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Lidar optics 1

From the basics to the specific application at the instrument

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Ministero dell'Università e della Ricerca

Italiadomani

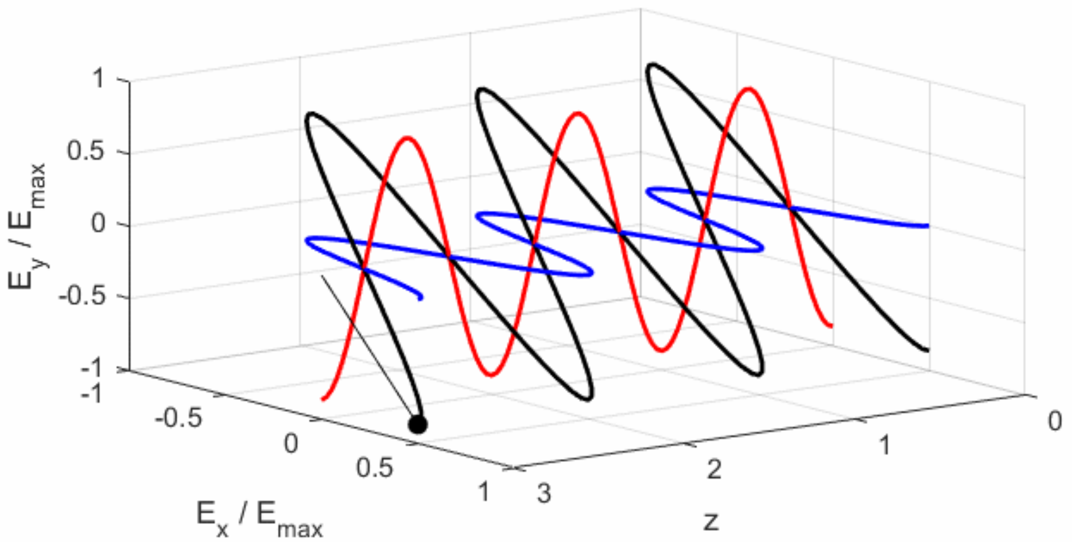
Contents

- **Basic physical principles for lidar optics**
  - Electromagnetic waves, reflection/refraction, polarisation
- **Technical optics**
  - Lenses, mirrors, filters, …
- **Applied lidar optics: From transmitter to photon detector**
  - Transmitter, receiver, analyser, recorder

Light as electromagnetic wave

$$\vec{E}(z,t) = \begin{pmatrix} e_x \cdot \cos(\omega t - kz + \varphi_1) \\ e_y \cdot \cos(\omega t - kz + \varphi_2) \\ 0 \end{pmatrix}$$

ω: frequency, t: time, k: wavenumber, z: space coordinate
$\varphi_{1,2}$: phase offset, e_x/e_y: component amplitudes

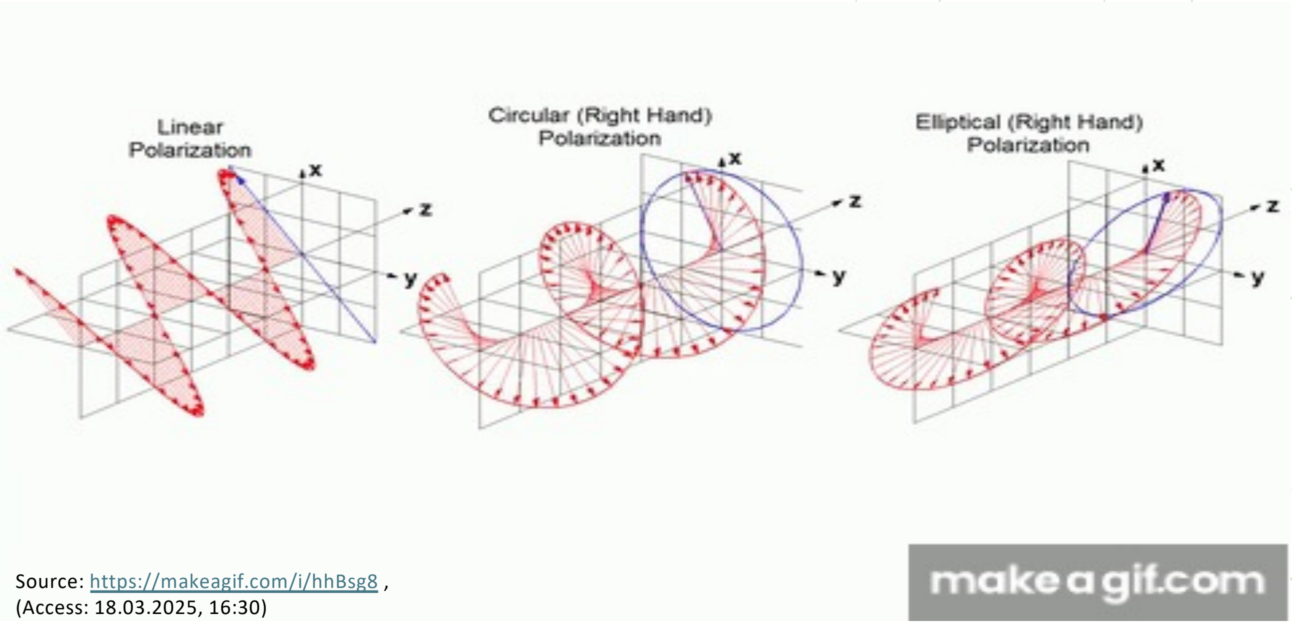


Source: https://d-arora.github.io/Doing-Physics-With-Matlab/mpDocs/op1007.htm , (Access: 18.03.2025, 16:30)

State of polarisation depends on $\Delta\varphi = \varphi_2 - \varphi_1$:

- Linear polarization: $\Delta\varphi = 0$
- Circular polarisation: $\Delta\varphi = \pm 0.5\,\pi$
- **$\Delta\varphi$ also called retardation**
- **Angle** of linear polarisation depends on amplitude ratio
- $\theta_{lin.Pol.} = \arctan\left(\frac{e_y}{e_x}\right)$

Light as electromagnetic wave



Source: https://makeagif.com/i/hhBsg8 ,
(Access: 18.03.2025, 16:30)

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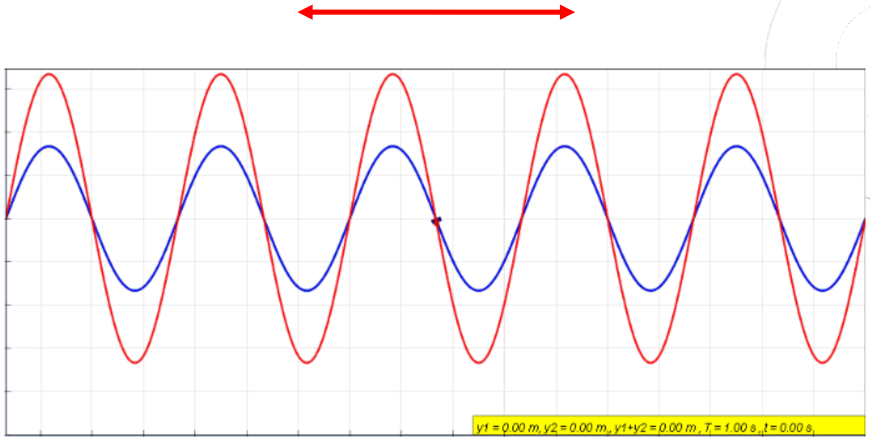
Light as electromagnetic wave

Light interference

- Constructive interference in phase
- Destructive interference out of phase

Phase difference



Source: https://en.wikipedia.org/wiki/Wave_interference#/media/File:Waventerference.gif , (Access: 14.01.2025, 16:00)

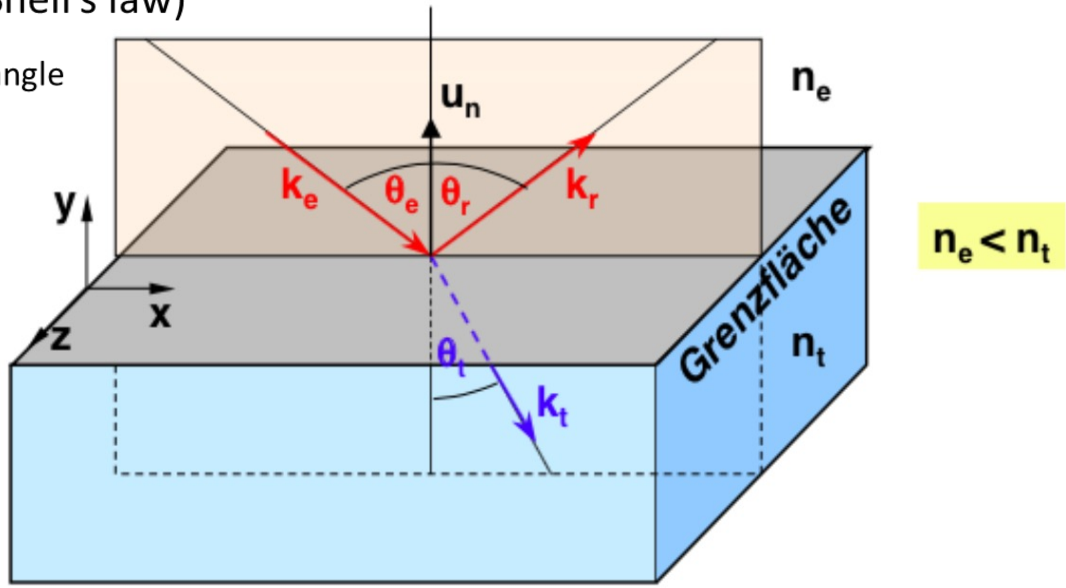
Refraction and reflection

Light at material interfaces (air -> glass -> …)

Change of direction by:

- Reflection: $\theta_e = \theta_r$
- Refraction: $n_e \, sin(\theta_e) = n_t \, sin(\theta_t)$ (Snell's law)

θ_e: incidence angle, θ_t: transmission angle, θ_r: refelction angle
n_e/n_t: refractive indices, c: speed of light, λ: wavelength



Source: Konzepte der Experimentalphysik 3: Optik und Quantenmechanik, Gabriele Semino, TUM, 2015.

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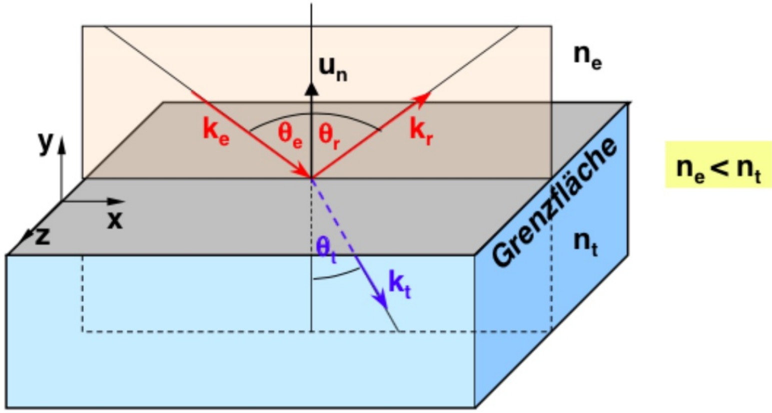


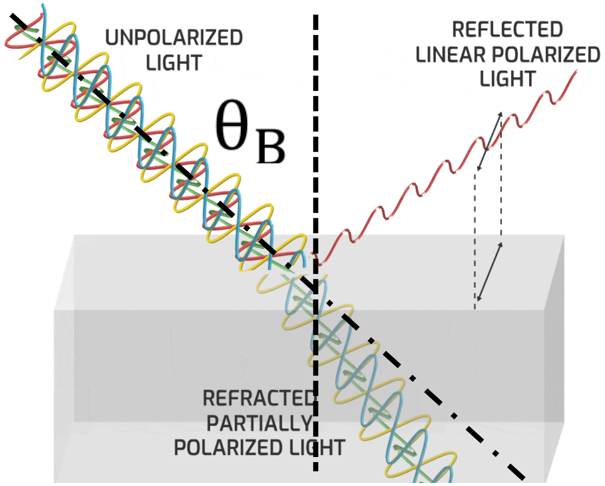
Source: Konzepte der Experimentalphysik 3: Optik und Quantenmechanik, Gabriele Semino, TUM, 2015.

- **Keep in mind**: $c = c(n)$ and $\lambda = \lambda(n)$

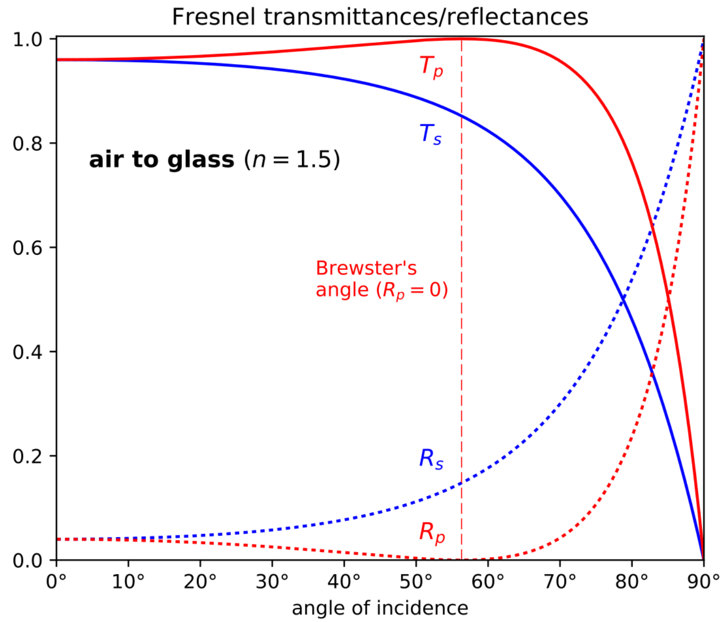
How much light is reflected, how much is refracted/transmitted?

- **Fresnel equations:** (https://en.wikipedia.org/wiki/Fresnel_equations)
  - Splitting depends on the polarisation of light
  - Electric field component parallel or perpendicular to incidence plane?

Fresnel equations



Source: https://www.baumer.com/de/en/service-support/technology-highlights/polarization/a/Polarization , (Access: 19.03.2025, 14:00 CET)



Source:https://en.wikipedia.org/wiki/Fresnel_equations#/media/File:Fresnel_power_air-to-glass.svg , (Access: 19.03.2025, 14:00 CET)

Special cases:

- **Brewster angle**: $\theta_B = \text{acrtan}(n_t/n_e)$ (electric field component parallel to incidence plane fully transmitted)
- **Total reflection**: $\theta_T = \text{acrsin}(n_t/n_e)$ (all incident light is relfected for $\theta_e \geq \theta_T$)
- **Keep in mind!**: Phase jumps between parallel and perpendicular component for external reflection
- **Transmission/reflection dependence on polarisation called diattenuation**

Müller-Stokes formalism

Stokes vector: $\vec{\mathrm{I}} = \begin{pmatrix} \mathrm{I} \\ \mathrm{Q} \\ \mathrm{U} \\ \mathrm{V} \end{pmatrix}$

- Unpolarised: $\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$
- Linear horizontal/vertical: $\begin{pmatrix} 1 \\ \pm 1 \\ 0 \\ 0 \end{pmatrix}$
- Left-/rigth-handed circularly polarised: $\begin{pmatrix} 1 \\ 0 \\ 0 \\ \pm 1 \end{pmatrix}$

Müller matrix: $\mathbf{M}(\boldsymbol{\theta}, \boldsymbol{\delta})$

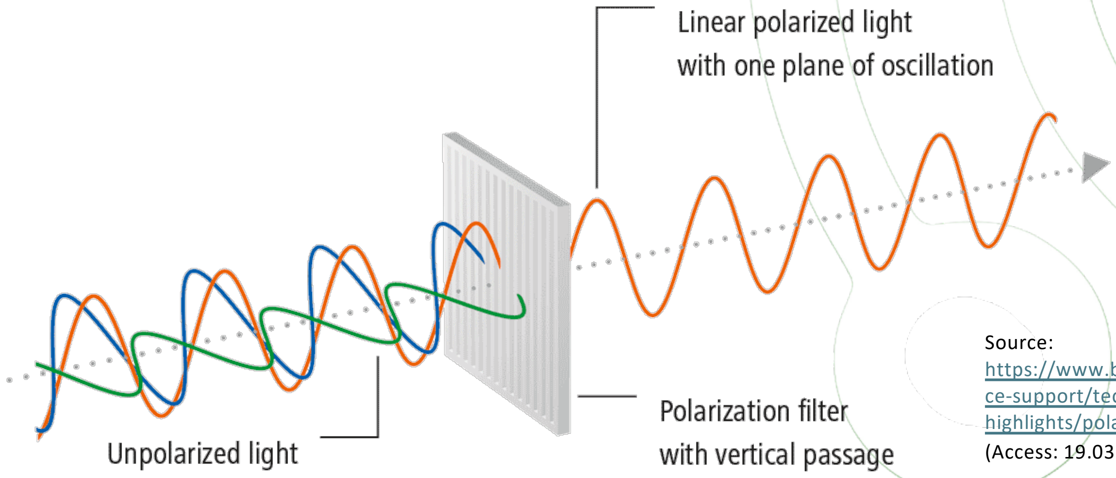
-> Represents **rotation** ($\boldsymbol{\theta}$) and **retardation** ($\boldsymbol{\delta}$) of polarization by an optical element

-> $\mathbf{M}(\boldsymbol{\theta}, \boldsymbol{\delta})$ transforms Stokes vector from old to new polarisation state by matrix-vector multiplication

$$\vec{\mathrm{I}}_{new} = \mathbf{M}(\boldsymbol{\theta}, \boldsymbol{\delta}) \cdot \vec{\mathrm{I}}_{old}$$

