DEP. OF SIGNAL THEORY AND COMMUNICATIONS

Chap.7. Raman Systems

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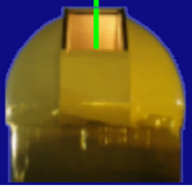
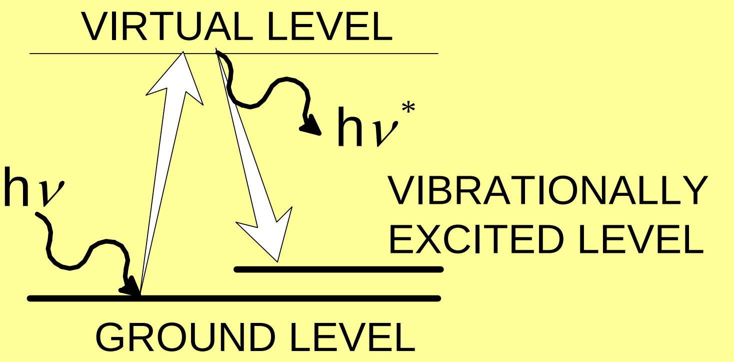


RAMAN LIDAR

MEASUREMENTS:

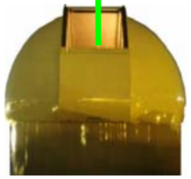
- Direct: Concentration of chemical species in the atmosphere such as
  SO_2, NO, CO, H_2S, C_2H_4, CH_4, H_2CO, H_2O, N_2, O_2...
- Indirect: Temperature, Humidity, α, β, S_M

INELASTIC INTERACTION

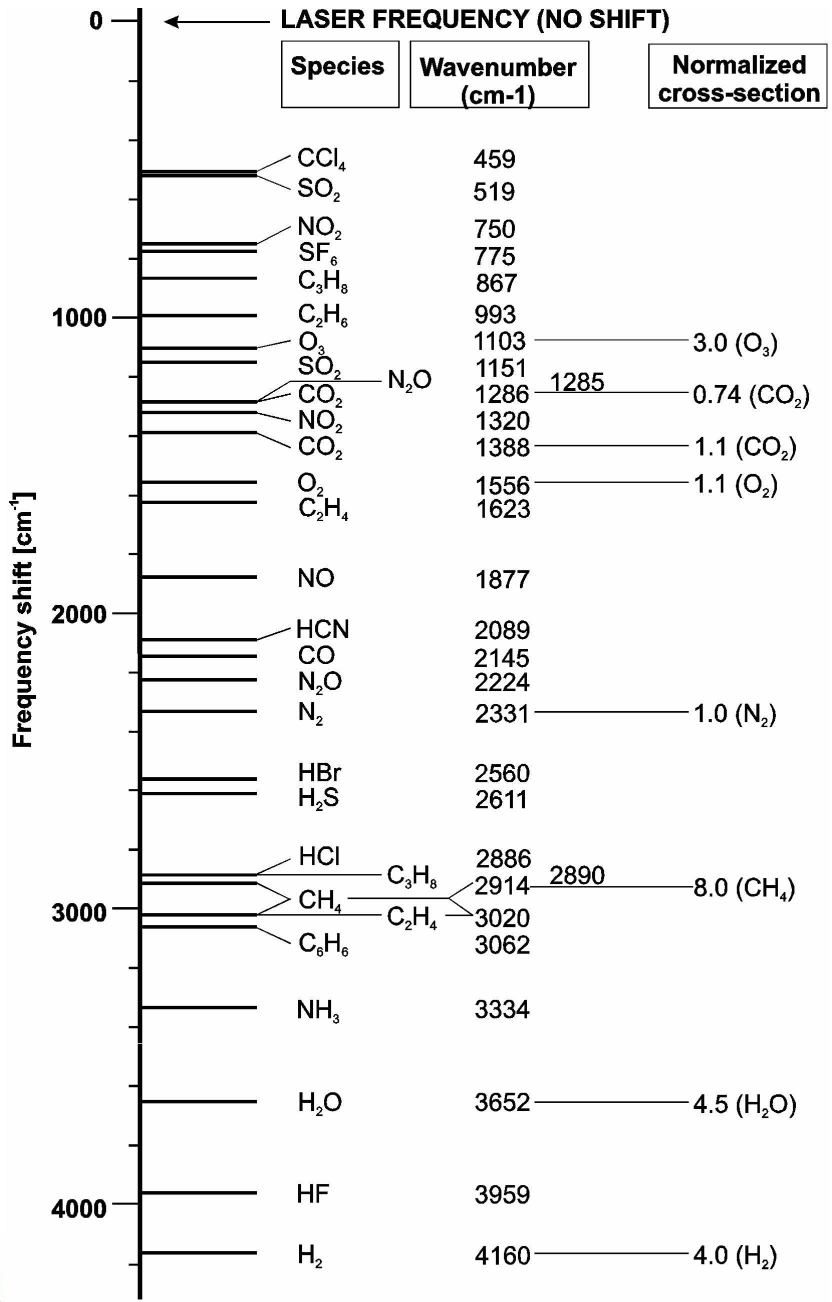


LASER TYPES:

- Ruby (λ = 694.3 nm, 347.2 nm)
- N_2 (λ = 337 nm)
- Nd:YAG (λ = 1060 nm, 532 nm, 266 nm)
- Excimer (λ ~ 350 nm)



RAMAN LIDAR



OPERATIONAL PRINCIPLE

1) In contrast to elastic systems, the return wavelength, λR, is shifted from the incident one, $\lambda 0$.

2) Wavelength shift, κ, depends on each molecular species.

$$\lambda_R = \frac{\lambda_0}{1-\kappa\lambda_0}$$

3) Very faint returns.

- *requires photon counting*
- *very often, night-time operation*

Fig. ADAPTED FROM: Inaba, H. Detection of Atoms and Molecules by Raman Scattering and Resonance Fluorescence. In *Laser Monitoring of the Atmosphere,* Hinkley, E. D., Ed.; Springer-Verlag: New York, 1976; Chap. 5, 153-236.

RAMAN SPECTRUM CHARACTERISTICS

The Raman shift, κ:

