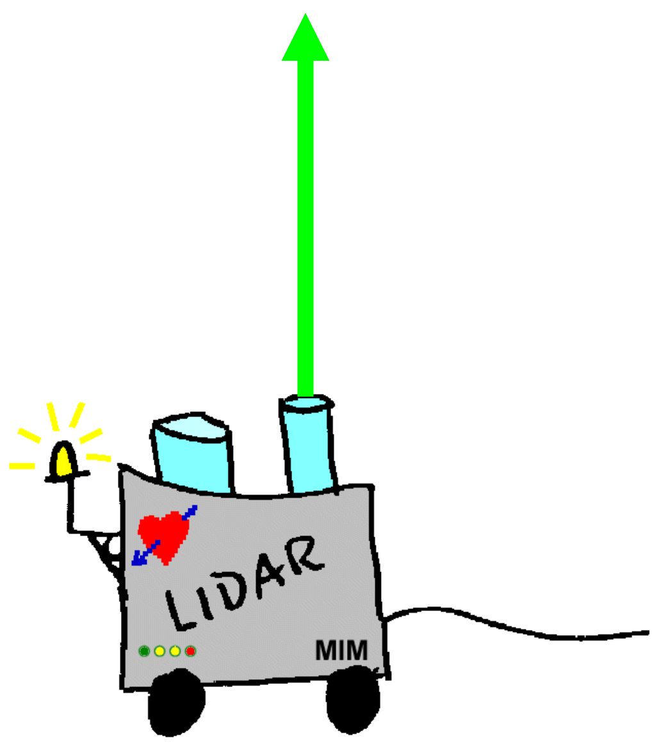

Optimized background suppression in near field lidar telescopes

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Full text:

Introduction

The measurement of boundary layer aerosol with lidar requires that the receiving telescope can see the lidar beam already at short ranges. That means that the field of view of the receiving telescope (RFOV) fully overlaps with the field of view of the laser transmitter (TFOV). Measurements at Munich during three years of EARLINET [1] show that the distance of full overlap (DFO) should be much smaller than 500 m in order to detect the boundary layer during winter time [2]. Measurements of the boundary layer aerosol are in particular required during daytime, when the convective forces and the influence of the aerosol on the radiation budget are strongest. In order to enhance the S/N ratio of the lidar signal small bandwidth interference filters (IFF) are generally used to suppress the bright daylight sky radiance. They recently became available with bandwidths as small as 0.15 nm [3]. Their drawback is the decrease of acceptance angle with decrease of bandwidth, which in turn limits the possible DFO. Other possibilities for background suppression are the shaping of the receivers field of view diaphragm [4] (FOVD) in the focal plane of the telescope and the tilt of the laser axis relative to the telescope axis. In the following we shortly list the mutual dependence and constraints of the basic parameters of the optical lidar setup, and present results of ray tracing calculations with respect to optimized FOVD design and alignment for background suppression.

Optical lidar setup

Figure 1 shows a typical setup of the receiving optics of a lidar. The backscattered light is collected by a telescope (represented here by a large lens T) and focused on its focal plane where it is spatially filtered by the field of view diaphragm (FOVD), The FOVD usually is a circular iris, centered on the optical axis. The diverging beam must be collimated by a first lens (L1) with diameter D1 and focal length F1 because of the limited acceptance angles A_{max} of the IFFs (see appendix). With paraxial optics and small angle approximation we find from figure 1 the relation

$$RFOV = \frac{F1}{FT} A_{\max} \qquad (1)$$

For the use of a small bandwidth IFF with small A_{max} it is necessary to keep the RFOV small or to make F1/FT large. In biaxial lidar systems the RFOV is determined by the laser and the telescope parameters and becomes larger with shorter DFO. From figure 2 we get

$$RFOV = \frac{2DTL + DT}{2DFO} + TFOV \qquad (2)$$

From figure 1 we see that F1/FT is limited by the diameters of D1 andDT by

$$\frac{F1}{FT} \le \frac{D1 - RFOV * F1}{DT + RFOV * F1} < \frac{D1}{DT} \qquad (3)$$

All these parameters must be balanced for optimum lidar performance for the given scientific objective. Note, that the diameter D1 of the optical parts is limited by their price rising and availability decreasing with increasing diameter.