Müller-Stokes formalism

Examples



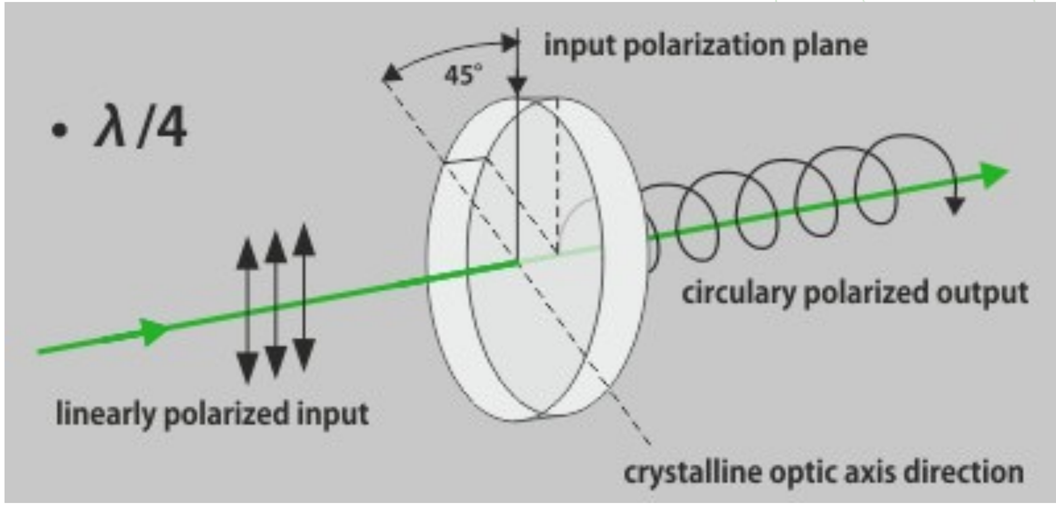
Source:
https://www.baumer.com/de/en/service-support/technology-highlights/polarization/a/Polarization ,
(Access: 19.03.2025, 14:00 CET)

- Unpolarised light through horizontal/vertical linear polariser, $\theta = 0$

$$\vec{I}_{new} = \mathbf{M}_{linpol} \cdot \vec{I}_{old} = \frac{1}{2}\begin{pmatrix} 1 & \pm 1 & 0 & 0 \\ \pm 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 \\ \pm 1 \\ 0 \\ 0 \end{pmatrix}$$

Refraction and reflection

Examples



Source: https://www.sr-optic.com/.cm4all/iproc.php/Diagramme/Grafik1.jpg/downsize_1280_0/Grafik1.jpg , (Access: 21.03.2025, 16:00 CET)

- Vertical linear polarised light through quater wave plate at, $\theta = \pm\pi/4, \delta = \pi/2$

$$\vec{I}_{new} = \mathbf{M}_{linpol} \cdot \vec{I}_{old} = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \pm 1 \\ 0 & 0 & 1 & 0 \\ 0 & \mp 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 \\ 0 \\ 0 \\ \pm 1 \end{pmatrix}$$

Questions?

Recommended literature:

- M. Bass, V.N. Mahajan: Handbook of optics, Voume 1; Third Edition; Mc Graw Hill; 2010.
- V. Freudenthaler: About the effects of polarizing optics on lidar signals and the Delta90-calibration; Atmos. Meas. Tech., 9; 2016.
- M. Haymann, J.P. Thayer: General description of polarization in lidar using Stokes vectors and polar decomposition of Mueller matrices; J. Opt. Soc. Am., Vol. 29 No. 4; 2012.

Technical optics

What does a lidar need?

- Reflecting and refracting light:
  - Lenses, mirrors, beam reducers/expanders, telescopes
- Polarisation transformation and analysis:
  - Beamsplitters, filters, waveplates
- Wavelength analysis:
  - Dichroic mirrors/beamsplitters, interference filters, spectrometry:
- Light attenuation:
  - Filters

Source: https://www.edmundoptics.de/p/75mm-diameter-x-50mm-flaspheric-condenser-lens/6712/, (Access: 14.03.2025, 12:00 CET)

Source: https://www.cloudynights.com/gallery/image/24461-edmund-scientific-6-f5-reflector/ , (Access: 14.03.2025, 12:00 CET)

Source: https://productimages.edmundoptics.com/5617.jpg?quality=80 , (Access: 14.03.2025, 12:00 CET)

Source: https://www.edmundoptics.com/c/dichroic-mirrors-harmonic-separators/1483/#, (Access: 14.03.2025, 12:00 CET)

Approximations

Geometric optics = ray optics

Used to describe the path of light in terms of rays (geometrical objects obeying certain rules)

(-> Sufficient for imaging calculations – Insufficient for describing diffraction or interference!)

Paraxial (Gauß) approximation:

$$n_e \sin(\theta_e) = n_t \sin(\theta_t) \rightarrow n_e \theta_e = n_t \theta_t$$

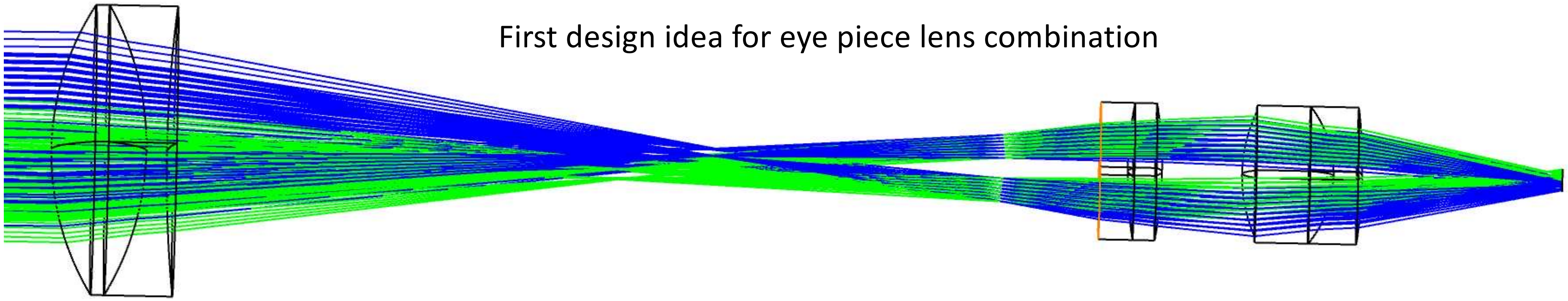
(-> approximation for small angles!)

→

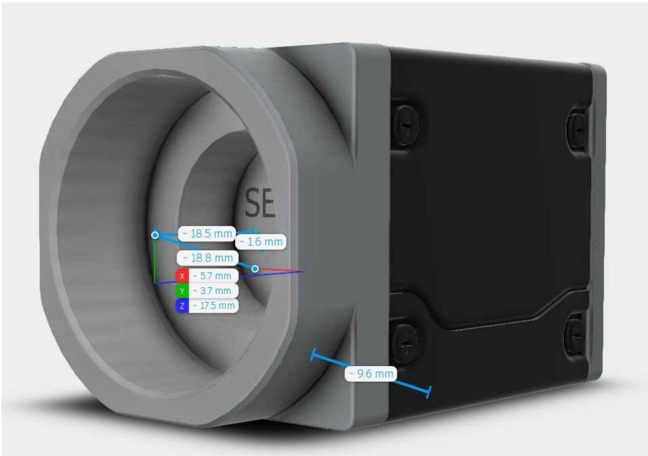
Zemax for non-paraxial ray tracing:
(-> accurate!)

Example of Zemax simulation

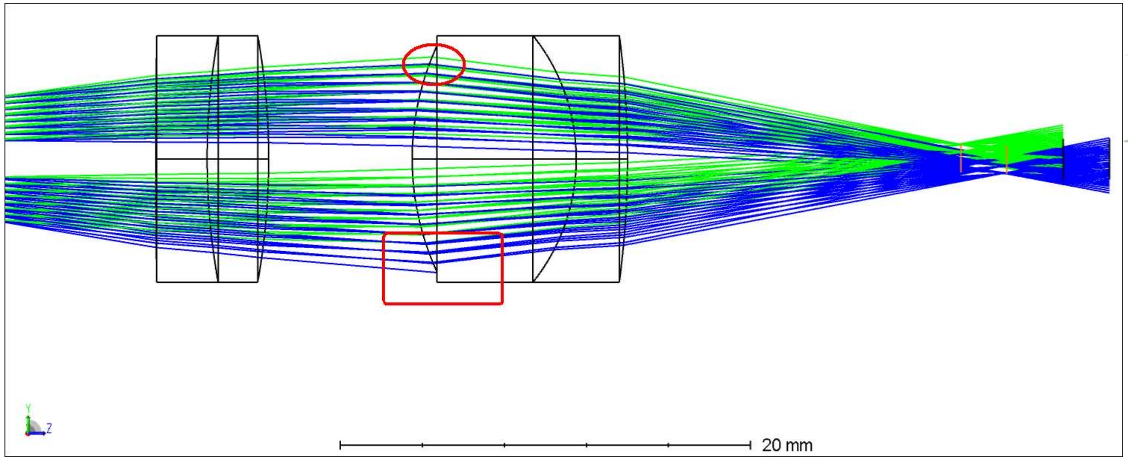
First design idea for eye piece lens combination



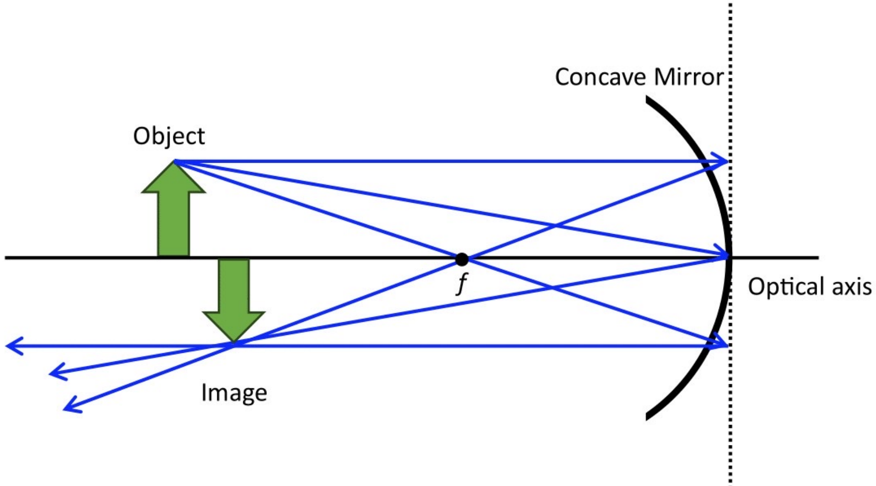
New alignment camera



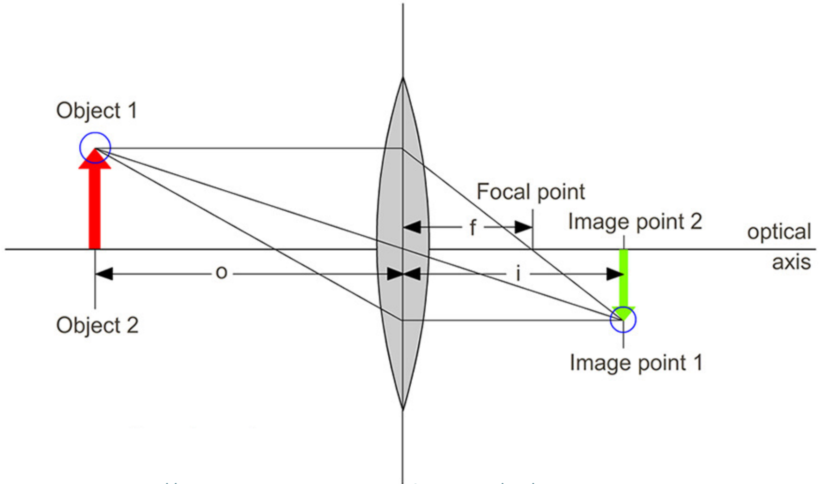
Possible problems in the design



Lenses and mirrors



Source: https://lipa.physics.oregonstate.edu/external/optics/concave.jpg , (Access; 21.02.2025, 18:00 CET)



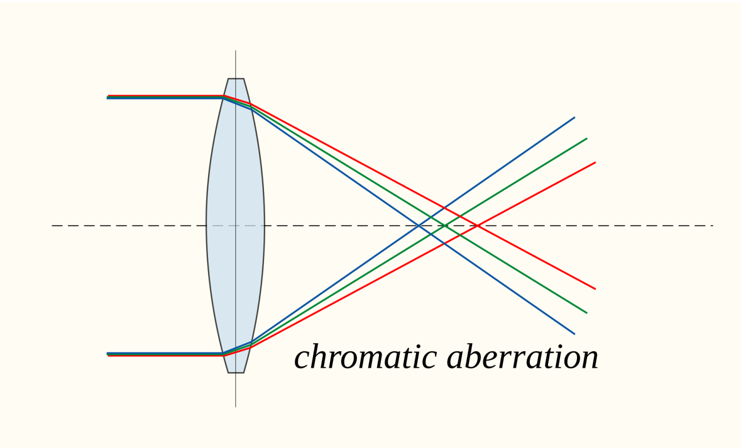
Source: https://medienportal.siemens-stiftung.org/lib/obj_view.php?objid=104133 , (Access: 21.03.2025, 18:00 CET)

Mirror equation: $\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$ (spherical mirrors!!)

Lens equation: $\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$ (thin spherical lenses!!)

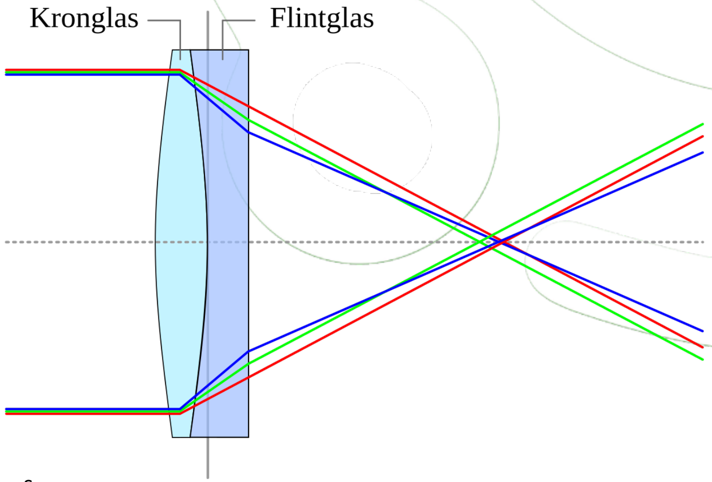
Lenses and mirrors: Imaging errors

Chromatic aberration (only for lenses)



Source:
https://en.wikipedia.org/wiki/Chromatic_aberration#/media/File:Chromatic_aberration_lens_diagram.svg , (Access: 21.03.2025, 17:30 CET)

Solution 1: **Achromatic** lens

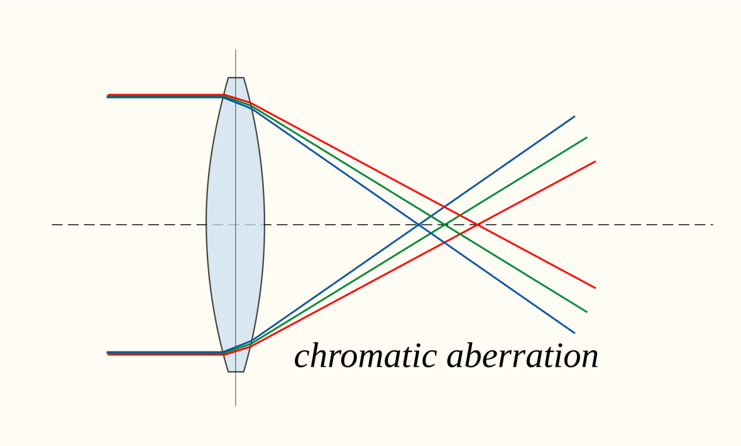


Source:
https://de.wikipedia.org/wiki/Achromat#/media/Datei:Achromat_de.svg ,
(Access: 21.03.2025, 17:30 CET), Modified by M. Haimerl

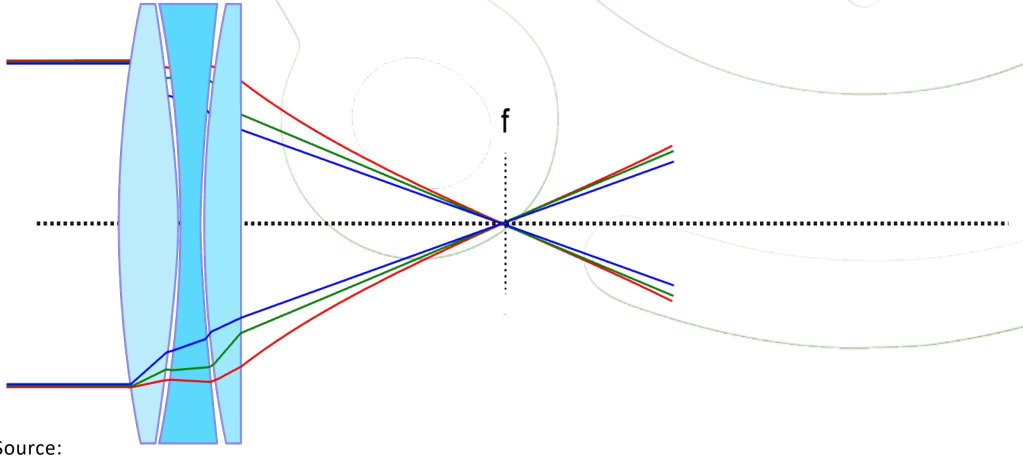
Lenses and mirrors: Imaging errors

Chromatic aberration (only for lenses)

<u>Solution 2</u>: **Apochromatic** lens



Source:
https://en.wikipedia.org/wiki/Chromatic_aberration#/media/File:Chromatic_aberration_lens_diagram.svg , (Access: 21.03.2025, 17:30 CET)