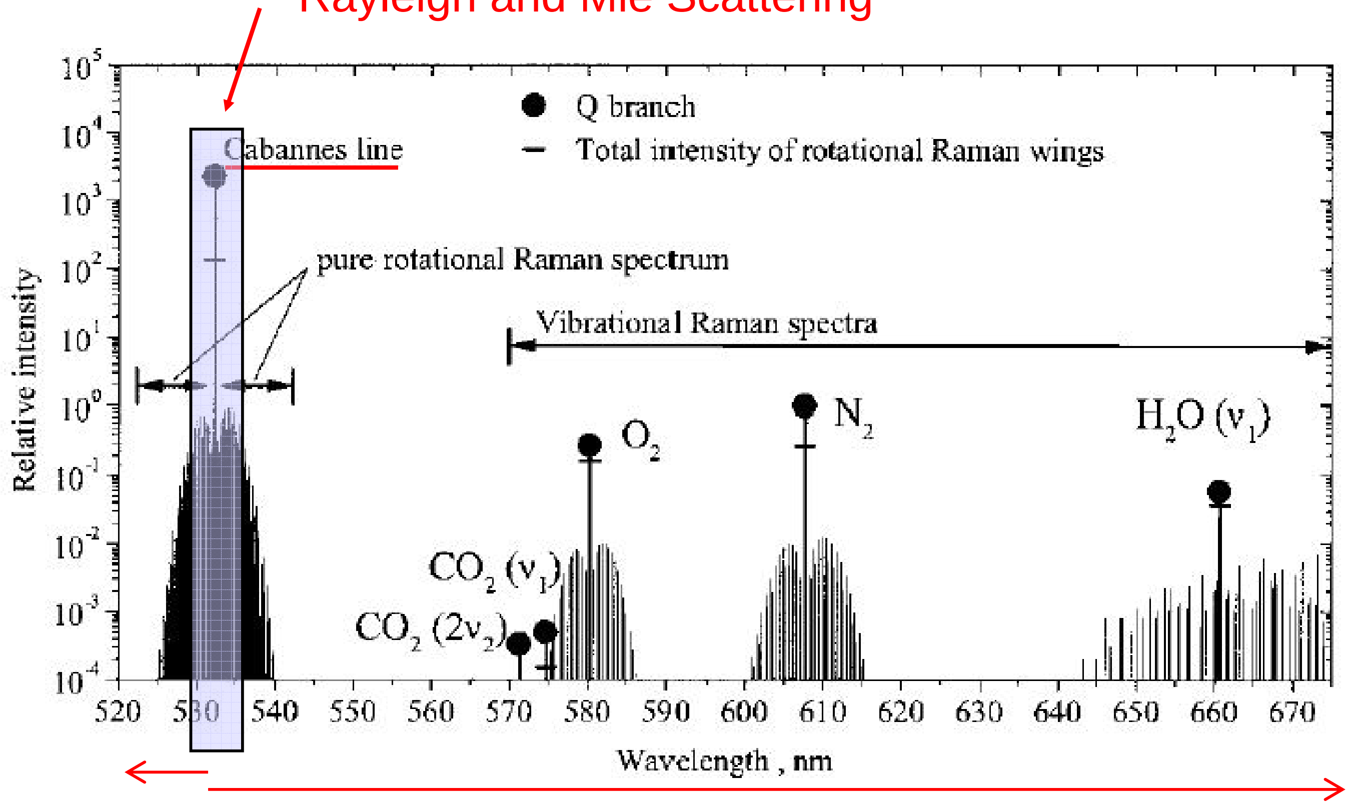
1) does not depend on the excitation wavelength λ_0 and,

2) it is specific of the chemical species

A) Laser need not be tunable

B) The Raman spectrum is characteristic of each molecule

C) Conveys temperature info.



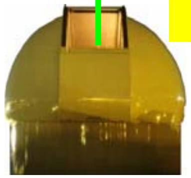
Rayleigh and Mie Scattering

Anti-Stokes

Stokes lines

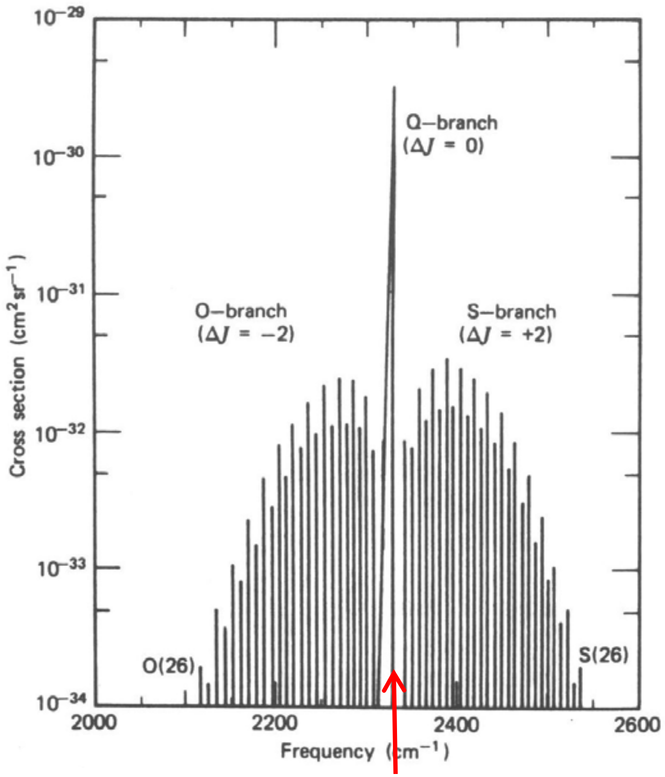
Overview of the lidar backscatter signals for 532-nm laser excitation wavelength.

Fig. SOURCE: Behrendt, A., et al., “Combined Raman lidar for the measurement of atmospheric temperature, water vapor, particle extinction coefficient, and particle backscatter coefficient”, *Appl. Opt.* **41** (36), 7657-7666, (2002).



RAMAN LIDAR

KEY CONCEPTS



Common Raman shifts:

N_2	2331 cm^{-1}	H_2O	3654 cm^{-1}
O_2	1556 cm^{-1}		

Fig. SOURCE: Inaba, H. Detection of Atoms and Molecules by Raman Scattering and Resonance Fluorescence. In *Laser Monitoring of the Atmosphere,* Hinkley, E. D., Ed.; Springer-Verlag: New York, 1976; Chap. 5, p.162.

1) Raman components

- *Stokes lines*
  - – molecule gains energy from the radiation field
  - – scattered radiation is at $\lambda_R > \lambda_0$
- *Anti-Stokes lines* ($\lambda_R < \lambda_0$)

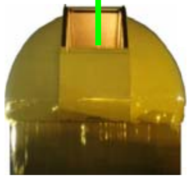
2) Motivation for the “wavenumber” concept (with κ, the Raman shift):

$$\frac{1}{\lambda_R} = \frac{1}{\lambda_0} - \kappa, \quad \kappa\left[\mathrm{cm}^{-1}\right]$$