Tilting the laser by an angle A_{tilt} with respect to the laser axis (see figure 2) allows to decrease the RFOV with constant DFO. For a given DFO we find the optimum A_{tilt} by equating the maximum incident angles in the telescope from infinity (i.e. A_{tilt} + TFOV) and from DFO

$$A_{tilt} = \frac{2DTL + DT}{4DFO} \qquad (4)$$

Effects of FOVD optimization and laser tilt

The background intensity in the signal is proportional to the area of the FOVD. In order to determine optimized sizes of different FOVD alignments, we performed 3D Monte Carlo ray trace calculations with ZEMAX[6] with four types of FOVDs. The lidar parameters were taken from the lidar of the Meteorological Institute of the University of Munich, i.e. DT = 300 mm, DTL = 400 mm, FT = 940 mm, TFOV = 0.3 mrad, and DFO = 150 m. For the present investigation an optimized Ritchie-Cretien telescope was assumed. The laser beam was simulated by a disk of source rays, which was placed at 194 equidistant distances from the telescope between 150 m and 5 km, and 400 mm above the telescope axis. For each distance the size of the disk was calculated from the TFOV. The divergence of the beam emitted towards the telescope and the number of the rays (1e6 per disk) was kept constant. Figure 3 shows the resulting intensity distributions on the four FOVDs, integrated over all 194 locations of the source. From left to right these are a circular diaphragm (CD) with 3.7 mm radius centered on the axis and in the focal plane of the telescope, a slit (S) which cuts out the image of the laser beam on the CD, a shifted slit (SS) placed between the images of an infinite distant and of a 150 m distant point, and a tilted slit (TS), which was titled by 66° to the focal plane and placed as the SS. The background intensity is reduced by factors of about 4.5, 7.4, and 15.5 for the S, SS and TS, respectively, compared to the CD due to the reduced areas of the FOVDs. Second order effects for the TS are negligible according to test runs of the model with a diffuse emitting disk in the entrance pupil of the telescope as a simulation for the sky radiance.

With a laser tilt A_{tilt} according to (4) the RFOV and the diameter of the CD can be reduced, while the S, SS and TS must be shifted up by the equivalent amount. Thus, the background intensity in the CD is reduced by a factor of 2.25, and additionally a IFF with smaller bandwidth could be used (see and appendix).

Conclusion

The use of very small bandwidth IFF for background suppression in near field lidar telescopes is limited by their small acceptance angle, especially if we account for the uncertainties in the alignment of the mechanical setup of the lidar optics and for the temperature coefficient of the filters. Optimized FOVDs, as proposed e.g. by Abramochkin and Tikhomirov[4], can reduce the background signal very efficiently, especially with near field setups. But as before, mechanical misalignment and non perfect optics can decrease the gain. 3D ray tracing of realistic lidar setups are necessary to show the benefit of better but more expensive optical parts. Their real performance with regard to the image of the lidar beam in the focal plane should be controlled for example by means of a CCD camera.

Appendix

The center wavelength λ_0 of an interference filter (IFF) is shifted to λ_s with an incident angle A according to[3,5]

$$\frac{\lambda_S}{\lambda_0} = \sqrt{1 - \left(\frac{n}{n_e}\sin(A)\right)^2} \qquad (5)$$

with the effective refractive index of the filter n_e and the refractive index of the environment n. The shift is to smaller wavelengths with increasing A, and the more the larger n_e. Examples for IFF are a Barr[5] Filter with 0.5 nm bandwidth (BW, full width at half max.) at 532 nm, n_e = 1.99 and a temperature coefficient of 0.0021 nm/°C, and a Andover[3] filter with BW 0.15 nm at 532 nm, n_e = 1.45, and a temperature coefficient of 0.016 nm/°C. The incident angles A are limited by the maximum allowed wavelength shift for acceptable transmission, which we set at 0.7 * BW/2, i.e. about 0.18 nm (Barr) and 0.05 nm (Andover). This results in A_{max} of 2.9° (Barr) and 1.14° (Andover).