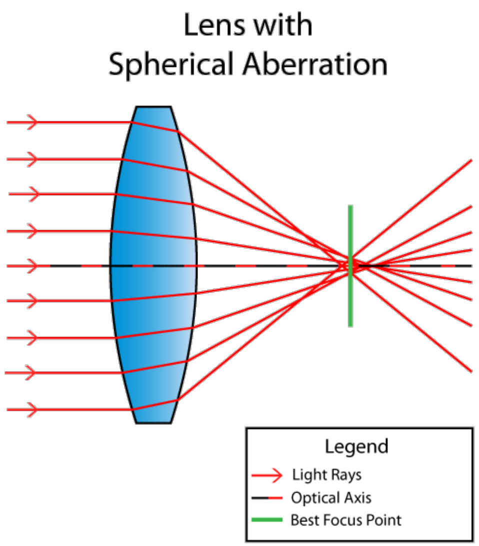
Source:
https://de.wikipedia.org/wiki/Apochromat#/media/Datei:Apochromat.svg , (Access: 21.03.2025, 17:30 CET), Modified by M. Haimerl

But!: 355nm – 1064nm is also for an apochromatic lens to wide

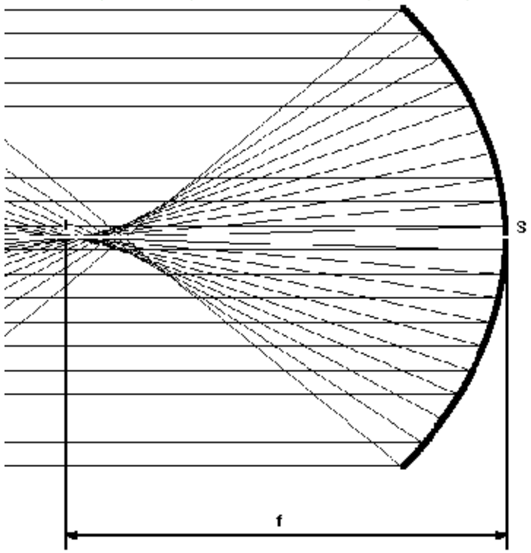
-> Achromatic lens offers good compromise for price and aberration reduction

Lenses and mirrors: Imaging errors

Spherical aberration



Source: https://photographylife.com/what-is-spherical-aberration , (Access; 14.03.2025, 12:30 CET)



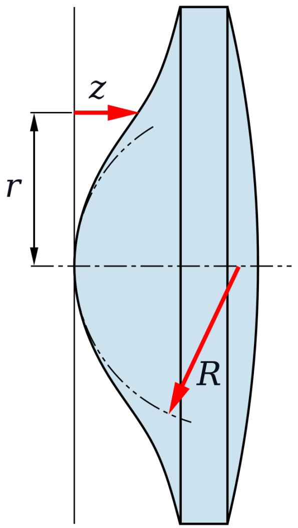
Source: https://www.researchgate.net/figure/The-spherical-aberration-of-the-mirror-with-the-focal-ratio-f-1_fig1_2355649 , (Access; 14.03.2025, 12:30 CET)

Solutions:

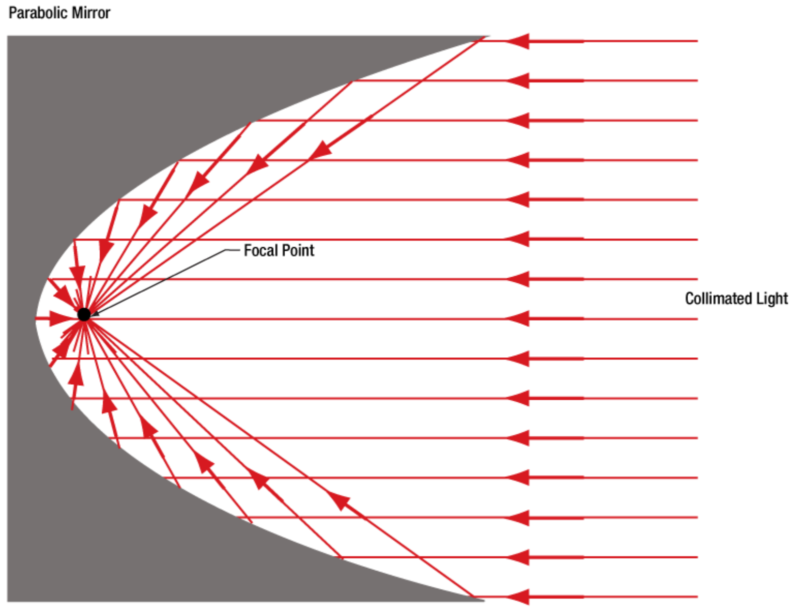
- Aspheric lenses (really sensitive to alignment)
- Aspheric (parabolic, hyperbolic) mirrors

Lenses and mirrors: Imaging errors

Spherical aberration



Source: https://en.wikipedia.org/wiki/Aspheric_lens#/media/File:Pfeilh%C3%B6he.svg , (Access; 06.05.2025, 11:00 CET)



Source: https://www.thorlabs.com/images/tabimages/Parabolic_Mirror_Focus_A2-780.gif , (Access; 06.05.2025, 11:00 CET)

Solutions:

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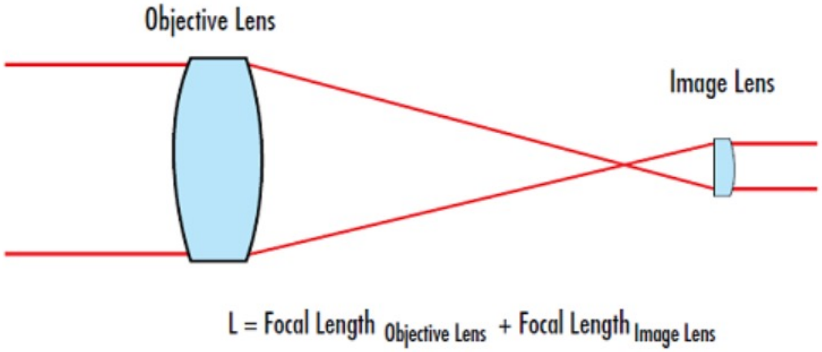
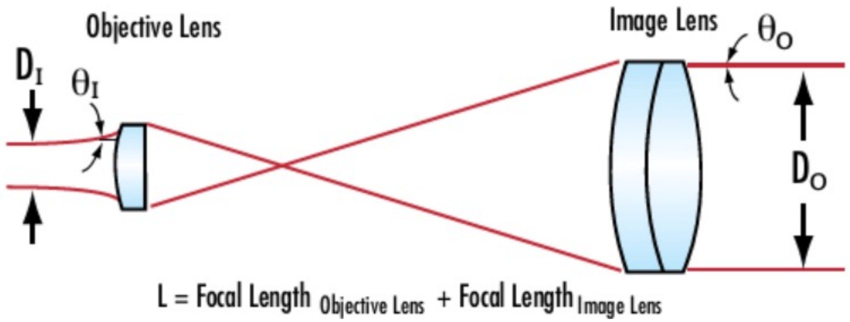
Beam reducer/expander





$$\text{Magnifying Power (MP)} = \frac{1}{\text{Magnification [m]}}$$

$$\text{MP} = -\frac{\text{Focal Length}_{\text{Objective Lens}}}{\text{Focal Length}_{\text{Image Lens}}}$$

$$\text{MP} = \frac{\text{Input Beam Divergence } (\theta_I)}{\text{Output Beam Divergence } (\theta_O)} = \frac{\text{Output Beam Diameter } (D_O)}{\text{Input Beam Diameter } (D_I)}$$

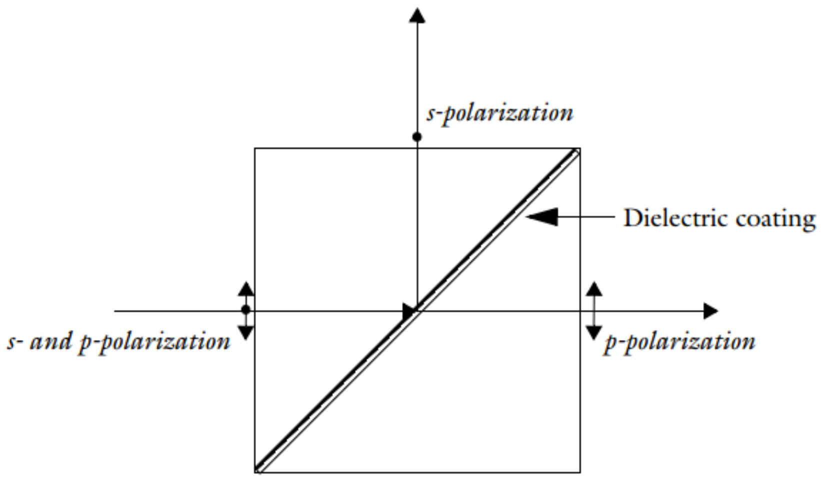
Important: - Increase of beam width
- Decrease of beam divergence

EdmundOptics -> Beam expander

Source: https://www.edmundoptics.de/knowledge-center/application-notes/optics/can-a-beam-expander-be-used-in-reverse/, (Access; 14.03.2025, 12:30 CET)

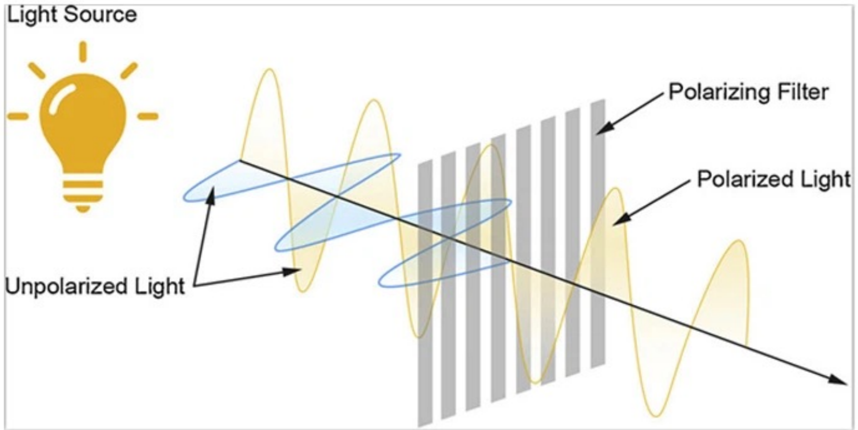
Polarisation transformation and analysis

Polarising beam splitter cube



Source: https://www.comsol.com/blogs/study-the-design-of-a-polarizing-beam-splitter-with-an-app , (Access; 14.03.2025, 12:30 CET)

Linear polarisers



Source: https://www.rinalgp.com/info/what-is-a-polarizer-film-sheet-and-what-does-i-76405383.html , (Access; 14.03.2025, 12:30 CET)

Polarisation transformation and analysis

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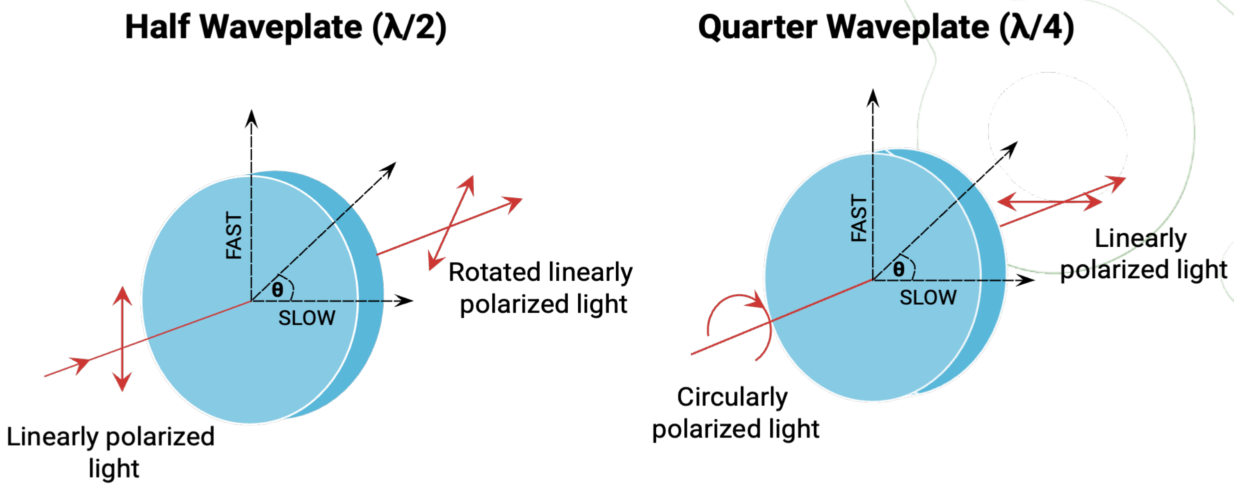
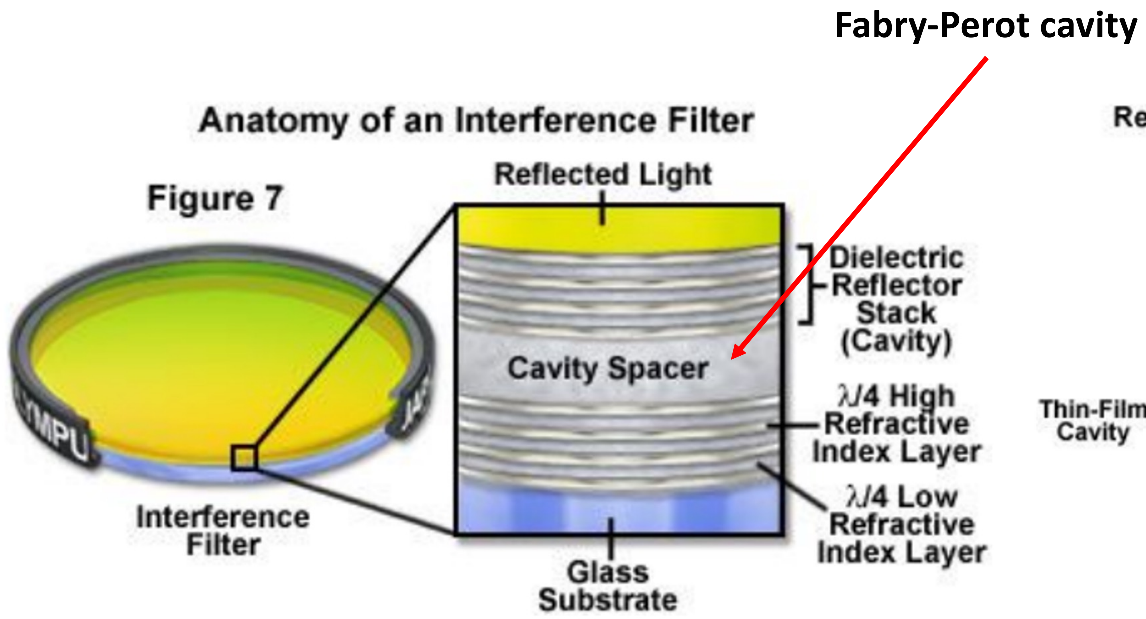
Waveplates

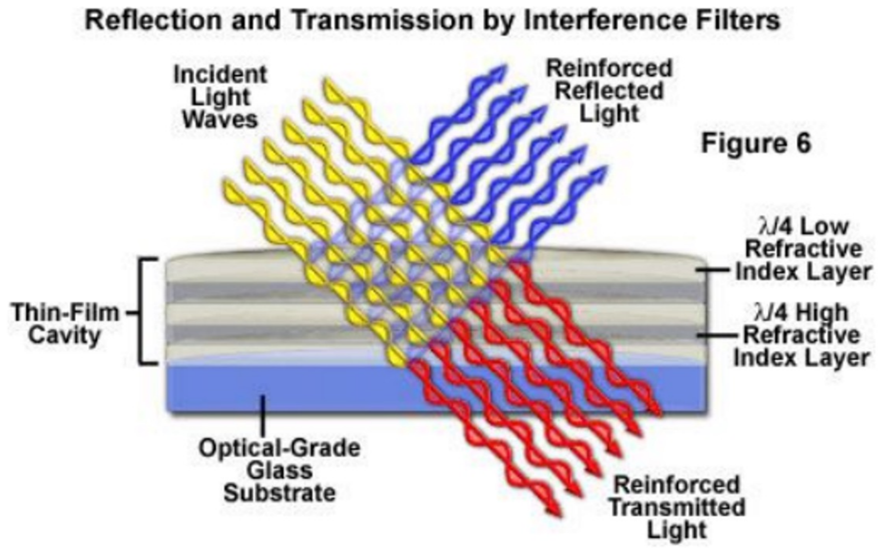


Source: https://www.meetoptics.com/academy/waveplates#what-are-waveplates ,
(Access; 14.03.2025, 12:30 CET)

Wavelength analysis

Interference filter (IF)

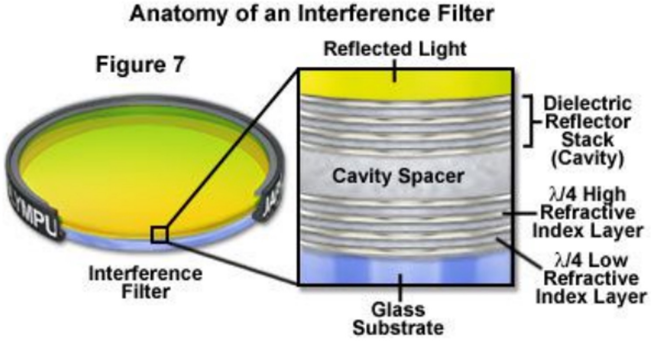


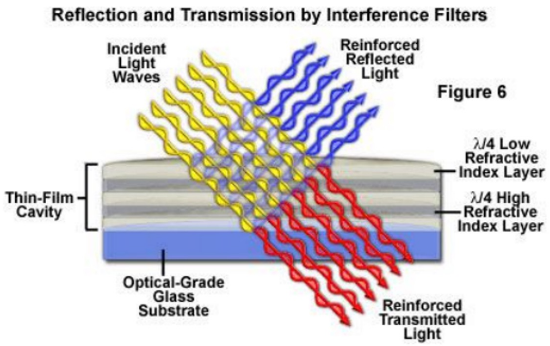


Source: https://micro.magnet.fsu.edu/primer/java/filters/interference/index.html , (Access; 21.03.2025, 17:00 CET)