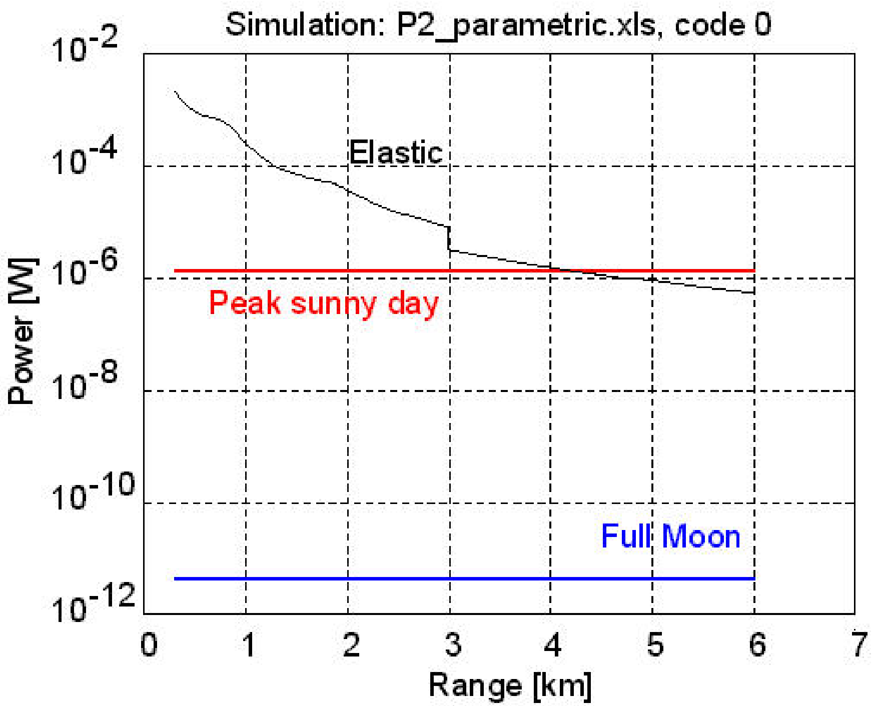
3) Raman cross-sections

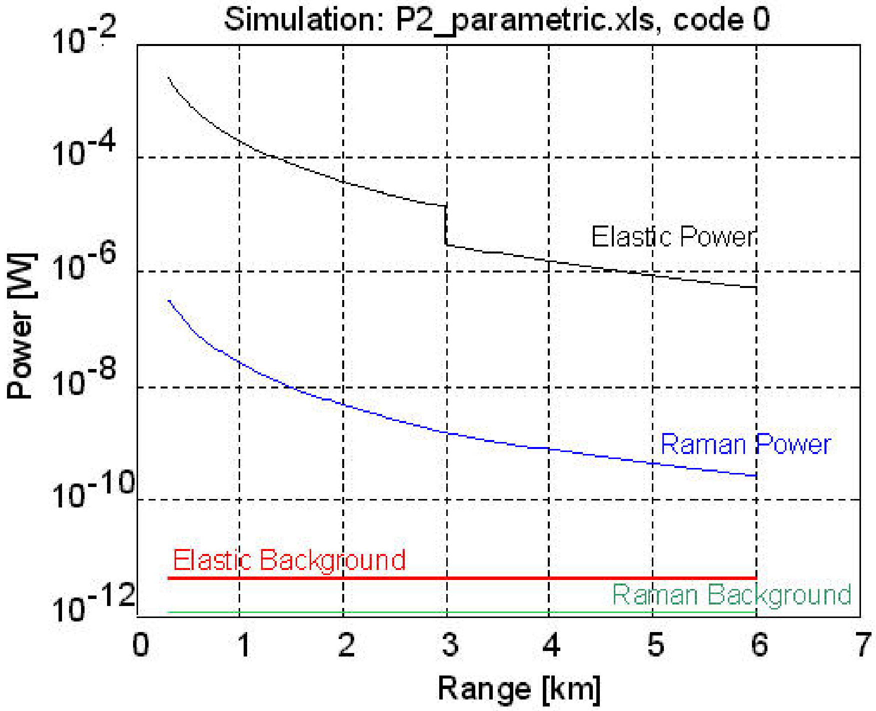
- *dependency* $\propto \lambda^{-4}$

$$\left.\frac{d\sigma(\pi)}{d\Omega}\right|_{Raman} \approx 10^{-3,-4} \left.\frac{d\sigma(\pi)}{d\Omega}\right|_{Ray}$$

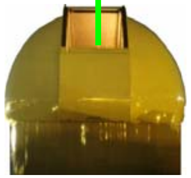


RAMAN LIDAR LINK-BUDGET

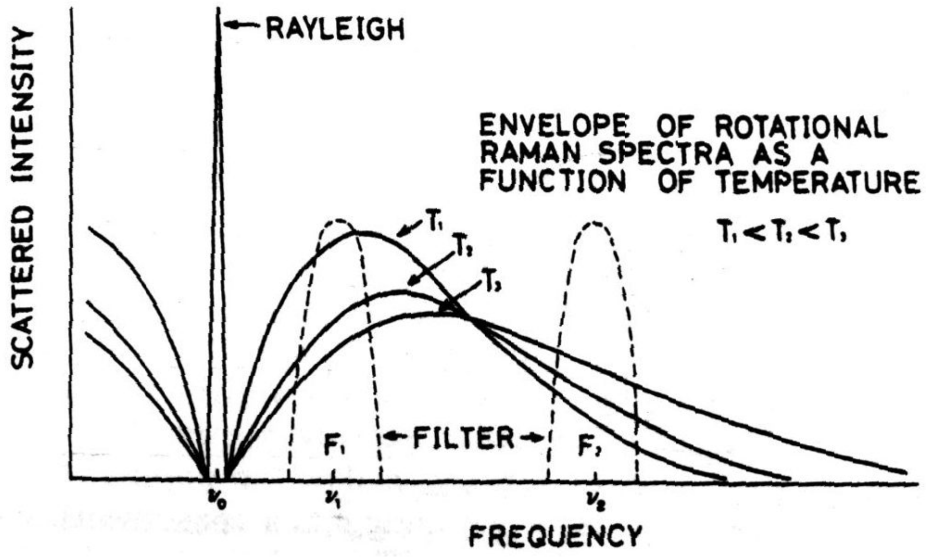




CATEGORY	PARAMETER	VALUE (CODE 0)	UNITS
LASER	Energy	160	mJ
	PRF	20	Hz
TELESCOPE	Primary lens diameter	0,2032	m
ELASTIC CHANNEL	PHOTODIODE, Multiplication factor	150	no units
	PHOTODIODE, Excess-noise factor	4,5	no units
RAMAN CHANNEL	INTERFERENCE FILTER, bandwidth	3	nm
	PMT, Multiplication factor	3,00E+06	no units
	Anode dark current	1	nA
	Anode radiant sensitivity	3,00E+04	A/W
ATMOSPHERE	Visibility margin	39,12	km
	Lidar ratio, SM	25	sr
	Boundary-layer height	3	km
	System operation (question 2)	night-time	



TEMPERATURE MEASUREMENT (I)



KEY

Raman signatures are direct measures of the relative populations among the internal molecular modes

- (In termal equilibrium) → fundamental def. of temperature

Fig. SOURCE: Inaba, H. Detection of Atoms and Molecules by Raman Scattering and Resonance Fluorescence. In *Laser Monitoring of the Atmosphere,* Hinkley, E. D., Ed.; Springer-Verlag: New York, 1976; Chap. 5, 153-236.

METHODS

1) Rotational Raman (RR)

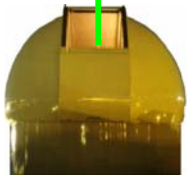
- *Comparison of the envelope shape of all the lines*
- *Intensity ratio of selected spectral regions of the band*

Suitable for atmospheric profiling

2) Vibrational Raman (VR)

- +
- *Intensity ratio between Stokes and anti-Stokes components*
- *Width of a specific Q-branch*

Suitable for high-temperature diagnostics (e.g. flames)



TEMPERATURE MEASUREMENT (II)