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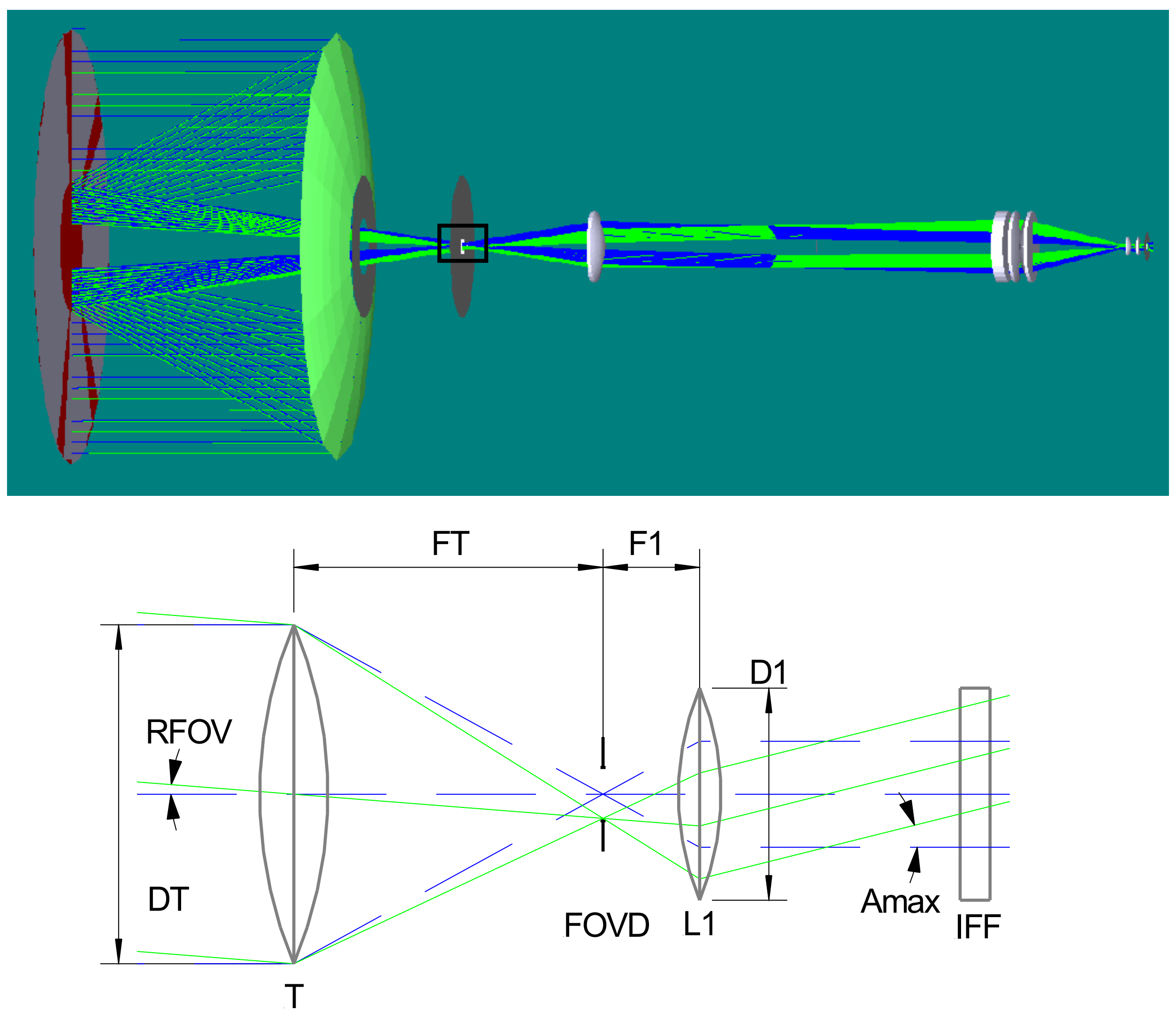