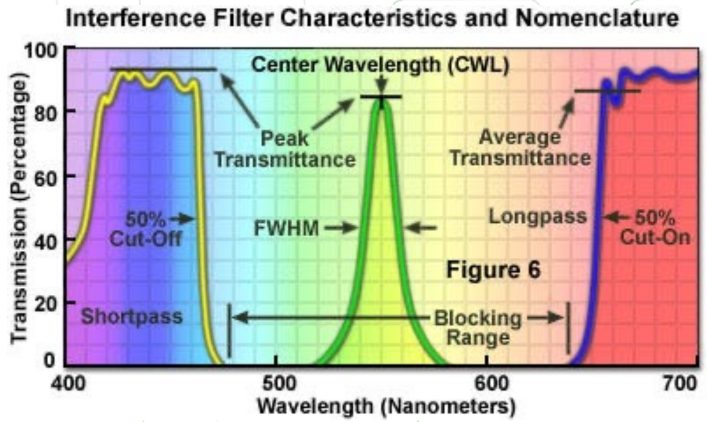
Wavelength analysis

Interference filter (IF)

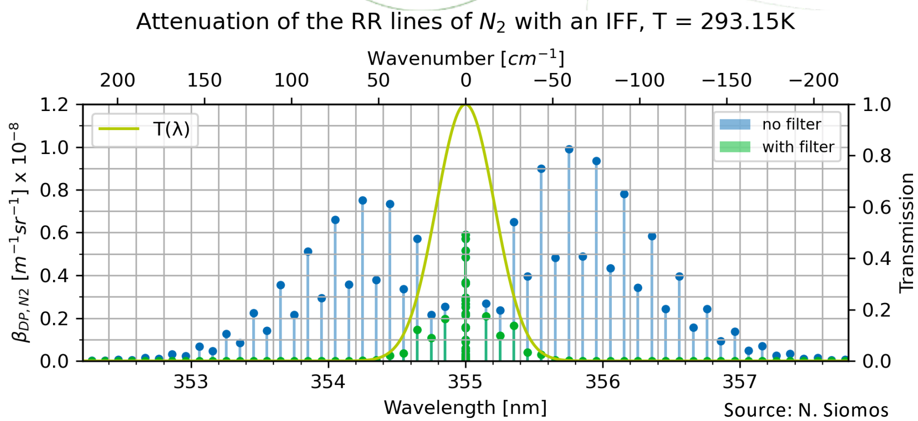




Source: https://micro.magnet.fsu.edu/primer/java/filters/interference/index.html , (Access; 21.03.2025, 17:00 CET)



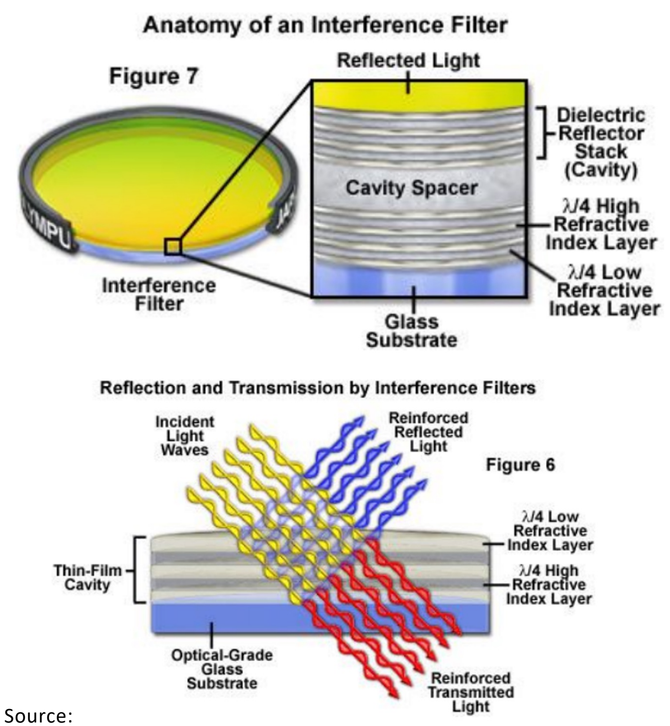
Source: https://evidentscientific.com/en/microscope-resource/knowledge-hub/techniques/fluorescence/interferencefilterintro , (Access; 14.03.2025, 13:00 CET)



Source: N. Siomos

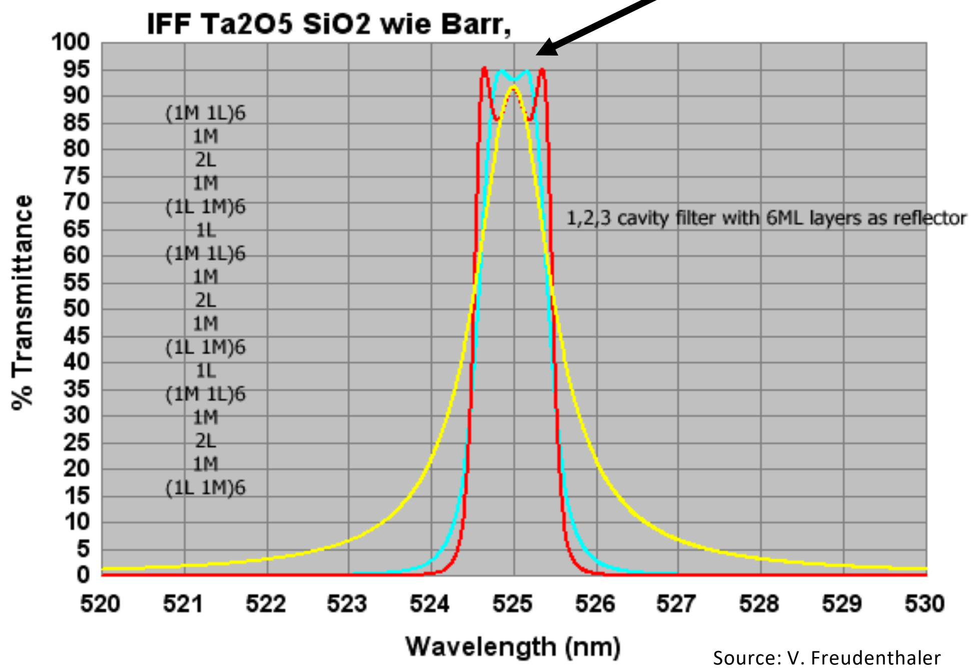
Wavelength analysis

Interference filter (IF) - Single vs. multi cavity



Source:
https://micro.magnet.fsu.edu/primer/java/filters/interference/index.html ,
(Access; 21.03.2025, 17:00 CET)

Flattening for multi-cavity filters



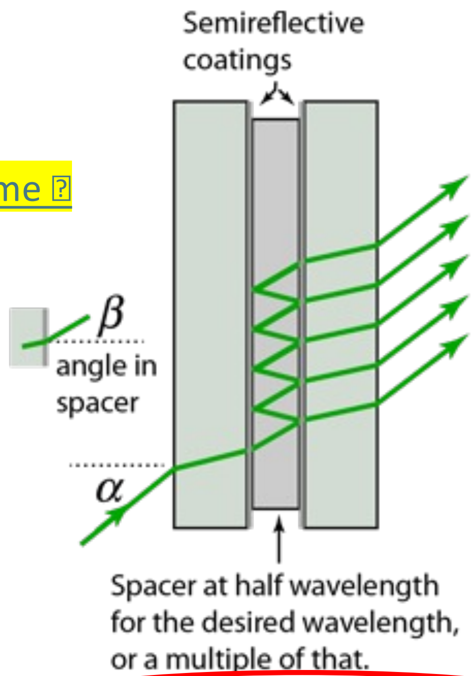
Source: V. Freudenthaler

-> Highly recommended are **2 cavity filters**
(Still acceptable costs and better filtering properties due to sharper/steeper flanks)

Wavelength analysis

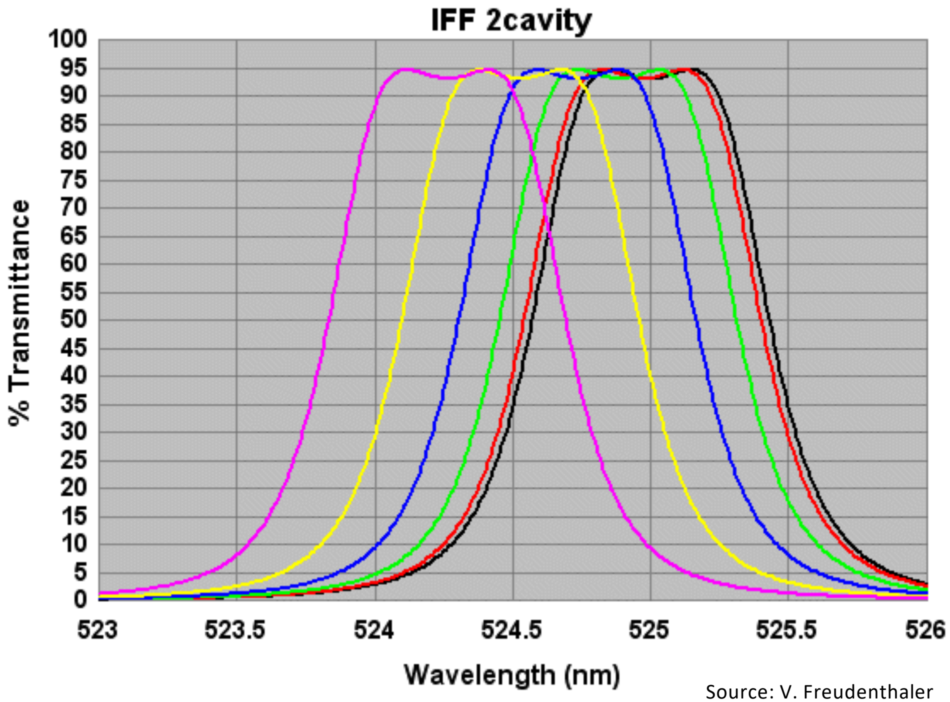
Interference filter (IF) – Angle dependent transmission

Click me ⍰



IF wavelength
calculator

Source: http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/intfilt.html , (Access; 23.03.2025, 11:00 CET)

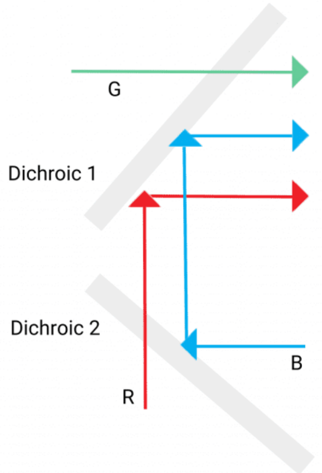


Source: V. Freudenthaler

Wavelength analysis

Dichroic optics

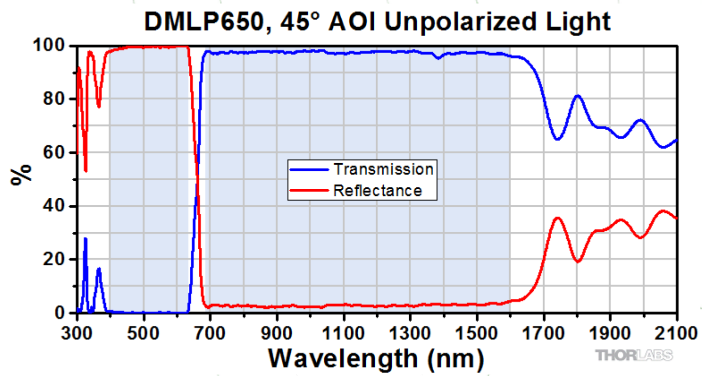
Dichroic Mirror Groups Application



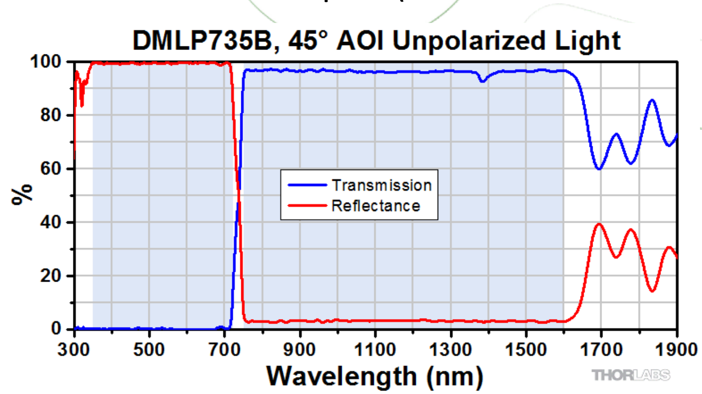
Dichroic 1: Transmit Red, Reflect Blue
Dichroic 2: Transmit Green, Reflect Red and Blue

Source: https://avantierinc.com/solutions/custom-optics/dichroic-mirrors/ , (Access; 14.03.2025, 12:30 CET)

Thorlabs longpass (HR 532 HT 1064):



Thorlabs multiband pass (HR 355 HR 532 HT 1064):

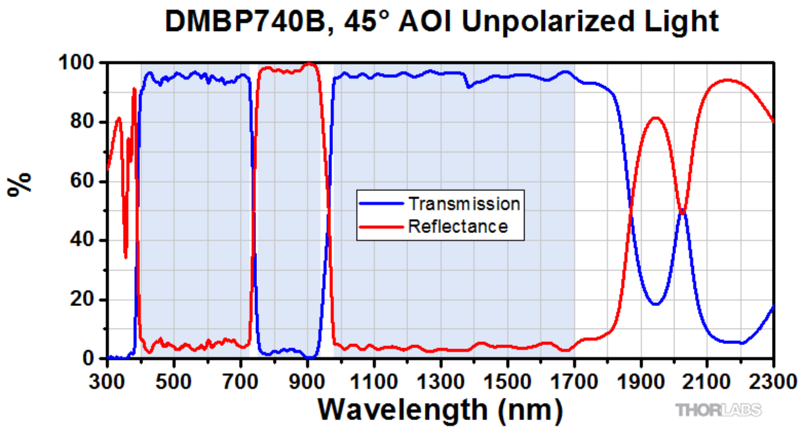


Source: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=3313 , (Access; 21.03.2025, 16:30 CET)

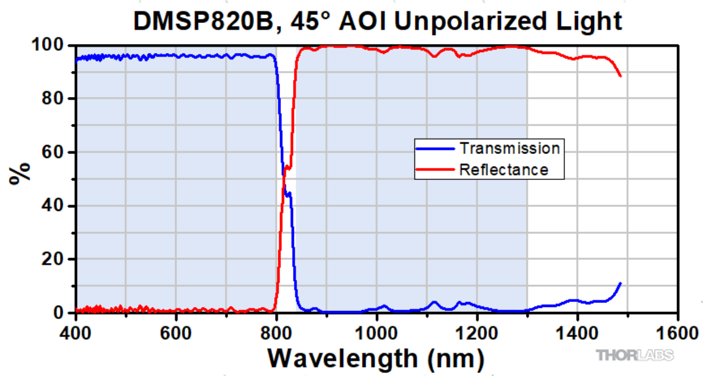
Wavelength analysis

Dichroic optics

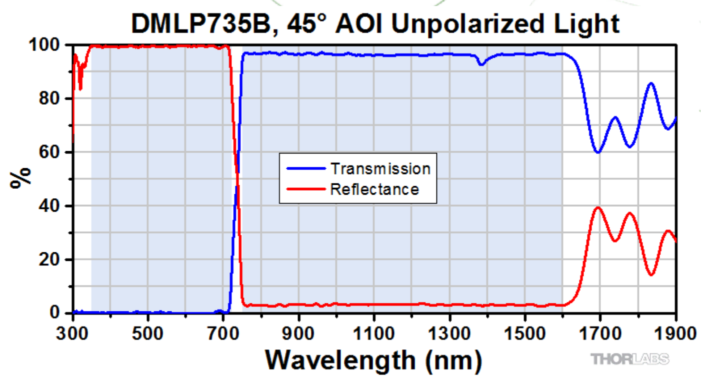
Thorlabs multi bandpass:



Thorlabs shortpass (HT 532 HR 1064):



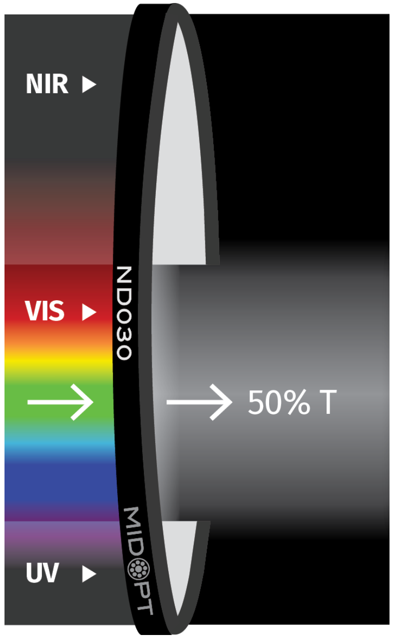
Thorlabs longpass (HR 355 HR 532 HT 1064):



Source: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=3313 ,
(Access; 21.03.2025, 16:30 CET)

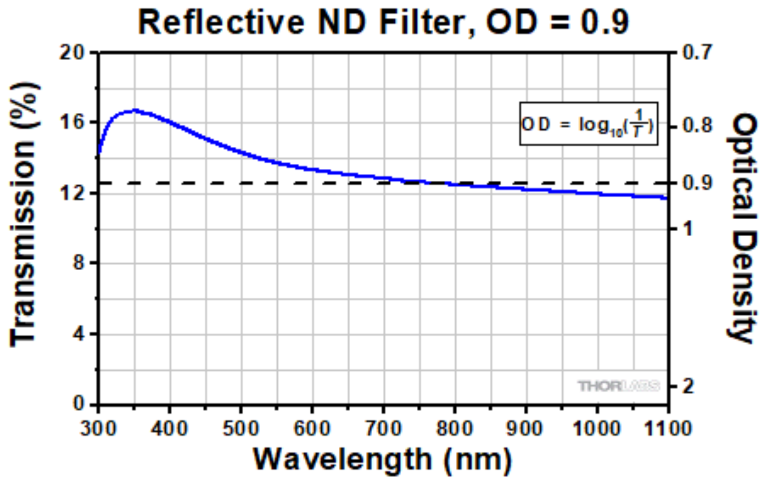
Light attenuation

Neutral density filter



Source: https://midopt.com/filters/nd030/ ,
(Access; 14.03.2025, 12:30 CET)

Thorlabs ND-filter:



Source: https://www.thorlabs.com/images/tabimages/ND09_Trans_OD_G1-450.gif ,
(Access: 19.03.2025, 10:00 CET)

- Transmittance ratio: $\frac{I}{I_0} = 10^{-d}$ (I, I_0: intensities, d: optical density)
- ND filters don't attenuate homogeneously over all wavelengths!