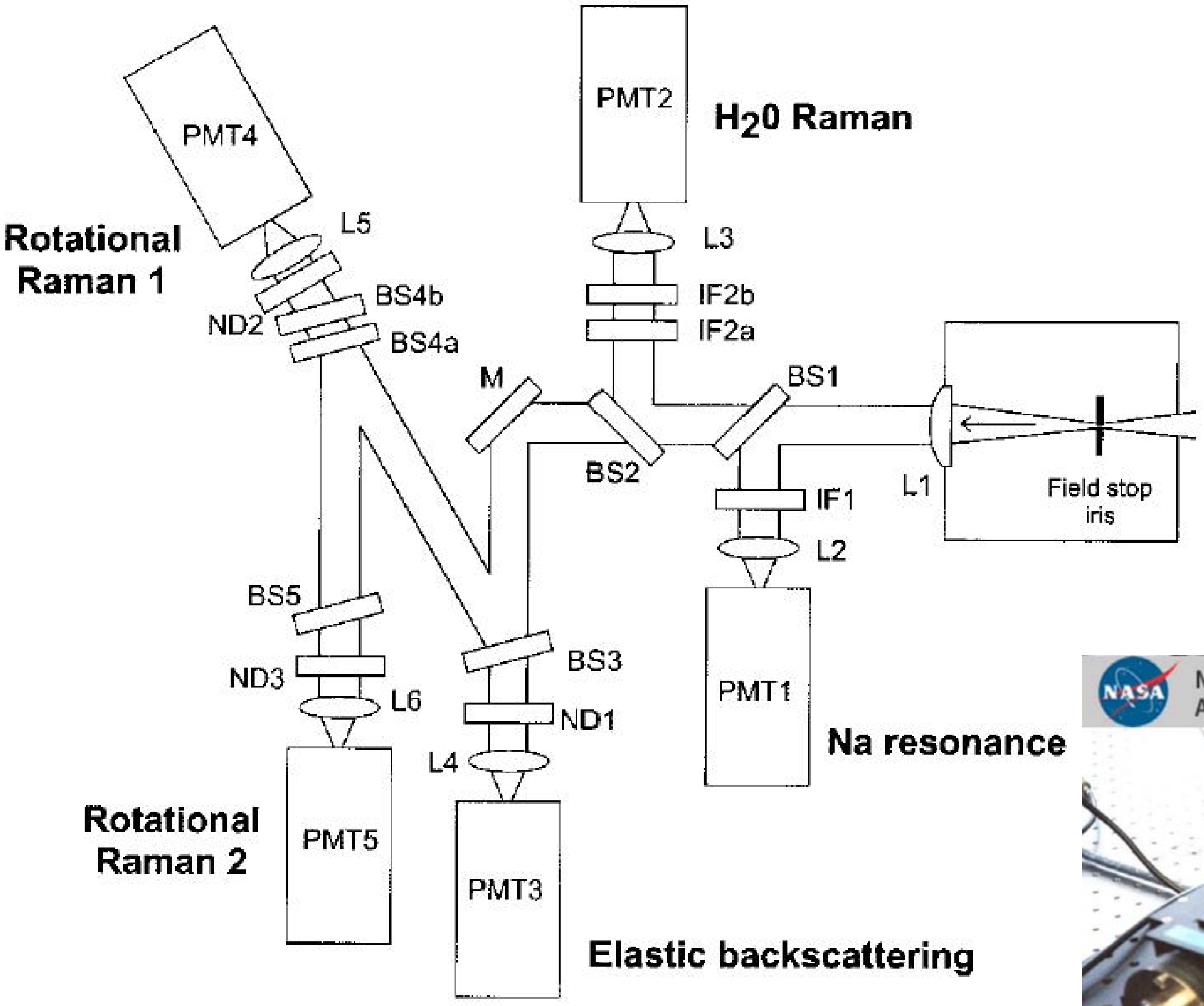


Fig. SOURCE: Behrendt, A., et al., “Combined Raman lidar for the measurement of atmospheric temperature, water vapor, particle extinction coefficient, and particle backscatter coefficient”, *Appl. Opt.* **41** (36), 7657-7666, (2002).

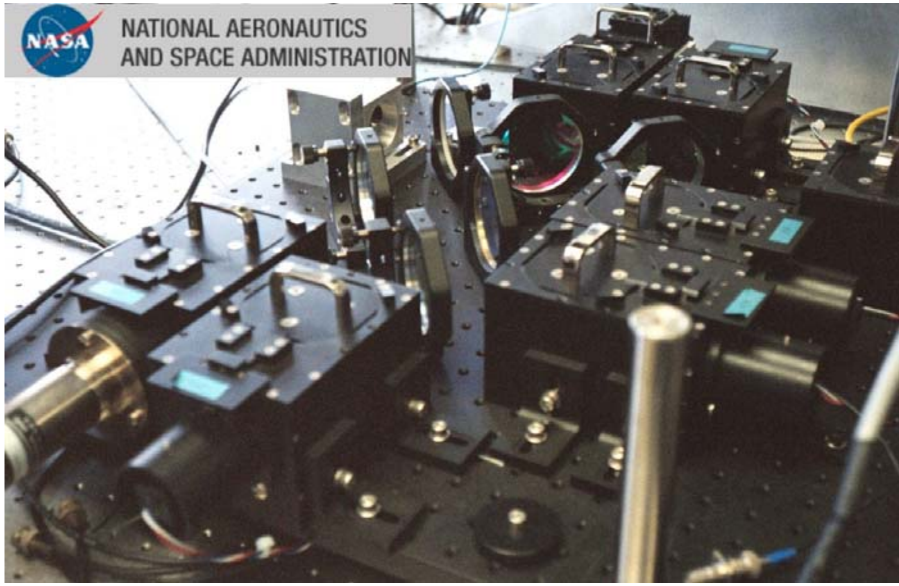
RASC (GKSS) lidar

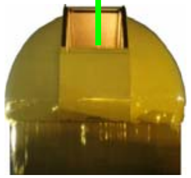
1) T (temperature)

2) WV (water vapor mixing ratio)