Figure 1. Typical optical setup of a lidar receiving optics with telescope T, field of view diaphragm FOVD, collimating lens L1, interference filter IFF. A ray with max. incident angle RFOV at the telescope (green), limited by the FOVD, reaches the IFF under an incident angle A_{max}. At top the ZEMAX model with rectangle enlarged in figure 4.

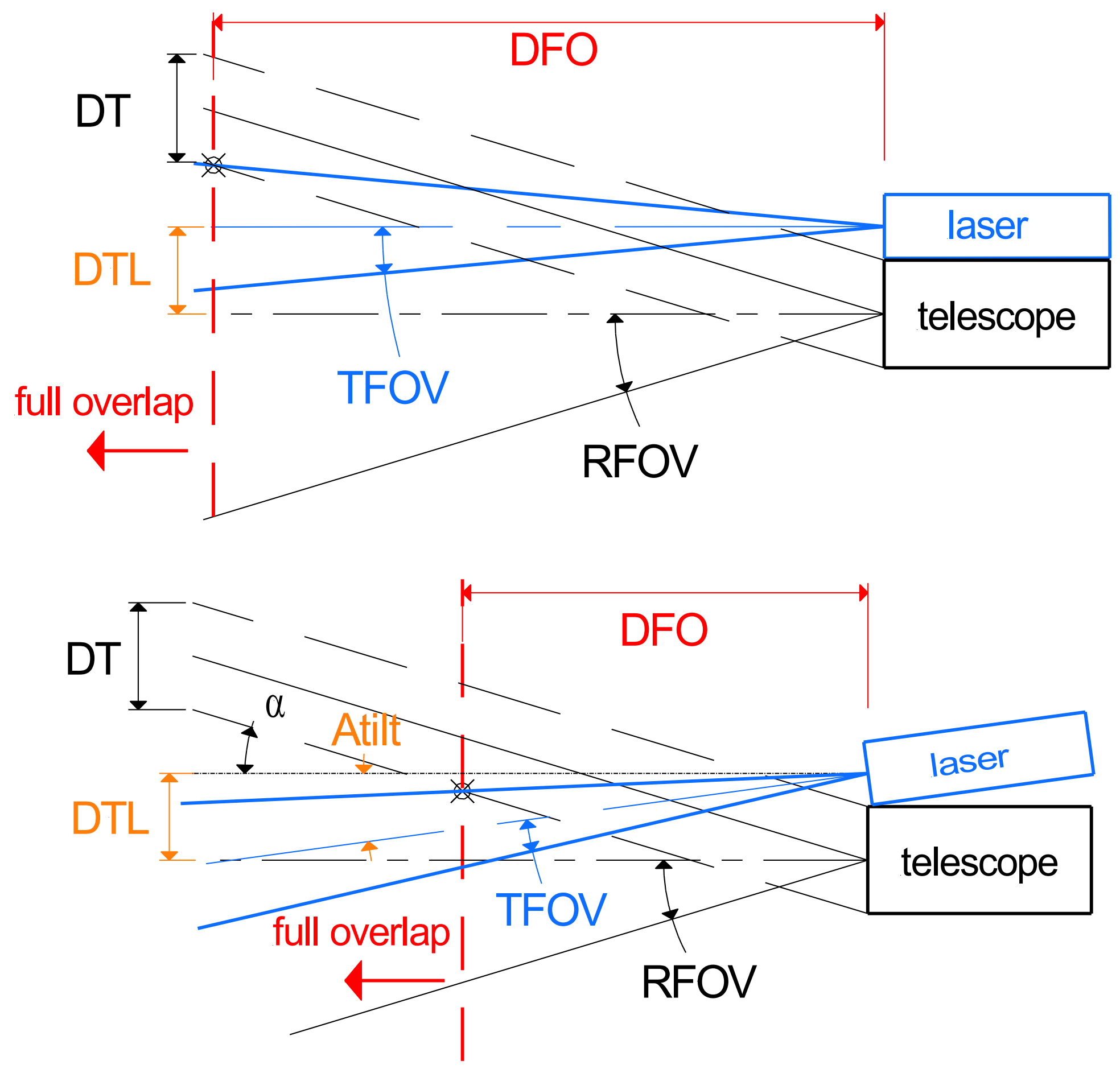

Figure 2. Above the laser and telescope axes are parallel, and the distance of full overlap (DFO) is larger than in the configuration below, where the laser is tilted by an angle A_{tilt}. RFOV and TFOV are receiver and telescope fields of view, respectively.