Questions?

Recommended literature:

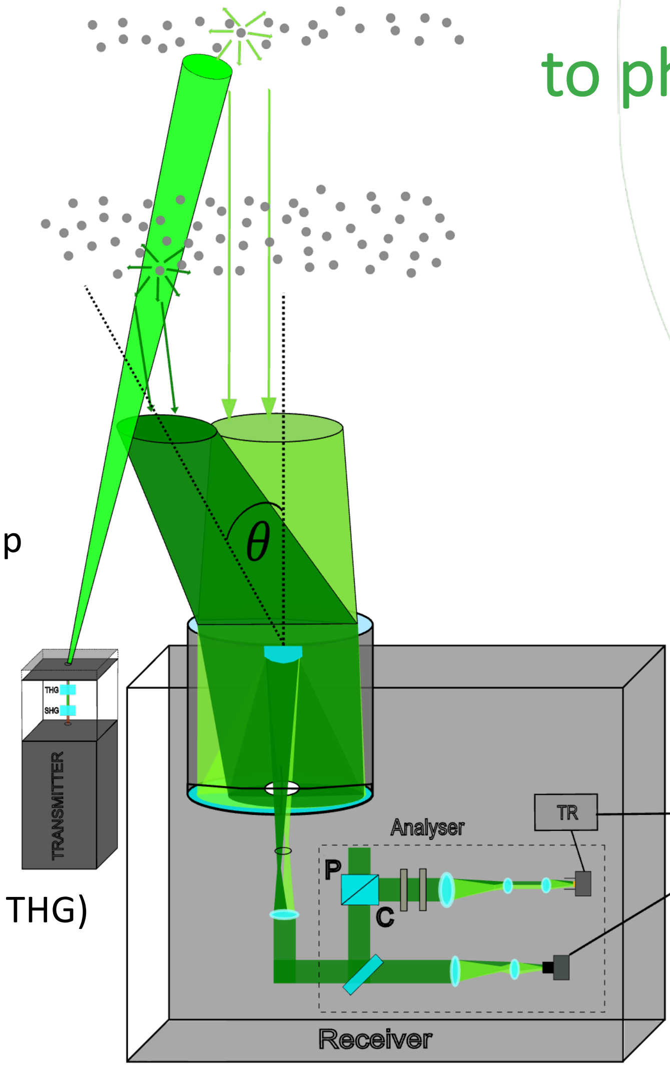
- M. Bass, V.N. Mahajan: Handbook of optics, Voume 1; Third Edition; Mc Graw Hill; 2010.
- Homepage of EdmundOptics: https://www.edmundoptics.de/knowledge-center/

Applied lidar optics

From transmitter to photon detector

Receiver (telescope)
- Field of view
- Field-stop/Iris
- Near range/far range
- Overlap function
- Distance of full overlap
- Beam collimation

Transmitter(laser)
- Harmonic generation (SHG, THG)
- Polarisation cleaning
- Beam expansion
- Beam profile



Analyzer
- Dichroic optics
- Polarisation analysers
- Interference filters
- Neutral density filter

Recorder
- Objective/eyepiece lenses
- APD/PMT
- Alignment camera
- Transient recorder

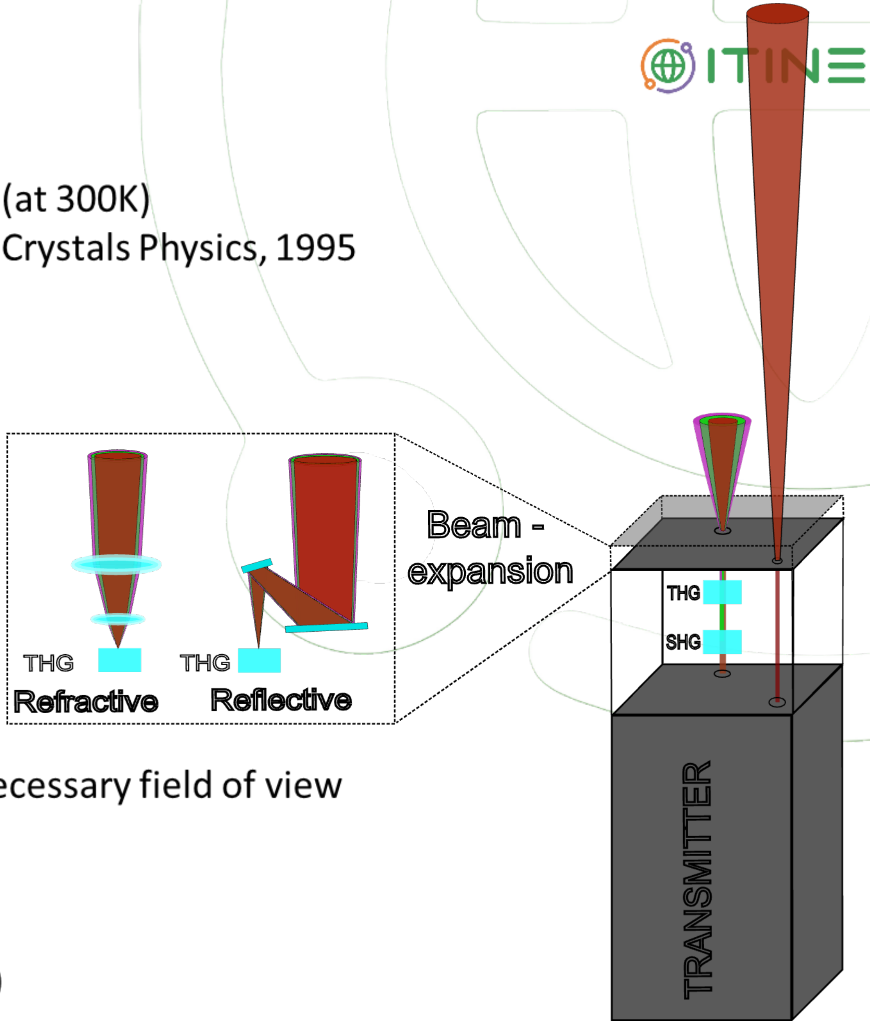
Source: https://www.istockphoto.com/de/vektor/moderne-computer-cartoon-gm862739386-143196107 , (Access: 19.03.2025, 11:00 CET)

Transmitter

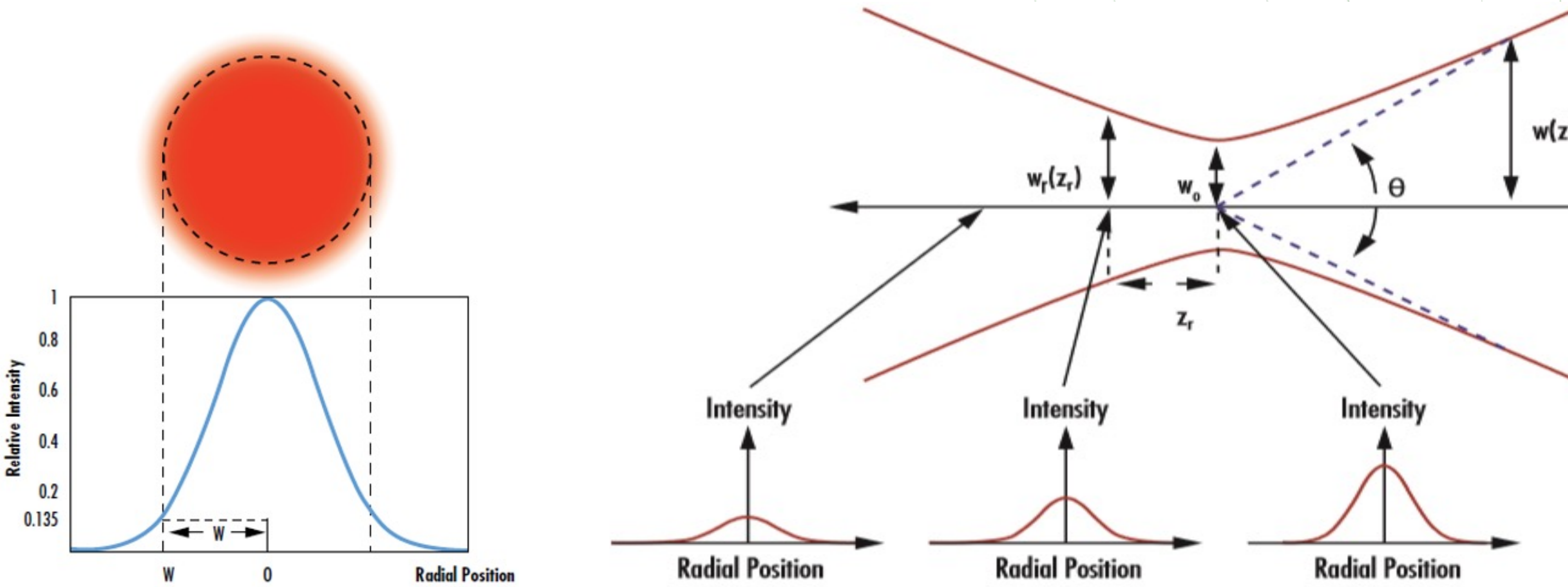
- **Laser:** Nd:YAG, flashlamp-/diode-pumped, $\lambda = 1064.14$ nm (at 300K)
  - Literature: A.A.Kaminsky, Tomorrow and Today of Laser Crystals Physics, 1995
- **Harmonic generation:**
  - Second harmonic generation, $\lambda/2 = 532.07$ nm
  - Third harmonic generation, $\lambda/3 = 354.71$ nm

- **Pure linear polarisation** through ideal SHG/THG crystals
  -> crystals polarisation selective

- **Beam expansion**
  - Increase of beam width, decrease of divergence
  - Why?:
    - Decrease of distance of full overlap/Decrease of necessary field of view
    - Eye-safety
  - Reflective with mirrors
  - Refractive with lenses
    (!! Influence on polarisation, unknown diattenuation !!)



Transmitter- Gaussian beam profile



z_r: Rayleigh length
w_0: min. beam waist
$w_r(z)$: beam waist
θ: beam divergence

Source: https://www.comsol.com/blogs/understanding-the-paraxial-gaussian-beam-formula , (Access: 17.01.2025, 17:30)

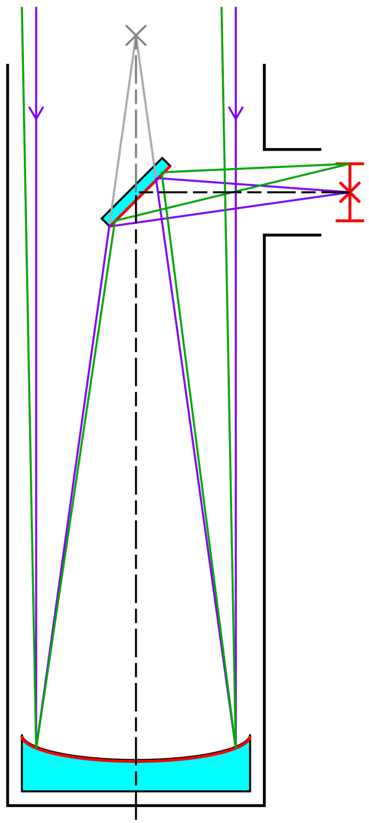
- Optimum beam profile, can be influenced by several parameters and optical elements
- Questionable is the influence of atmospheric phenomena?
- Has influence on overlap and lidar alignment

Receiver – Telescope types

Newtonian telescope

Primary mirror: parabolic
Secondary mirror: flat

Each telescope type has several subtypes correcting for different disadvantages!



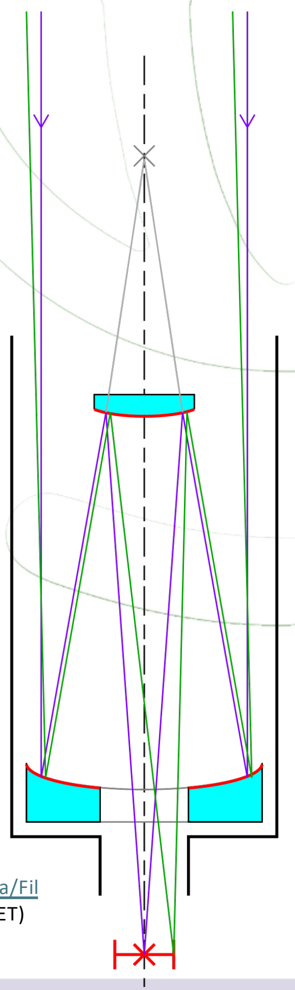
Source:
https://en.wikipedia.org/wiki/Reflecting_telescope#/media/File:Newtonian_telescope2.svg , (Access: 06.05.2025, 12:30 CET)

Cassegrain telescope

Primary mirror: parabolic
Secondary mirror: hyperbolic

Dall-Kirkham subtype:
Primary mirror: elliptical
Secondary mirror: spherical

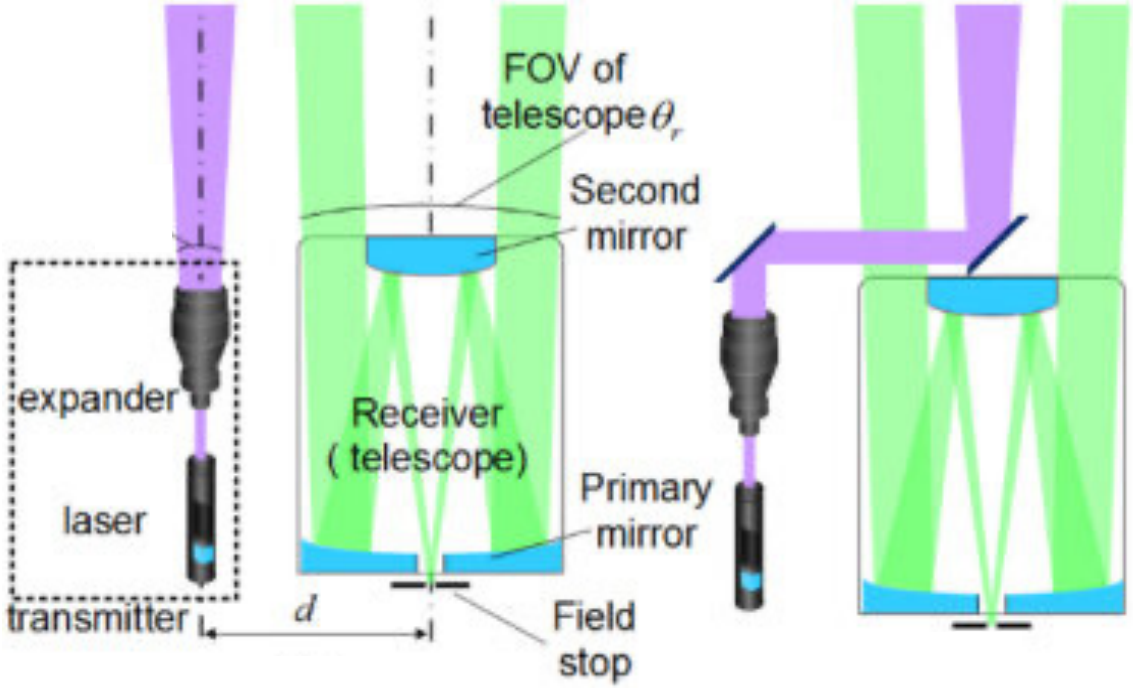
Alignment is more simple!