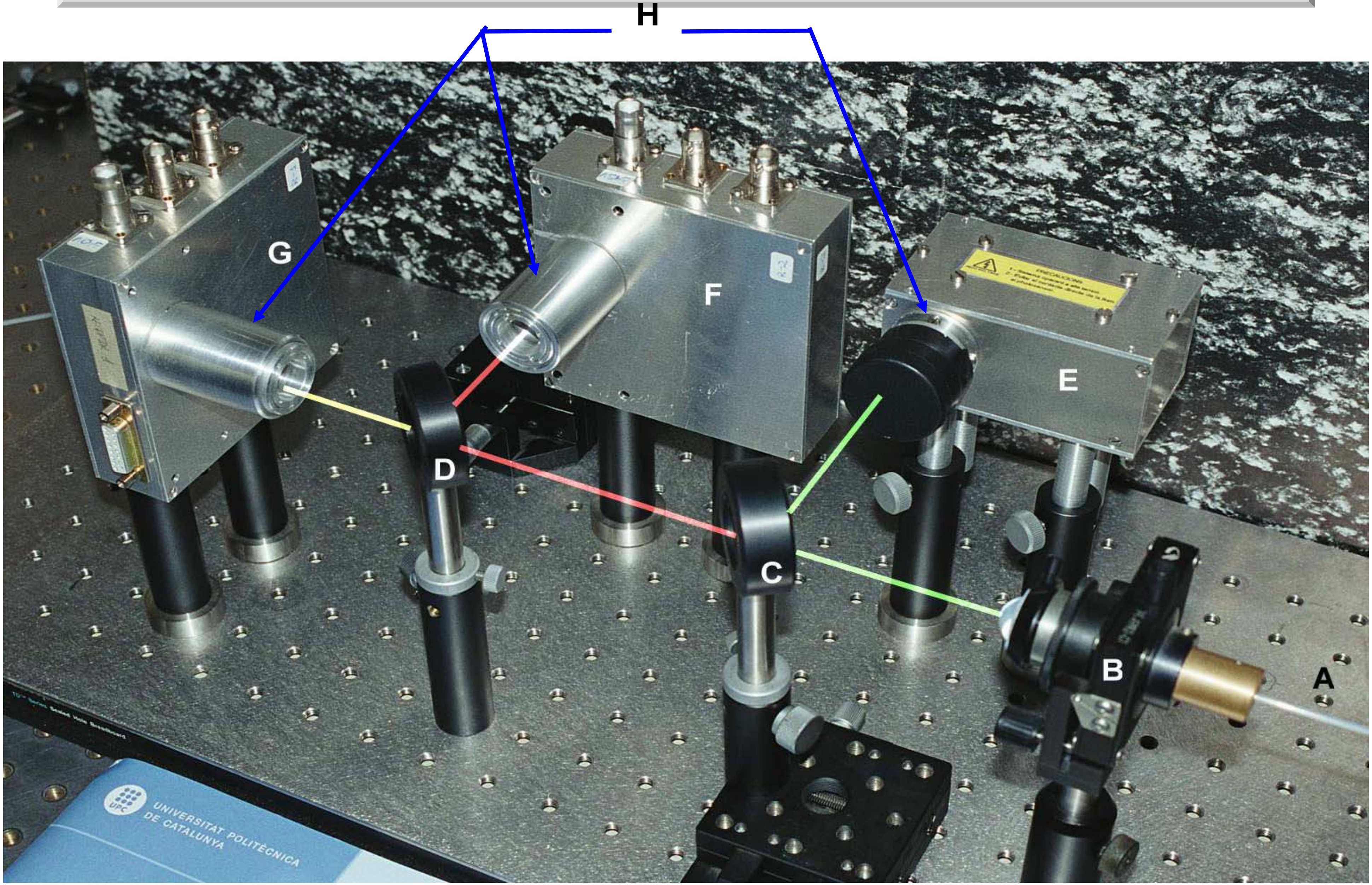
3) α, β, S_M

4) RH (humidity)



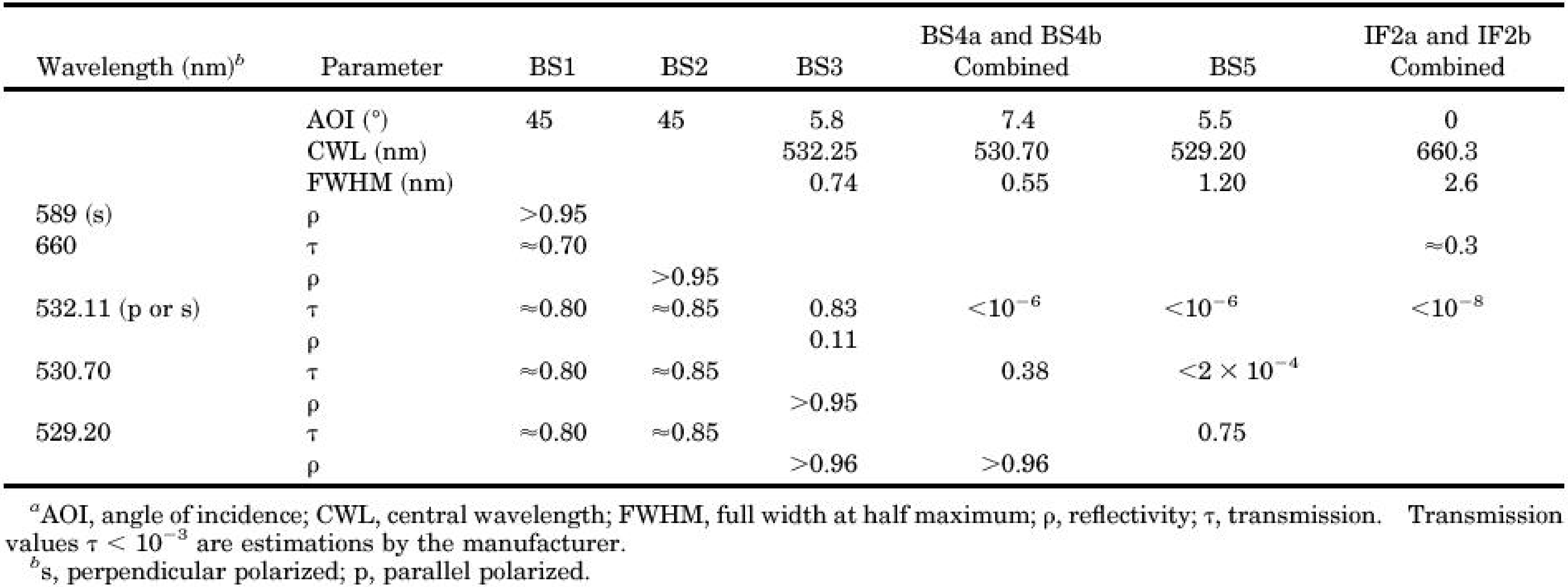


UPC POLYCROMATOR TEST LAYOUT



TEMPERATURE MEASUREMENT (III)

DISCUSSION PARAMETERS (RASC lidar LAYOUT)



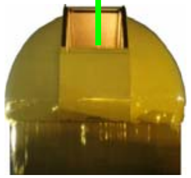
Wavelength (nm)[b]	Parameter	BS1	BS2	BS3	BS4a and BS4b Combined	BS5	IF2a and IF2b Combined
	AOI (°)	45	45	5.8	7.4	5.5	0
	CWL (nm)			532.25	530.70	529.20	660.3
	FWHM (nm)			0.74	0.55	1.20	2.6
589 (s)	ρ	>0.95					
660	τ	≈0.70					≈0.3
	ρ		>0.95				
532.11 (p or s)	τ	≈0.80	≈0.85	0.83	$<10^{-6}$	$<10^{-6}$	$<10^{-8}$
	ρ			0.11			
530.70	τ	≈0.80	≈0.85		0.38	$<2 \times 10^{-4}$	
	ρ			>0.95			
529.20	τ	≈0.80	≈0.85			0.75	
	ρ			>0.96	>0.96		

[a] AOI, angle of incidence; CWL, central wavelength; FWHM, full width at half maximum; ρ, reflectivity; τ, transmission. Transmission values $\tau < 10^{-3}$ are estimations by the manufacturer.
[b] s, perpendicular polarized; p, parallel polarized.

Note:

ND filters are used to cope with saturation effects in the RR channels in the lower troposfere (correction of photon-counter receiver dead-time effects).

Tab. SOURCE: Behrendt, A., et al., "Combined Raman lidar for the measurement of atmospheric temperature, water vapor, particle extinction coefficient, and particle backscatter coefficient", *Appl. Opt.* **41** (36), 7657-7666, (2002).



TEMPERATURE MEASUREMENT (IV)

Specific RR Temperature approaches:

Use of two RR channels with opposite temperature dependency

- *+ 3rd RR channel (isosbestic point) as reference or,*
- *combine them to obtain a temperature-indep. reference*