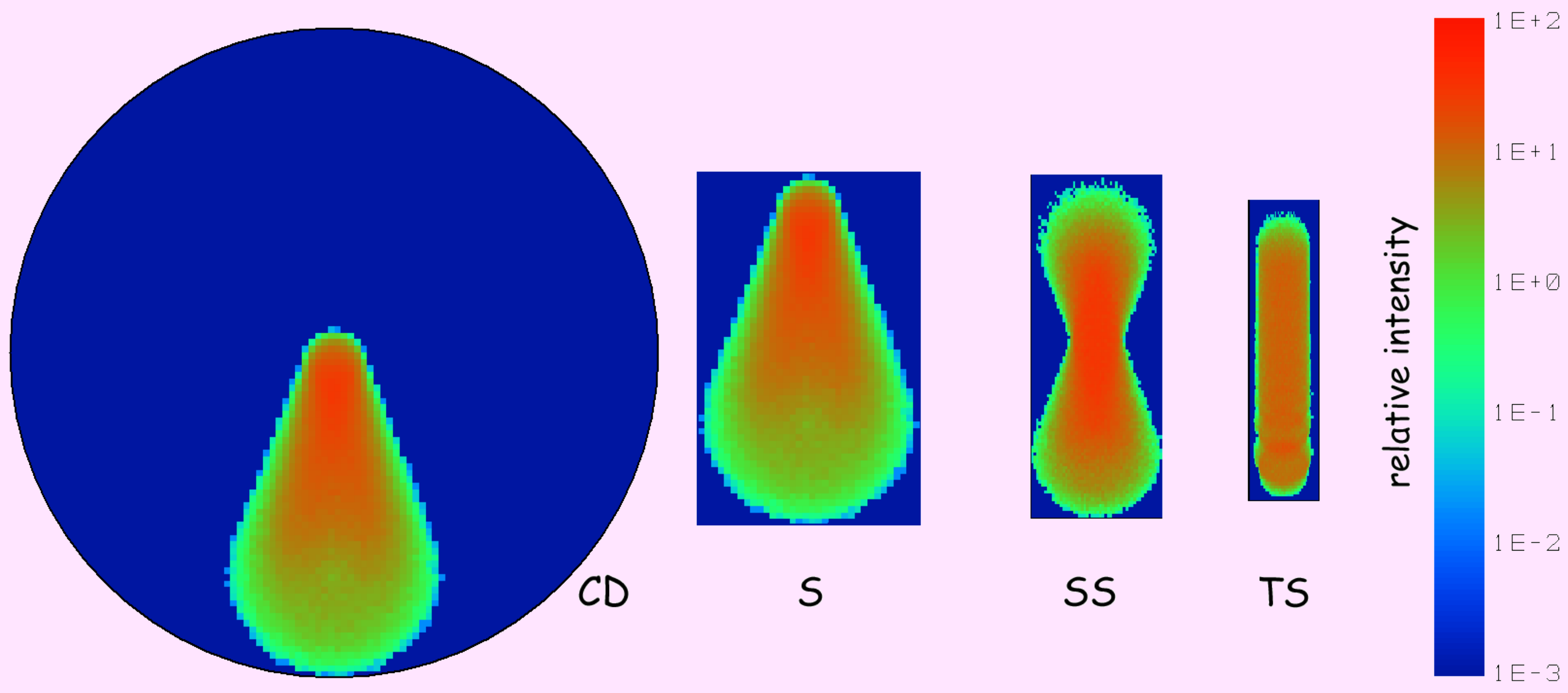

Figure 3. Simulated images of the laser beam between 150 m (bottom) and 5 km range (top) in four different field of view diaphragms of the receiving telescope (see fig. 4); from left to right: circular CD, slit S, shifted slit SS, and tilted slit TS projected on the plane of the other FOVDs. The background light suppression relative to the CD amount to 4.5 (S), 7.4 (SS), and 15.5 (TS) for an ideal telescope. The color bar shows the relative range corrected intensity of the laser beam images. The CD has a diameter of 7.4 mm.