Source:
https://en.wikipedia.org/wiki/Reflecting_telescope#/media/File:Cassegrain_Telescope.svg , (Access: 06.05.2025, 12:30 CET)

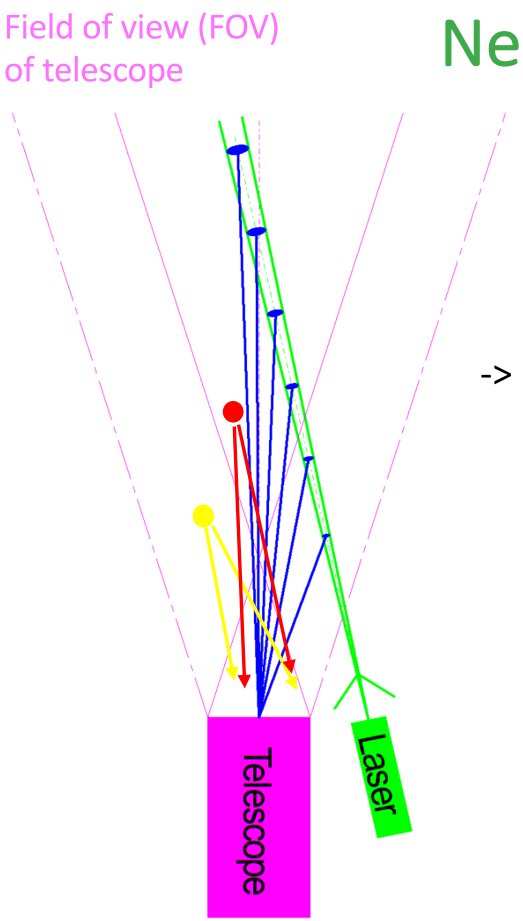
Receiver – Lidar geometries

Biaxial Coaxial



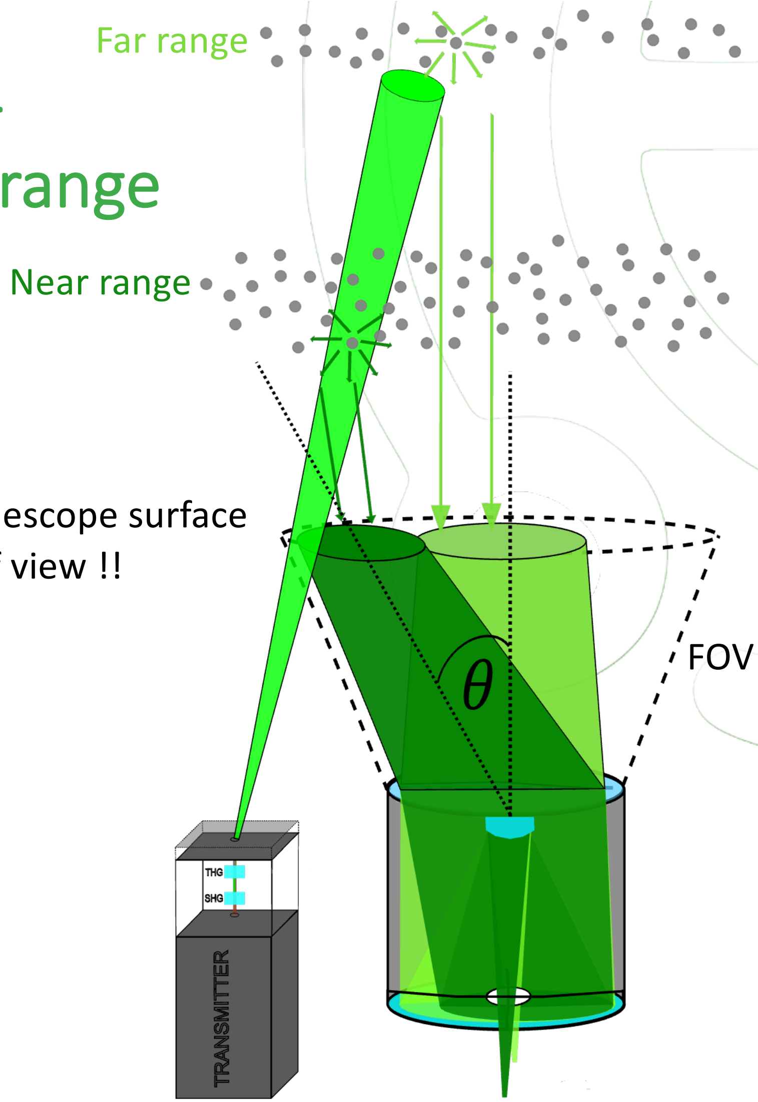
Source:
https://www.researchgate.net/publication/337684271/figure/fig3/AS:11431281335795476@1743376500649/Configurations-of-the-lidar-transceiver-anon-coaxial-configuration-bcoaxial.jpg , (Access: 06.05.2025, 13:00 CET)

Receiver – Near range/Far range



Source: V. Freudenthaler

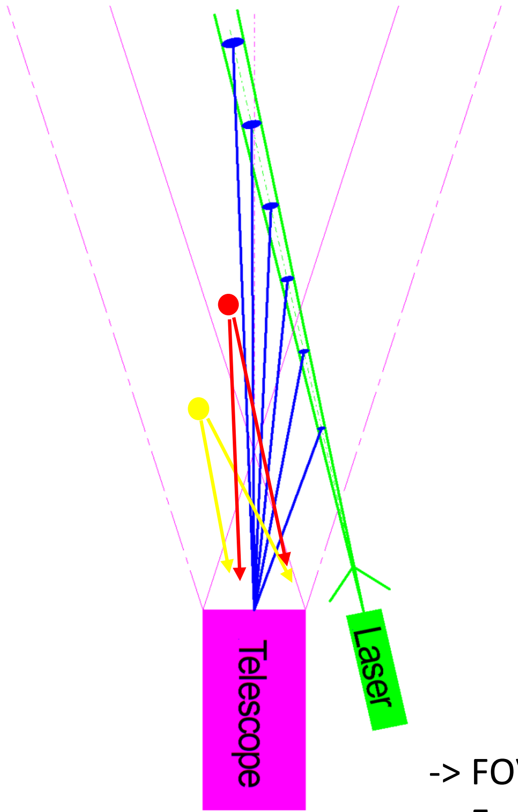
-> !! Each point on the telescope surface has the same field of view !!



Copyright: Michael Haimerl

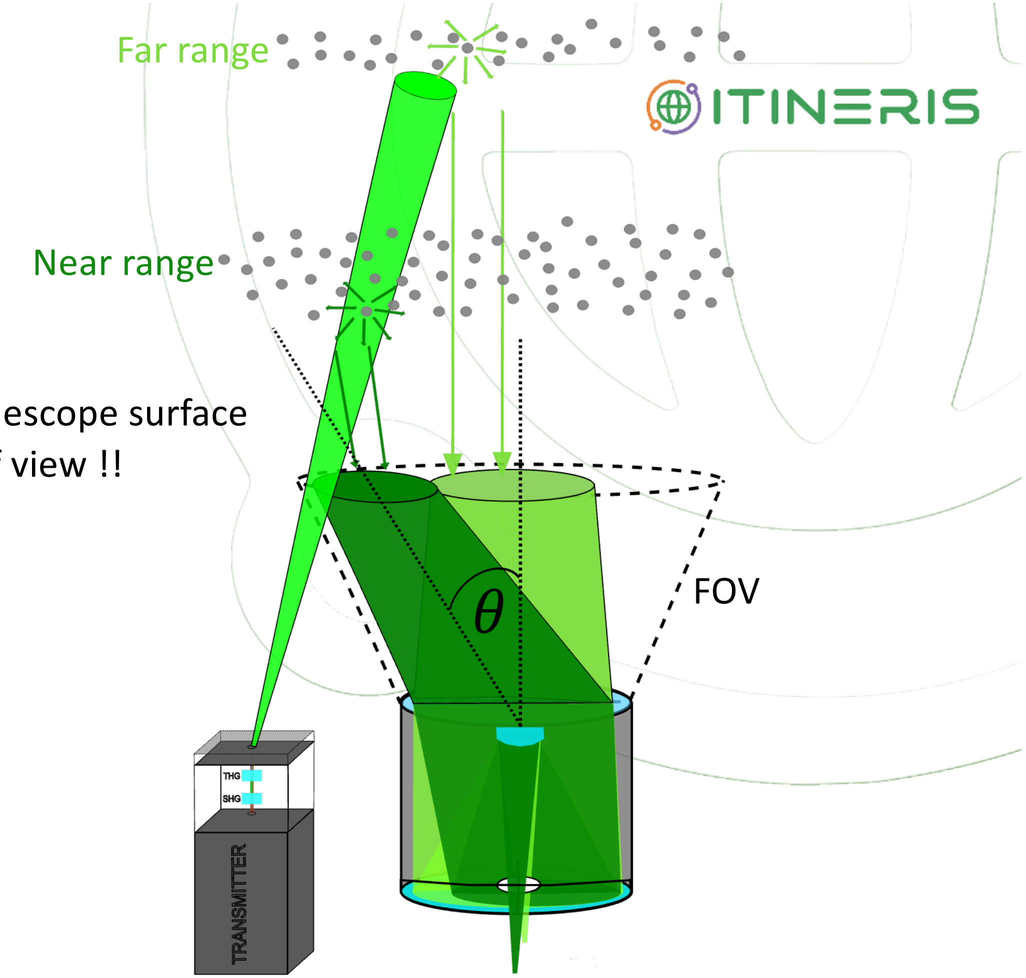
Receiver - Near range/Far range

Field of view (FOV)
of telescope



Source: V. Freudenthaler

-> !! Each point on the telescope surface has the same field of view !!

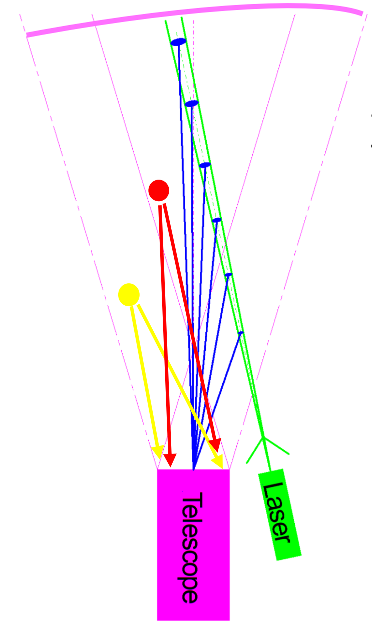


Copyright: Michael Haimerl

-> FOV sometimes referred to only by its **half-angle**

-> **Far range** and **near range** rays enter telescope under **different angles**

Receiver - Near range/Far range



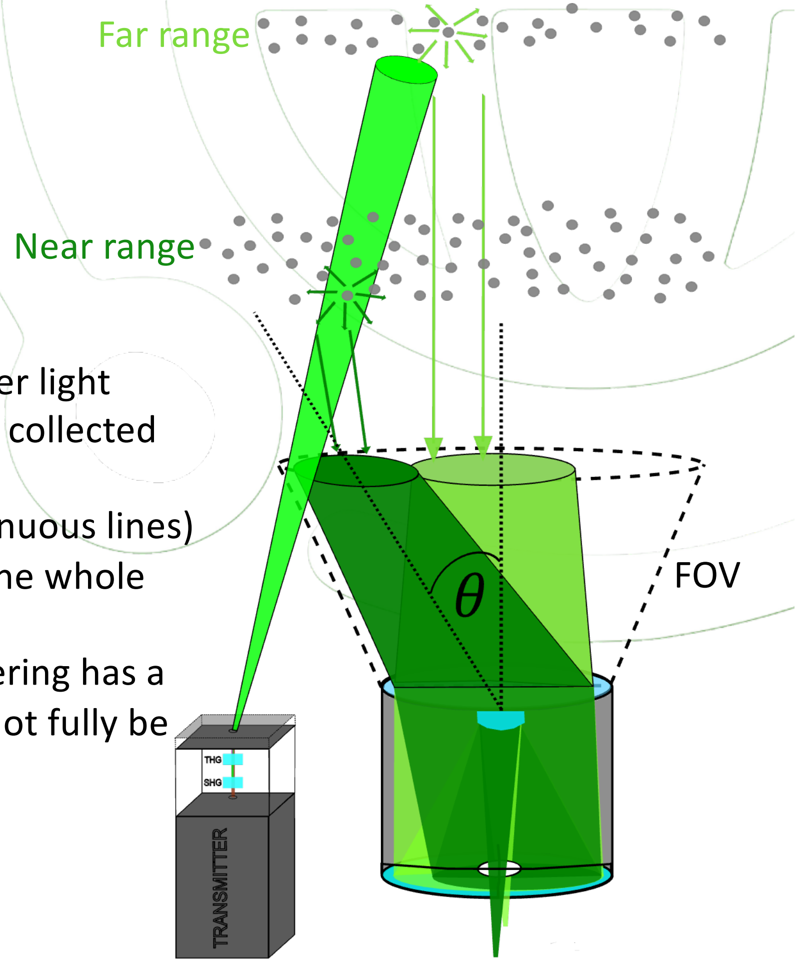
Source: V. Freudenthaler

<u>To the left scheme:</u>

- For a complete/reliable measurement all the laser light backscattered from the atmosphere needs to be collected from the telescope

-> only possible if laser enters the inner cone (continuous lines)

- Only **red** backscattering can be fully imaged by the whole telescope
- The right light ray at the of the yellow backscattering has a big angle with respect to the telescope and cannot fully be imaged by the telescope



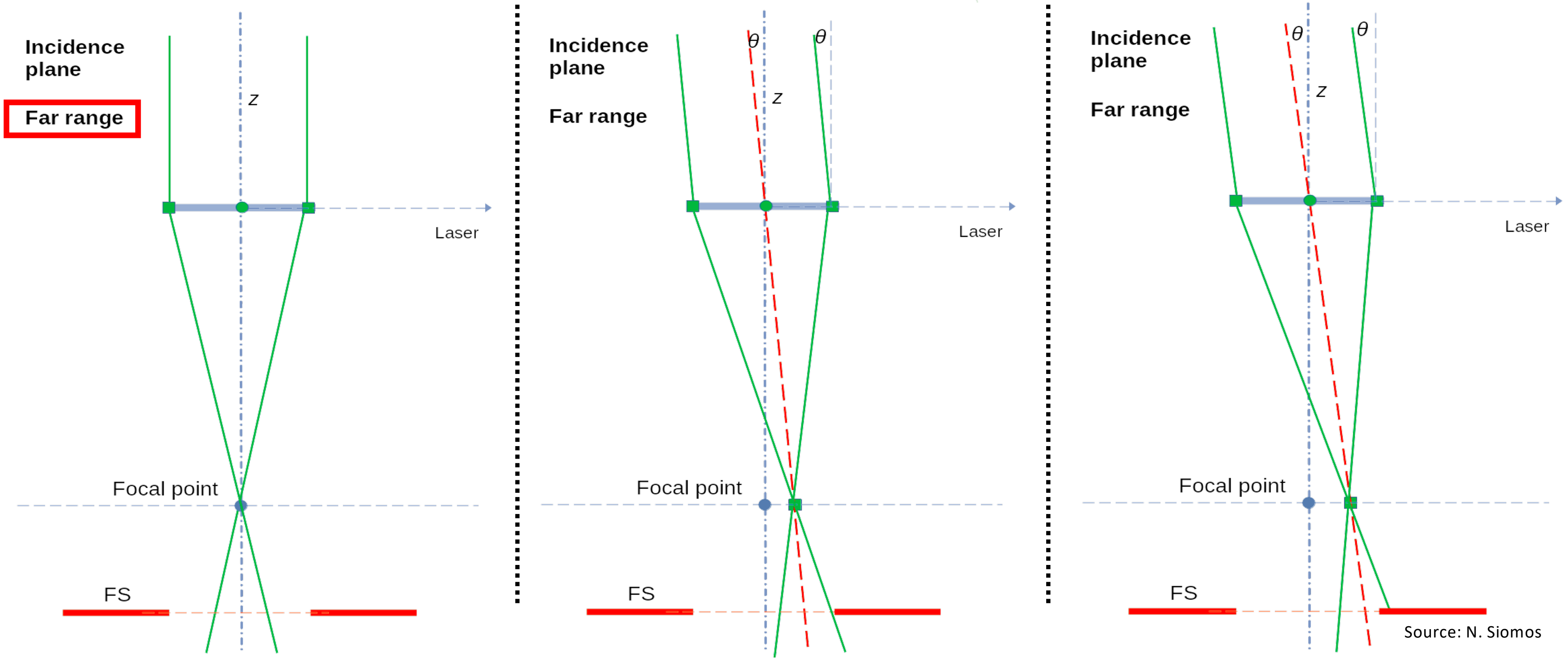
Copyright: Michael Haimerl

-> FOV sometimes referred to only by its **half-angle**

-> **Far range** and **near range** rays enter telescope under **different angles**

Receiver - Field of view, Iris/Field-stop

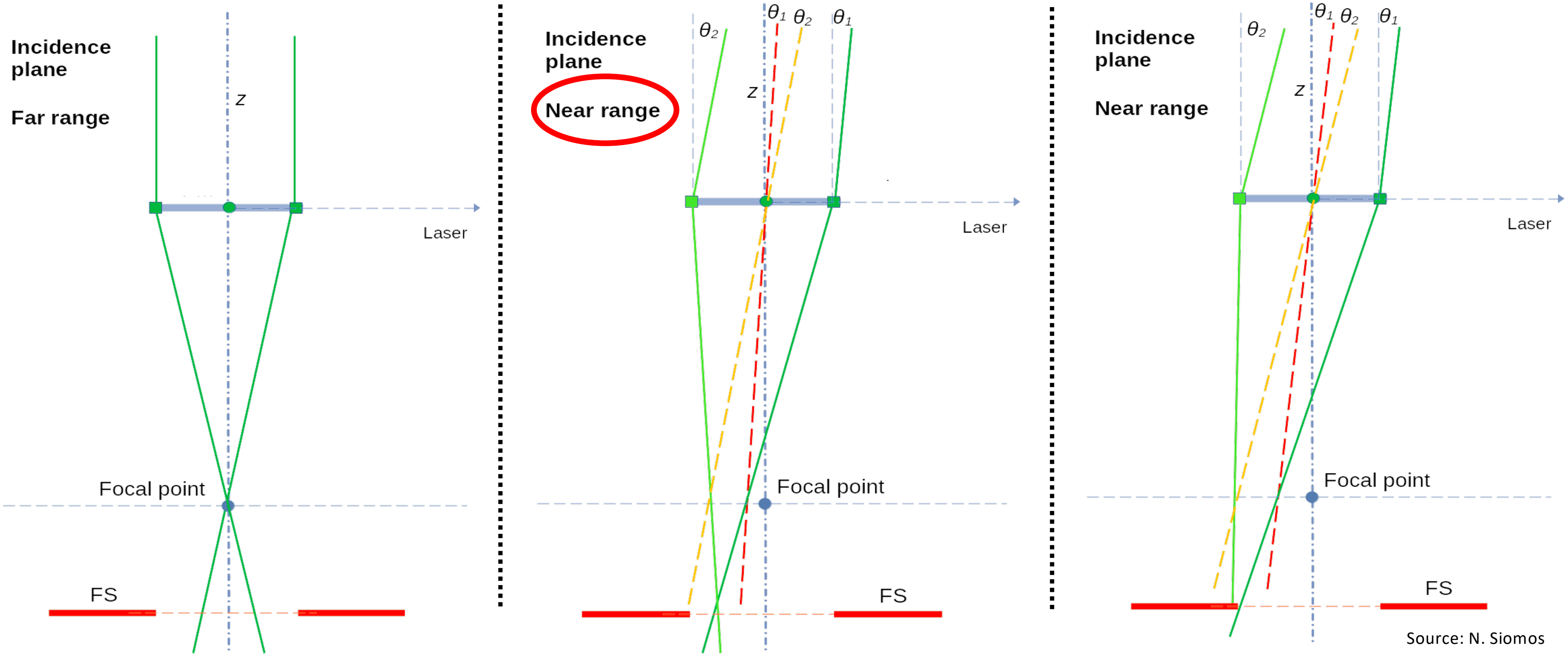
- Rays originate from **one point/scatterer** in the atmosphere in far range
- Far range -> rays can be assumed to be **parallel** at the telescope aperture