$$Q(T) = \frac{N_{RR2}(T)}{N_{RR1}(T)}$$

$$N_{ref}(z) = N_{RR1}(z) + cN_{RR2}(z)$$

- *calibrate Q(T) with a radiosonde*
  - find c for minimum temp. variation

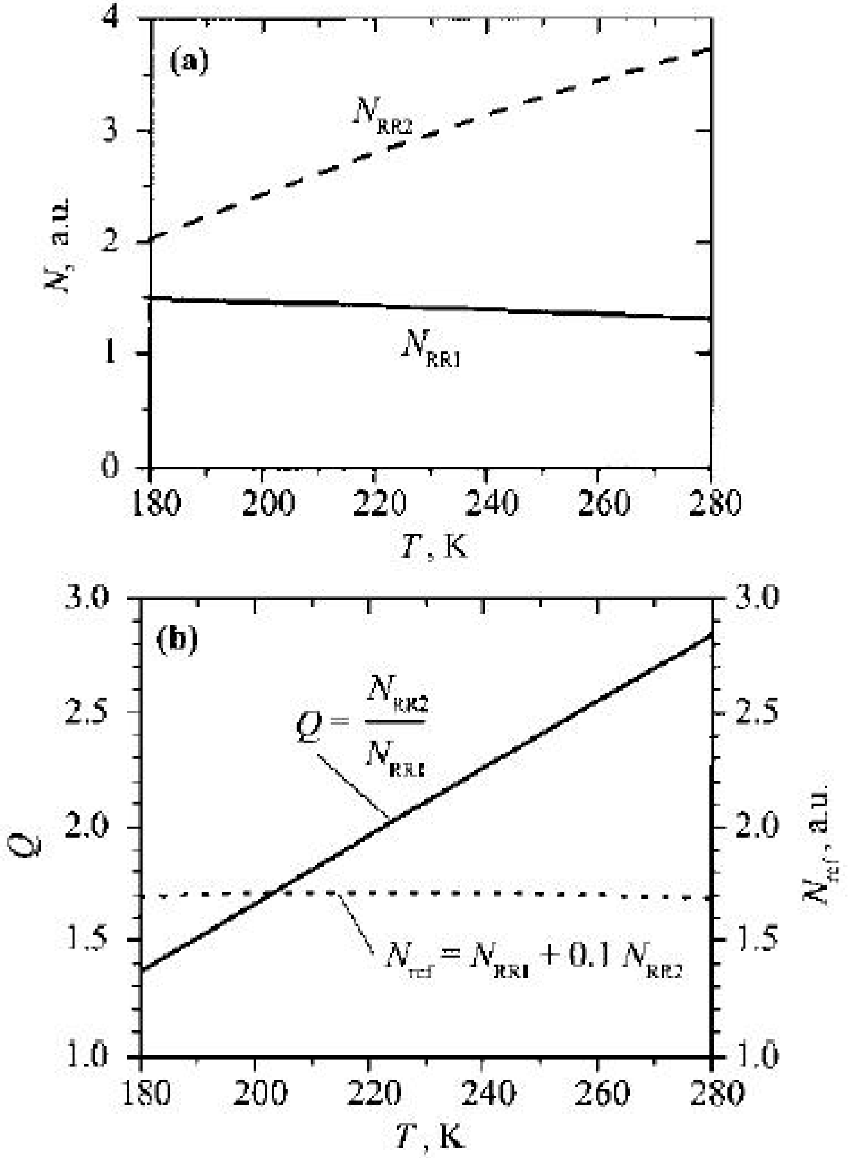
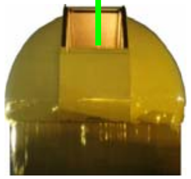
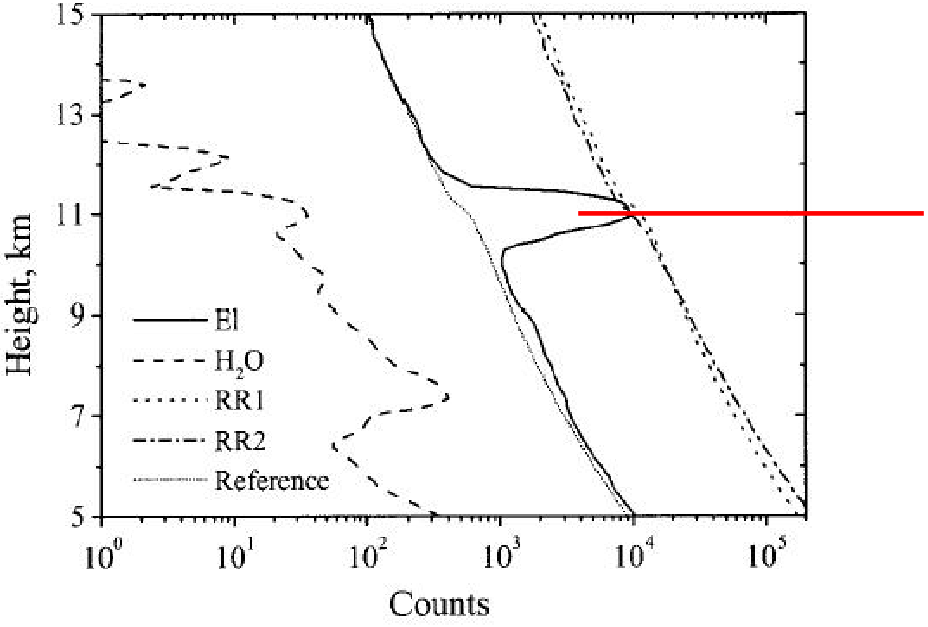
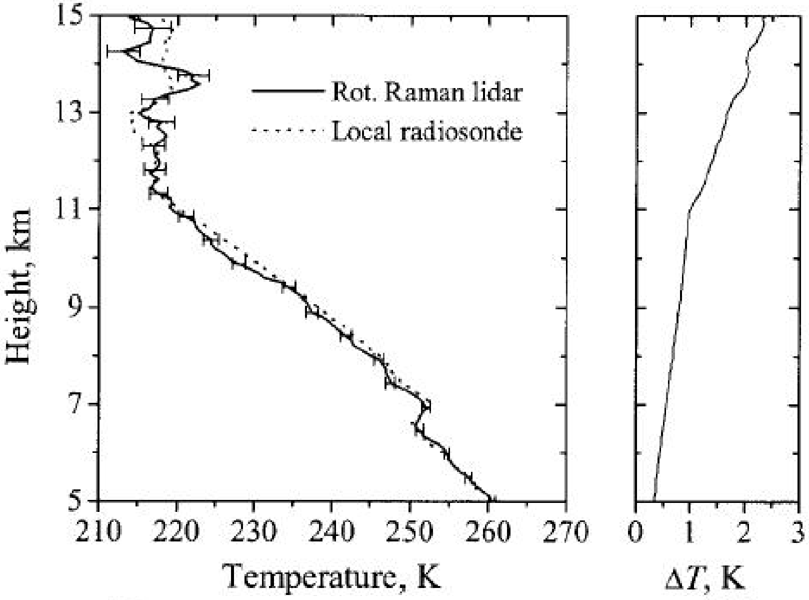


Fig. SOURCE: Behrendt, A., et al., “Combined Raman lidar for the measurement of atmospheric temperature, water vapor, particle extinction coefficient, and particle backscatter coefficient”, *Appl. Opt.* **41** (36), 7657-7666, (2002).



TEMPERATURE MEASUREMENT (V)





<u>Problem:</u> Elastic cross-talk with the RR channel

<u>Action:</u> Calibrate on a cirrus cloud using

$$Q(T) = \frac{N_{RR2}(T)}{N_{RR1}(T) - \varepsilon N_{El}(z)}$$

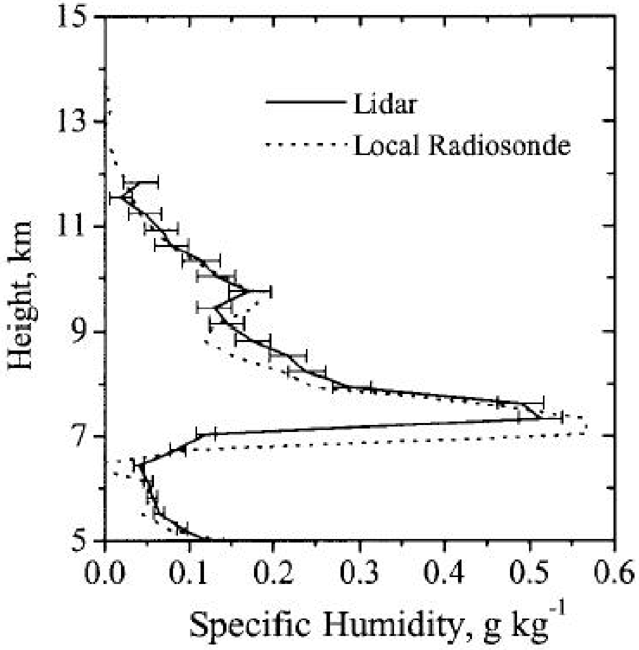
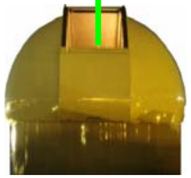


Fig. SOURCE: Behrendt, A., et al., “Combined Raman lidar for the measurement of atmospheric temperature, water vapor, particle extinction coefficient, and particle backscatter coefficient”, *Appl. Opt.* **41** (36), 7657-7666, (2002).