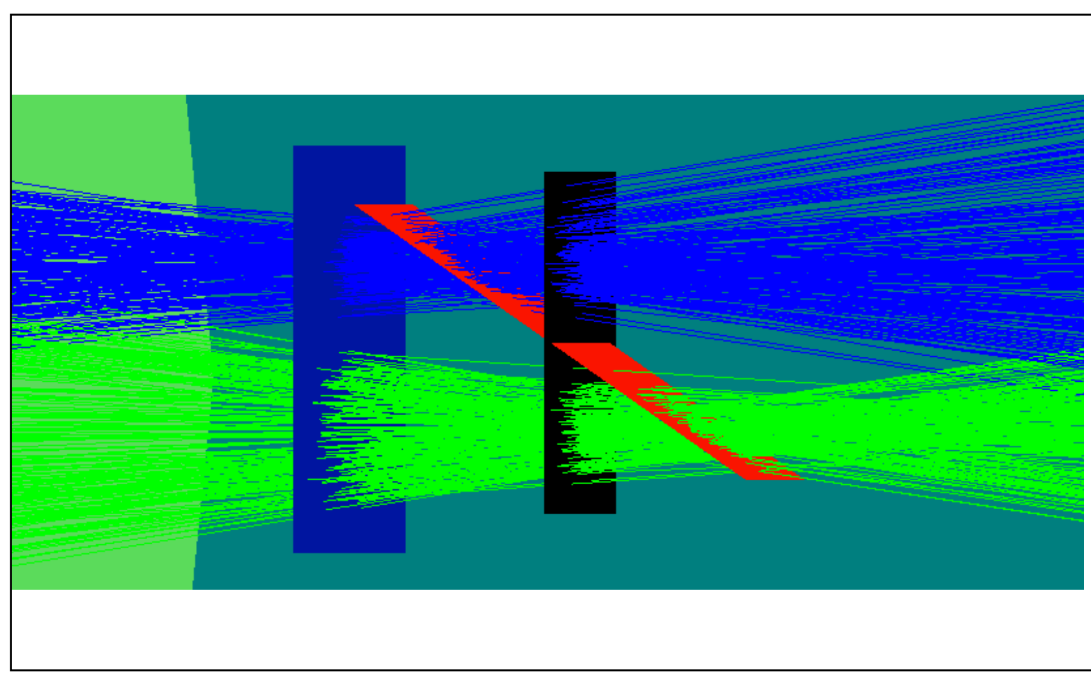

Figure 4. Enlarged rectangle from figure 1. The telescopes focal plane with blue and green rays emanating randomly from the lidar beam at 5 km (far field) and 150 m range (near field), respectively. The three field of view diapragms are the slit (S, blue) in the focal plane of the telescope, 3 mm behind the shifted slit (SS, black) between the near and far field foci, and the tilted slit (TS, red) with 66° inclination.