Source: N. Siomos

Receiver - Field of view, Iris/Field-stop

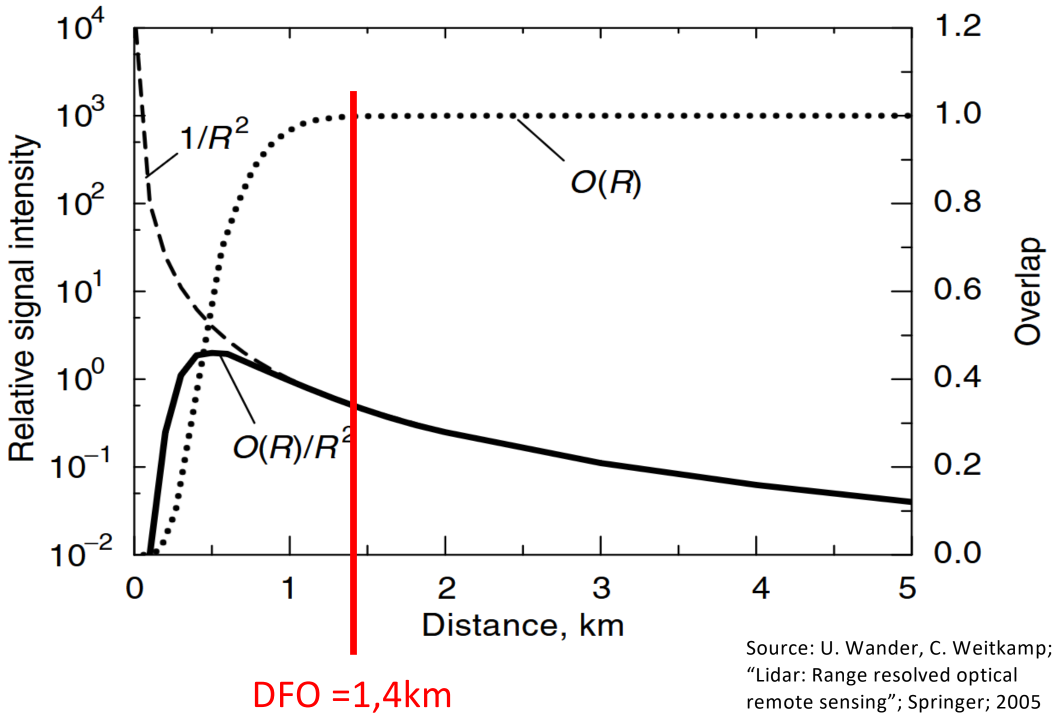
- Rays originate from **one point/scatterer** in the atmosphere in near range
- Near range -> rays **cannot** be assumed to be **parallel** at the telescope aperture



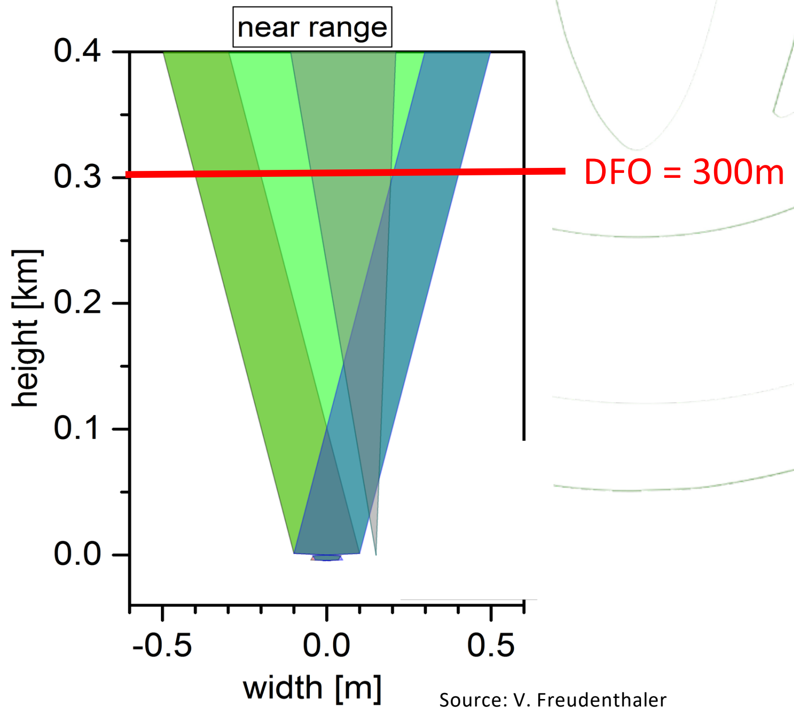
Source: N. Siomos

Receiver - Overlap function

Distance of full overlap (FOV):
-> Distance at which the full laser beam gets transferred through the field-stop



Source: U. Wander, C. Weitkamp; "Lidar: Range resolved optical remote sensing"; Springer; 2005



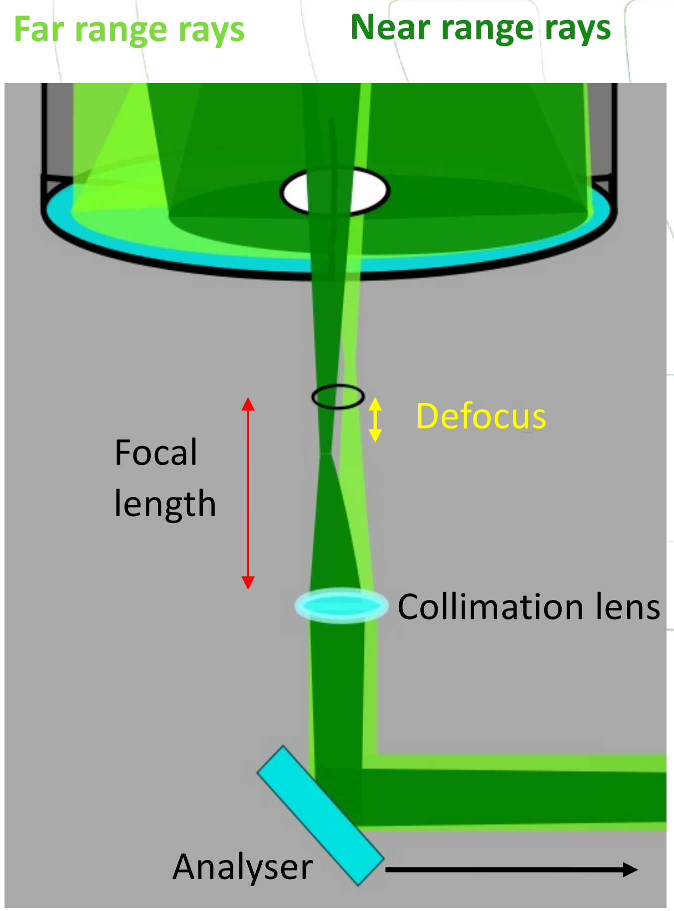
Source: V. Freudenthaler

Receiver

Beam collimation

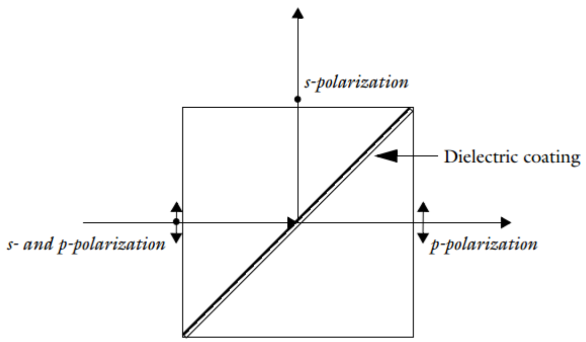
- Near and far range have different **focus positions**
- Near and far range emerge with different **divergence angles** from the foci

-> Impossible to fully collimate both fields at the same time
-> **Defocus** of collimation lens towards at mid range
-> Slight **convergence** of near range rays after lens (incidence angles of IF!!)
-> **Collimation** of far range rays

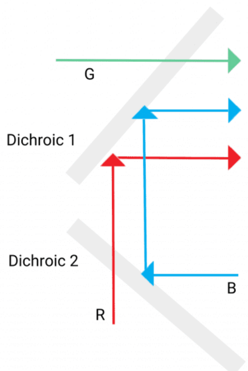


Little hint:
For a coaxial geometry both foci
On optical axis of telescope

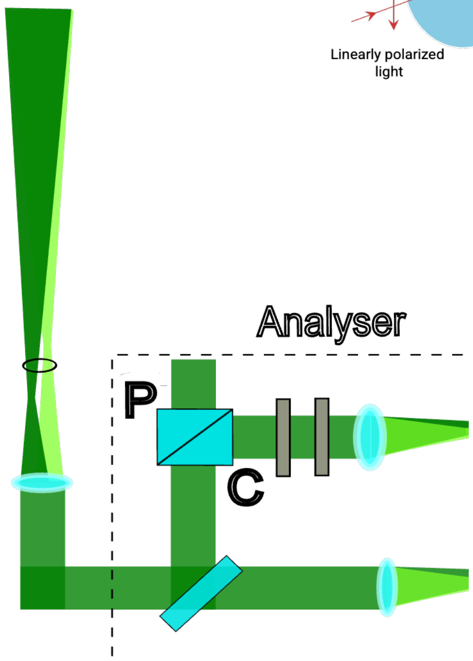
Analyser - Recap



Dichroic Mirror Groups Application

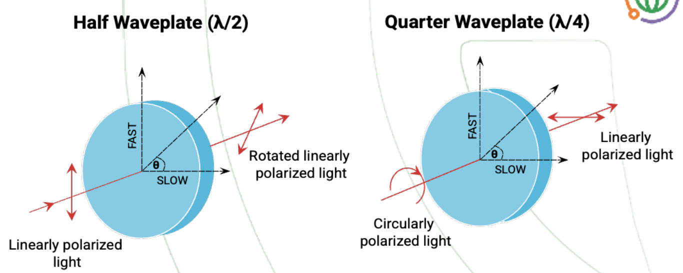


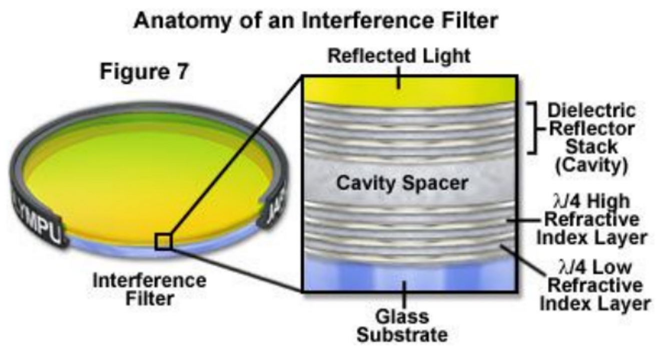
Dichroic 1: Transmit Red, Reflect Blue
Dichroic 2: Transmit Green, Reflect Red and Blue

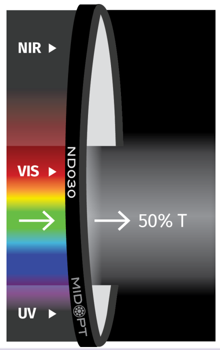


Copyright: Michael Haimerl

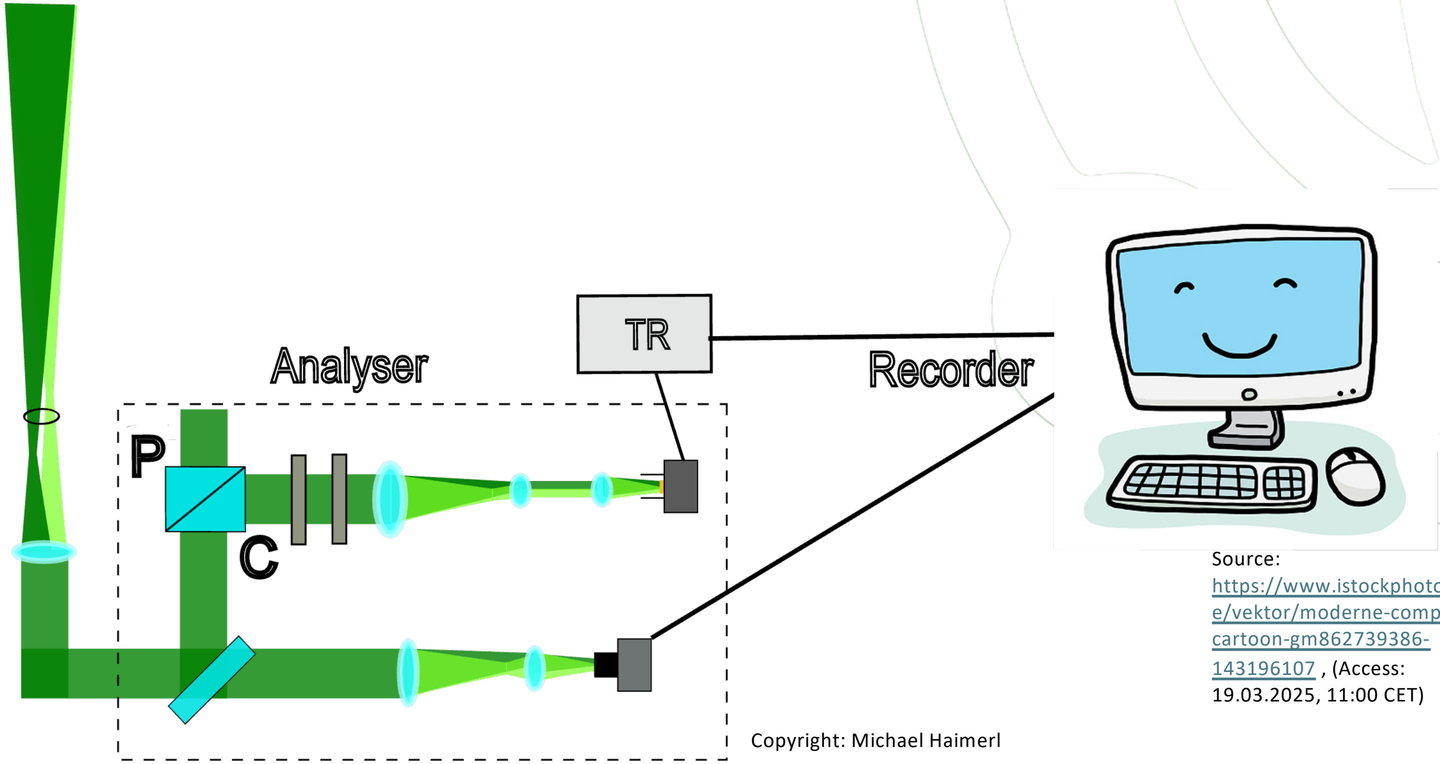
Waveplates







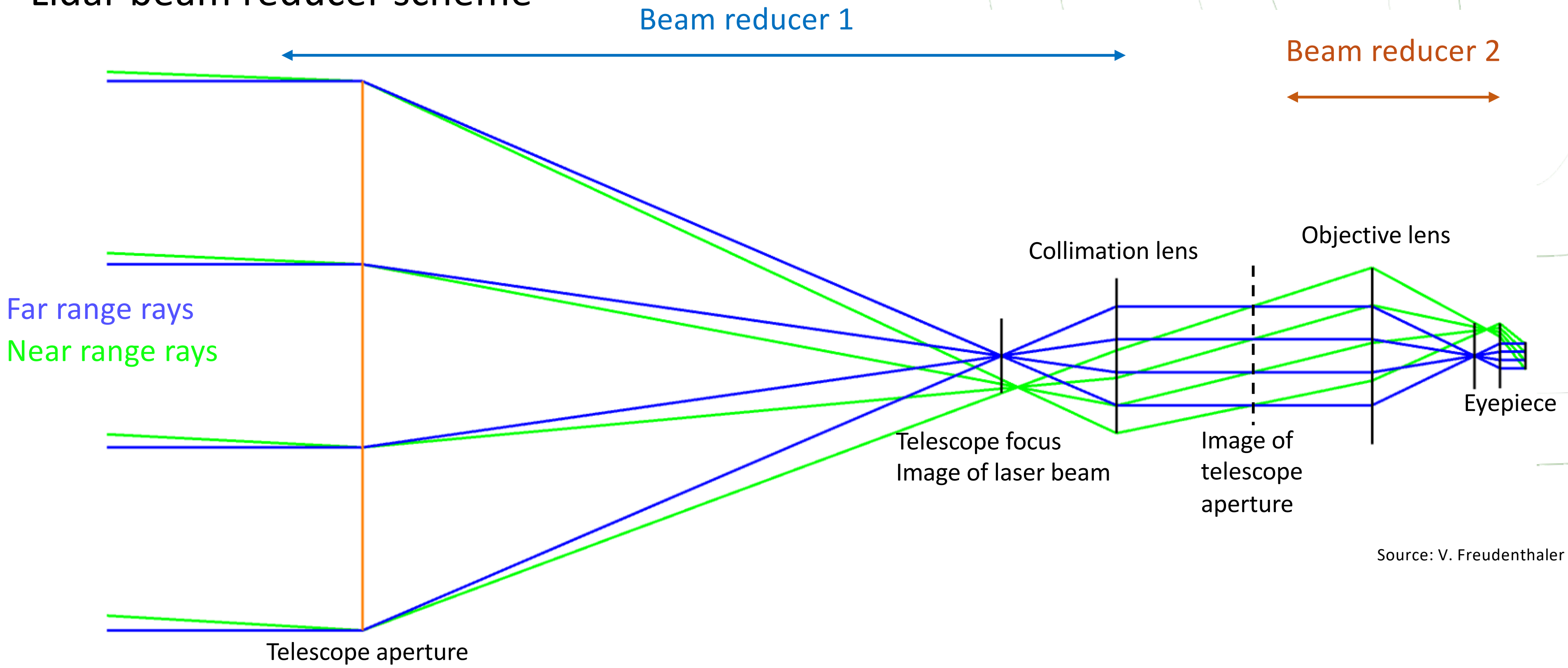
Recorder



Source:
https://www.istockphoto.com/de/vektor/moderne-computer-cartoon-gm862739386-143196107 , (Access: 19.03.2025, 11:00 CET)