MOLECULAR SPECIES (GAS) DETECTION (I)

CONCEPTS:

1) The absolute concetration of each molecular species can be performed by comparing the Raman backscattered intensity with that of the Raman line from N_2 which occupy the same volume.

1A) Raman-backscattered signal:

$$P_{\lambda_R}(R) = K_{\lambda_R}\frac{O(R)}{R^2}F_R(T,\Delta\lambda_R)\left[N_R(R)\frac{d\sigma_{\lambda_R}(\pi)}{d\Omega}\right]\times\exp\left\{-\int_0^R\left[\alpha^{tot}_{\lambda_0}(\xi)+\alpha^{tot}_{\lambda_R}(\xi)\right]d\xi\right\}$$

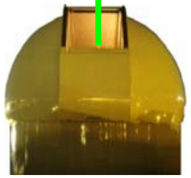
1B) (Oversimplified) Gas-to-N_2 normalised ratio

$$\frac{P_{\lambda_X}(R)}{P_{\lambda_N}(R)} = \cancel{\frac{O_X(R)}{O_N(R)}}\,\cancel{\frac{F_X(T,\Delta\lambda_X)}{F_N(T,\Delta\lambda_N)}}\,\frac{N_X(R)}{N_N(R)}\overbrace{\left[\frac{d\sigma_{\lambda_X}(\pi)/d\Omega}{d\sigma_{\lambda_N}(\pi)/d\Omega}\right]}^{N_2\text{-normalised cross section}}\cancel{\frac{\xi(\lambda_X)}{\xi(\lambda_N)}}\,\cancel{\Delta\tau(\lambda_X,\lambda_N,R)},$$

solve for $N_x(R)$

known (US-std model, radiosonde)

$$\text{where}\quad \Delta\tau(\lambda_X,\lambda_N,R) = \exp\left\{-\int_0^R\left[\alpha^{tot}_{\lambda_X}(\xi)-\alpha^{tot}_{\lambda_N}(\xi)\right]d\xi\right\}$$



(C) F. Rocadenbosch 2005-2006

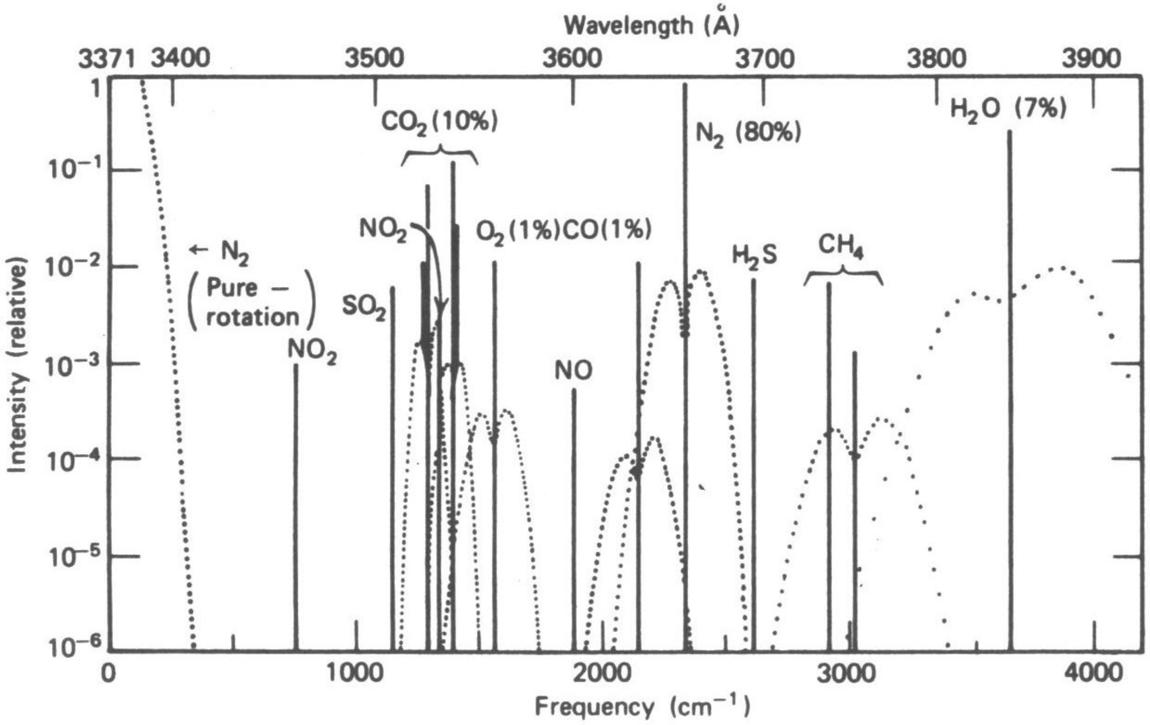
MOLECULAR SPECIES (GAS) DETECTION (II)

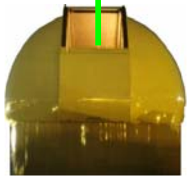
1C) (Estimation of the) **Differential Transmission term:**

- *Molecular extinction → US-std. atmosphere model + radiosonde*
- *Aerosol extinction → Cooperative elastic-Raman channel (N2)*
  - Only in hazy conditions (See Elastic-Raman inversion Sect. in Chap.7)
- *Angström coefficient → E.g. Sun photometer calibration*

2) The (VR) spectrum is preferred to the (RR)

- *RR lines of major atmospheric constituents overlap,*
- *large Rayleigh-Mie cross-talk.*
- *In contrast, VR cross-sections are usually lower than RR ones.*





MOLECULAR SPECIES (GAS) DETECTION (III)

SOME MEASUREMENT EXAMPLES

- Fig.1 Raman spectroscopy from the ordinary atmosphere
- Fig.2 Molecular species in an oil smoke plume