In brief:

- The sky light background in lidar signals is usually supressed by a small receiver field of view (RFOV) and small bandwidth (BW) interference filters (IFF).
- The IFF allow only limited incident angles smaller than A_{max}. The smaller the filter bandwidth, the smaller is A_{max}; e.g. for BW = 0.5 nm ⇨ A_{max} = 2.9° (see appendix).
- The maximum incident angles in the telescope (≙ RFOV) and at the IFF (≙ A_{max}) increase with decreasing lidar range (≙ DFO) according to (1) and (2).
- For boundary layer measurements a short distance of full overlap (DFO) between the transmitter and the laser fields of view is required (see fig.2). ⇨ large A_{max}, large IFF-BW, low BG supression.
- Common circular field of view diaphragms (FOVD) are centred to the telescopes optical axis. Most of their aperture is unnecessary for the lidar signal (see fig.3, CD, blue area). This results in a high signal BG and a reduced S/N-ratio.

How can we minimize the signal background BG with a given A_{max} and a desired DFO?

1. Tilt the laser according to (4), fig.2
⇨ reduces A_{max} , IFF-BW, and RFOV.

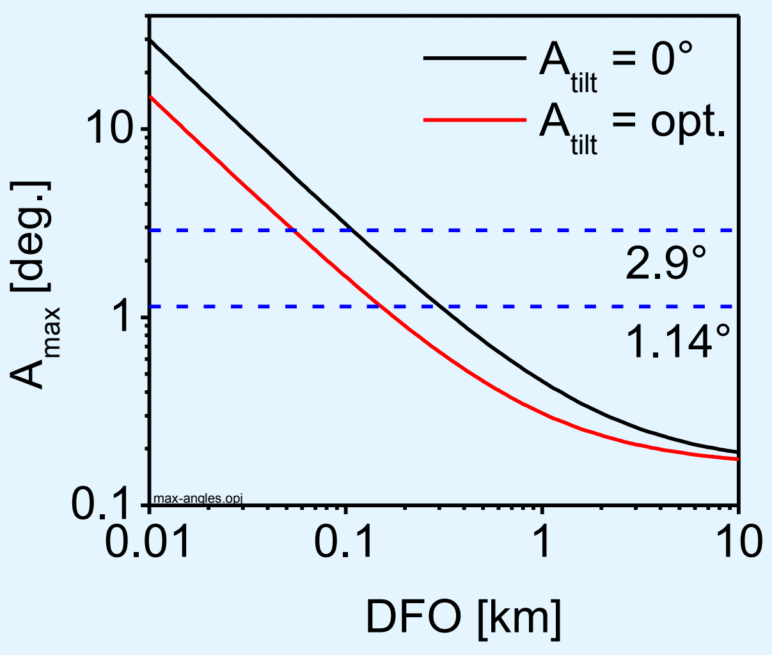

Figure 5. A_{max} is cut in about half with an optimum laser tilt for the same DFO. The two angles are A_{max} for the two IFF with 0.5 nm and 0.15 nm BW (see full text).

Further reduce BG stepwise by (fig. 5,6):

2. Use a slit (S) instead of cicular FOVD (CD)
⇨ removes unnecessary FOVD area.

3. Move slit between far- and nearfield focus (SS)
⇨ reduces necessary FOVD area.

4. Tilt slit (TS)
⇨ reduces necessary FOVD width.

Results:

A. Up to factor 15.5 background suppression with a tilt slit (TS) field of view diaphragm (FOVD) compared to the circular diaphagm (CD).

B. A steeper overlap function reduces the signal dynamic range (not shown here).

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