Recorder – Light path

Lidar beam reducer scheme

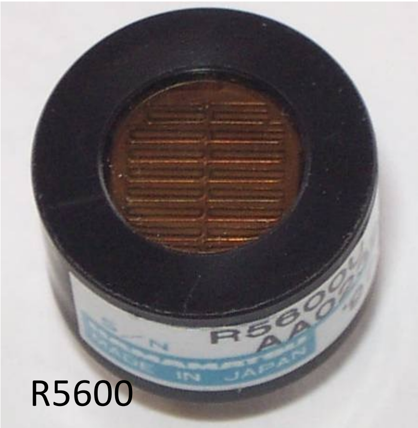


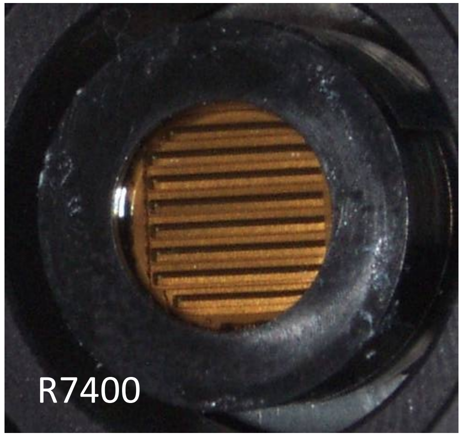
Source: V. Freudenthaler

Recorder - Detectors

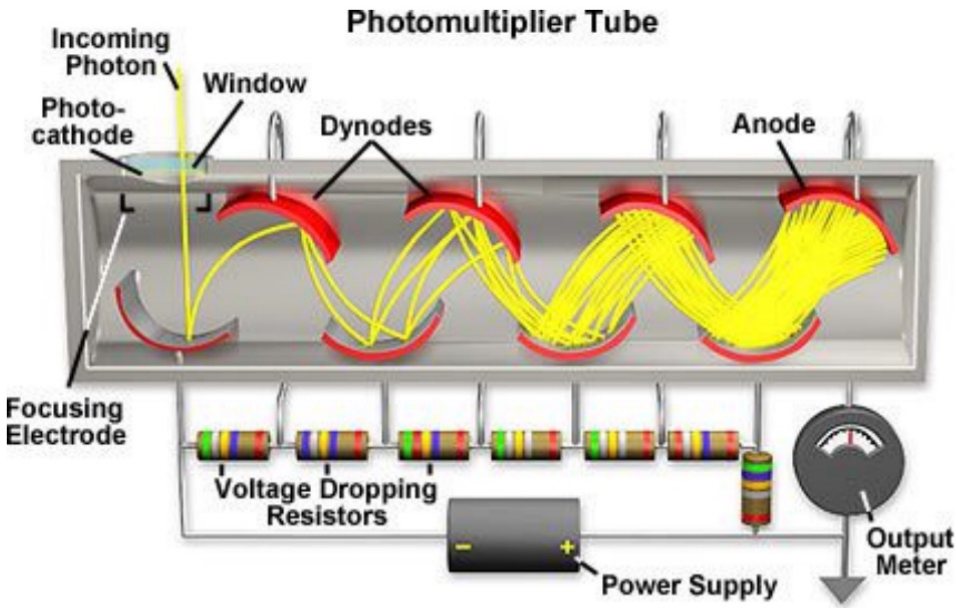
Photomultiplier tube (PMT)

Hamamatsu PMTs





Source: V. Freudenthaler

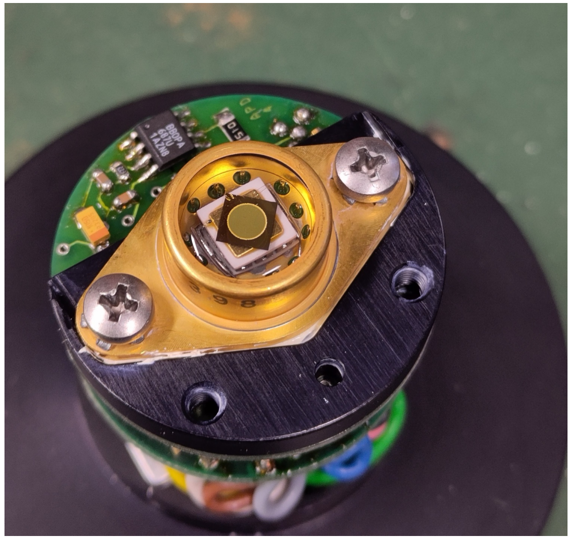


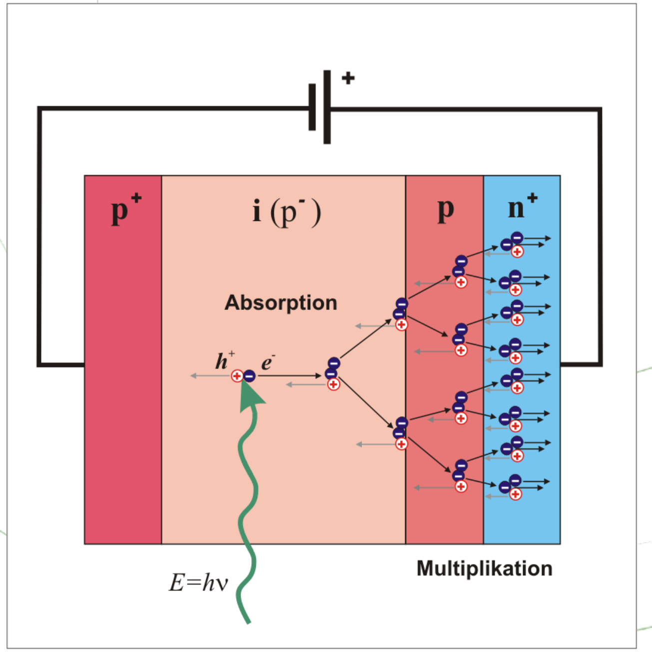
Source: V. Freudenthaler

- **High internal signal gain** -> no preamplification before transient recorder needed
- **Voltage dividers** can add **non-linearities** to the signal -> need to be optimized for lidar purposes
- Operated in **analogue** (high signal intensities) and **photo-counting** (low signal intensities) mode

Recorder – Light path

Avalanche photo diode (APD)





Source: https://de.wikipedia.org/wiki/Avalanche-Photodiode#/media/Datei:APD3_German.png , (Access: 05.05.2025, 10:30 CET)

- **Low internal signal gain** -> preamplification before transient recorder needed
  -> more susceptible to external interspersions (e.g. oscillating EM-fields) than PMTs
- Operated only in **analogue** mode
- Only used for 1064 nm due to higher quantum efficiency for this wavelength compared to PMTs

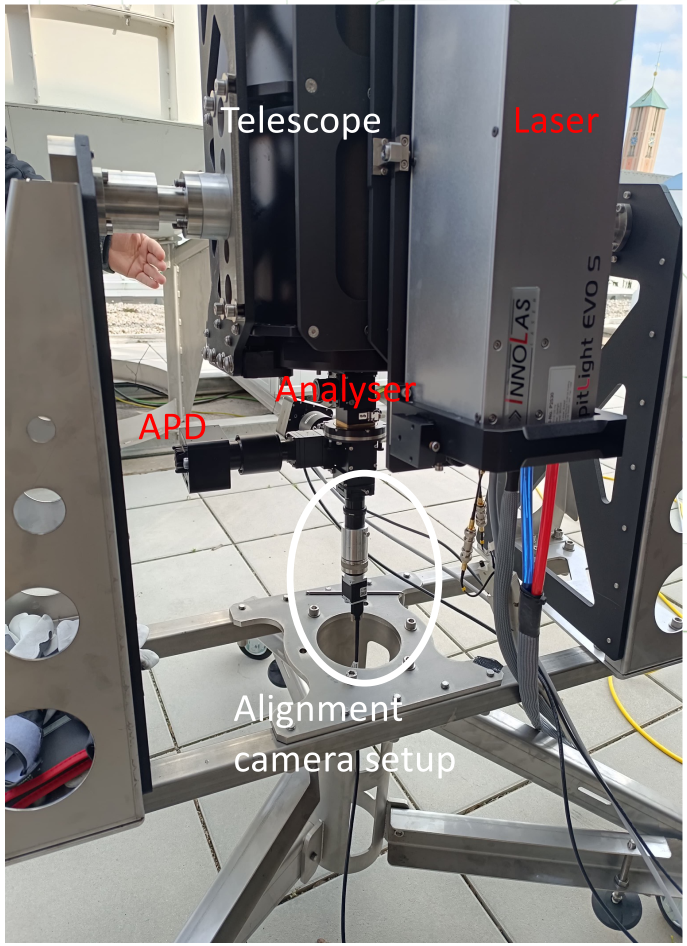
Recorder – Light path

Alignment camera

Source: https://www.baslerweb.com/de-de/shop/a2a1280-80gmswir/ , (Access: 05.05.2025, 10:30 CET)

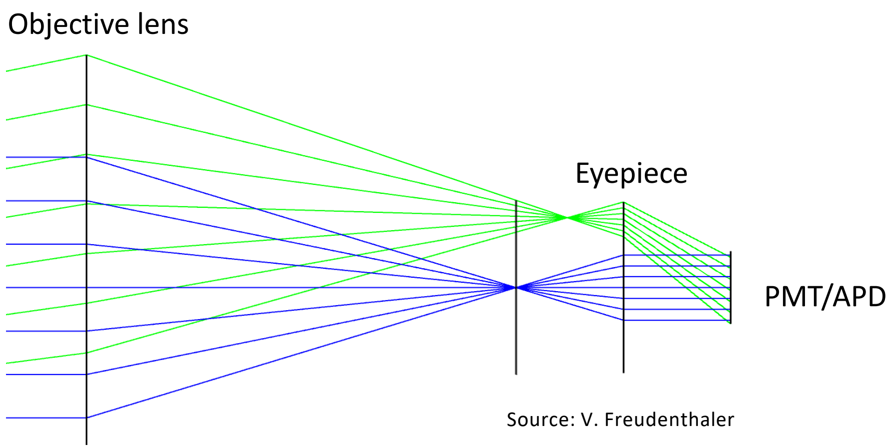
Why?:

- Align laser together with telescope
- Find misalignment in the optical system

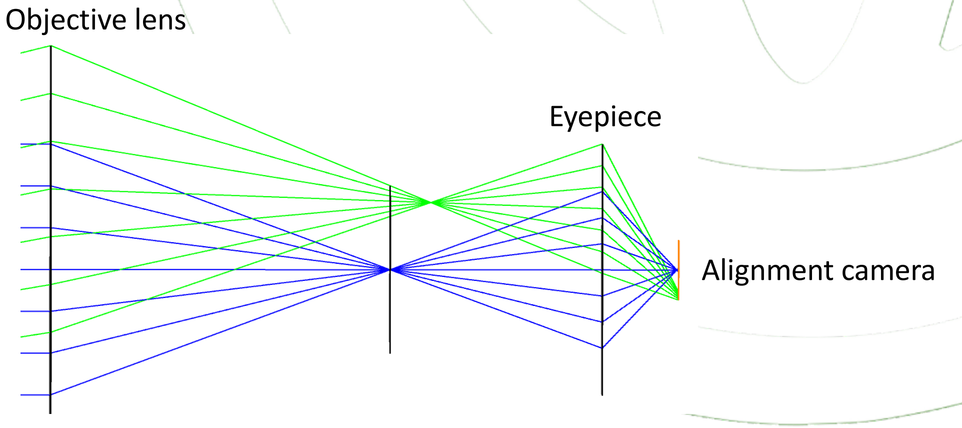


Recorder – Light path

Detectors: PMT/APD vs. alignments camera



Source: V. Freudenthaler



Source: V. Freudenthaler

Far range rays
Near range rays

-> Image of telescope aperture on PMT/APD

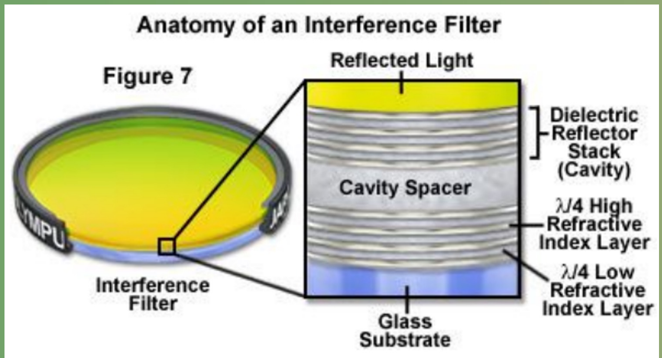
-> Eyepiece defocused
-> Image of telescope focus (laser beam) on PMT/APD

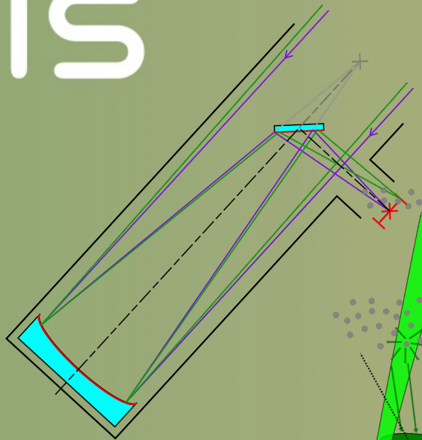
Questions?

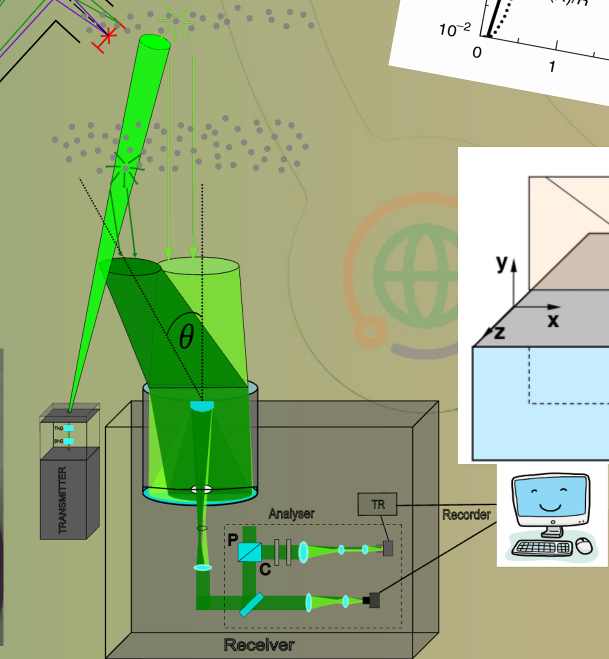
Recommended literature:

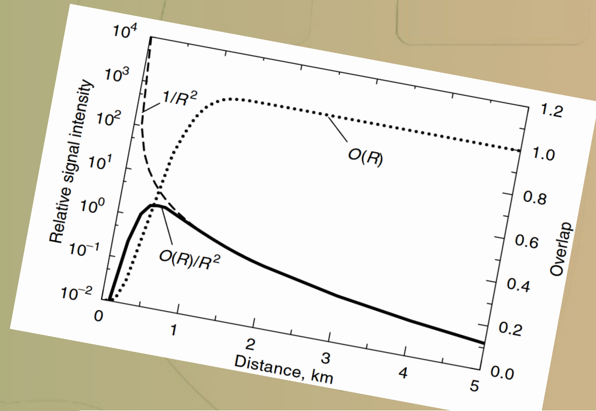
- C. Weitkamp: Lidar, Range-Resolved Optical Remote Sensing of the Atmosphere, Springer, 2005

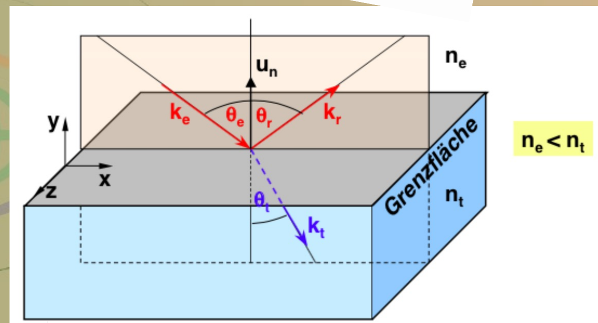
ITINERIS











THANKS!

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Italiadomani