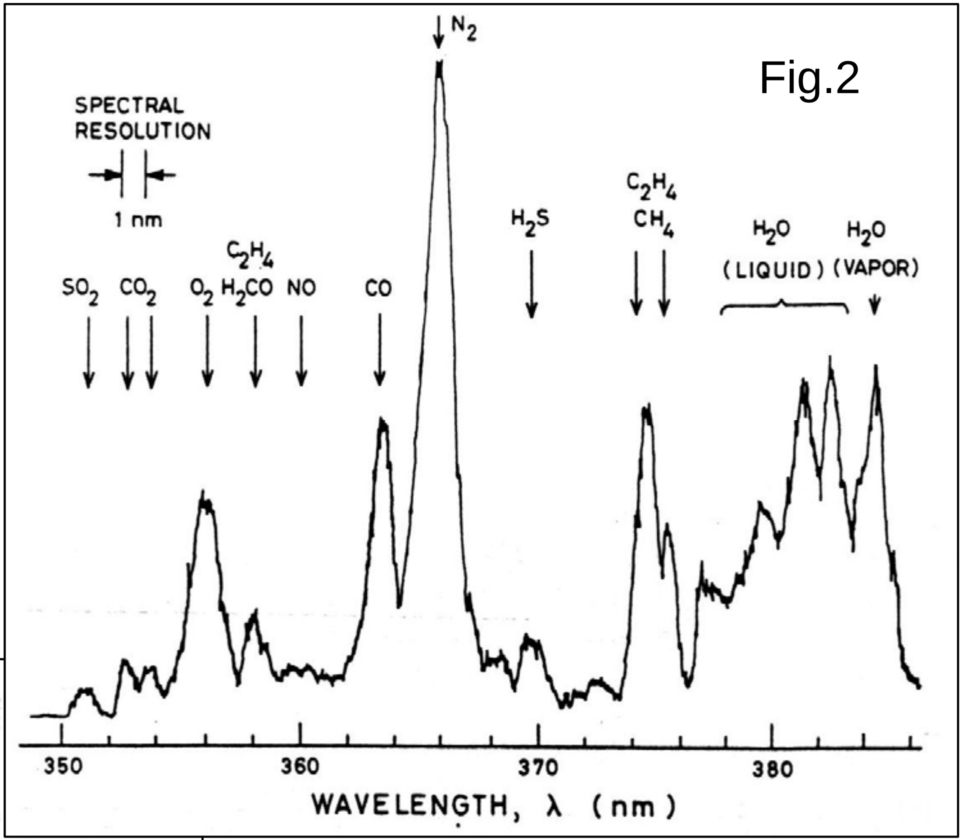


Fig.2

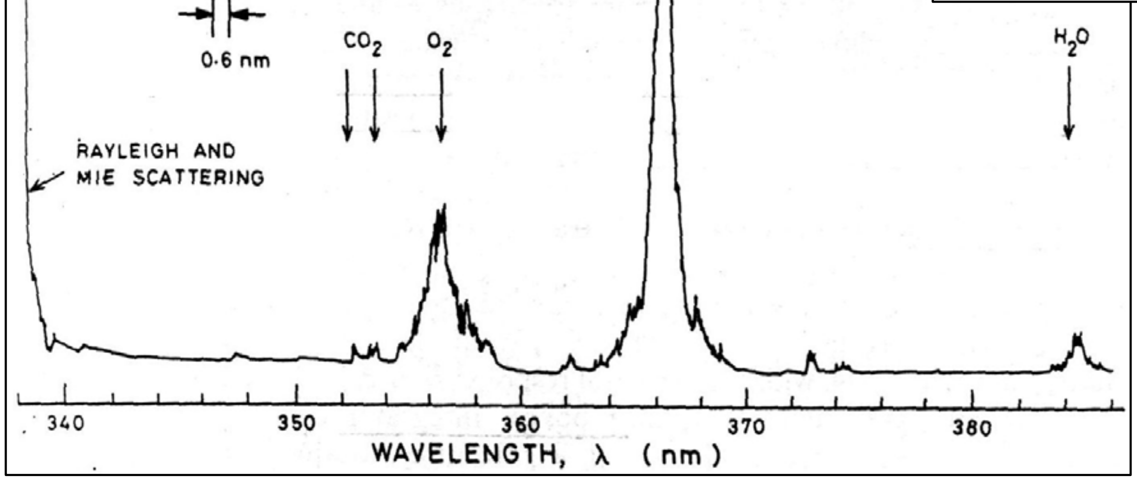
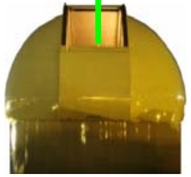


Fig.1

Fig. SOURCE: Inaba and Kobayasi, Opto-Electron 4, 101 (1972).



WATER-VAPOR MEASUREMENT (I)

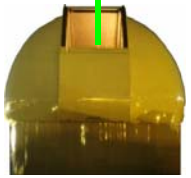
WATER-VAPOR (WV) KEYS:

- *Influences convective stability (likelihood of storm initiation)*
- *Most active green-house gas*
  - it absorbs terrestrial radiation more strongly than does CO_2
- *Water-vapor mixing ratio (w)*

$$w = \frac{MW_{H_2O}}{MW_{DryAir}} \frac{N_{H_2O}(R)}{N_{DryAir}(R)} \approx \frac{MW_{H_2O}}{MW_{DryAir}} \frac{N_{H_2O}(R)}{N_{N_2}(R)/0.78} \approx 0.485 \frac{N_{H_2O}(R)}{N_{N_2}(R)}$$

  - where MW_x stands for molecular weight (≈ 18g/mol for H_2O and ≈ 28.94 g/mol for dry air) and N_x stands for molecule number concentration.

- *Importance of the mixing ratio:*
  - It is conserved in atmospheric processes that do not involve condensation or evaporation
  - Serves well as a tracer of the movement of air parcels in the atmosphere



WATER-VAPOR MEASUREMENT (II)

DERIVATION FROM THE RAMAN CHANNELS

From Eq.(1B) in Slide 12

$$\frac{P_{\lambda_H}(R)}{P_{\lambda_N}(R)} = \frac{O_H(R)}{O_N(R)} \frac{F_H(T,\Delta\lambda_R)}{F_N(T,\Delta\lambda_R)} \frac{N_H(R)}{N_N(R)} \left[\frac{d\sigma_{\lambda_H}(\pi)/d\Omega}{d\sigma_{\lambda_N}(\pi)/d\Omega}\right] \frac{\xi(\lambda_H)}{\xi(\lambda_N)} \Delta\tau(\lambda_H,\lambda_N,R)$$

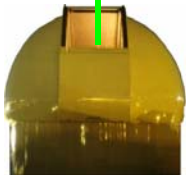
and the definition of the mixing ratio (w)

$$w = \underbrace{\boxed{0{,}485 \frac{O_N(R)}{O_H(R)} \left[\frac{d\sigma_{\lambda_N}(\pi)/d\Omega}{d\sigma_{\lambda_H}(\pi)/d\Omega}\right] \frac{\xi(\lambda_N)}{\xi(\lambda_H)}}}_{\text{System's calibration factor, } k^*(R)} \underbrace{\frac{F_N(T,\Delta\lambda_N)}{F_H(T,\Delta\lambda_H)}}_{\text{Temperature-dependent ratio}} \underbrace{\boxed{\frac{P_H(R)}{P_N(R)} \Delta\tau(\lambda_N,\lambda_H,R)}}_{\text{Measurement factor}}$$

- where $P_x(R)$ are background-substracted quantities.

In summary,

$$w = k_L^*(R) \frac{F_N(T,\Delta\lambda_N)}{F_H(T,\Delta\lambda_H)} R_w(R) \Delta\tau(\lambda_N,\lambda_H,R) \qquad R_w = \frac{P_H(R)}{P_N(R)}$$



WATER-VAPOR MEASUREMENT (III)

EXAMPLE

- *In the UV (λ_L=355 nm), Raman channels: λ_N=387 nm, λ_H=408 nm*

$$w = k_{355}^{*}(R)\frac{F_N(T,\Delta\lambda_N)}{F_H(T,\Delta\lambda_H)}\frac{P_H(R)}{P_N(R)}\Delta\tau(\lambda_N,\lambda_H,R) \qquad k_{355}^{*} \approx 0.22\frac{O_N(R)}{O_H(R)}\frac{\xi(\lambda_N)}{\xi(\lambda_H)}$$

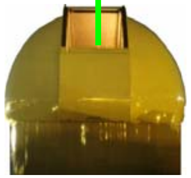
SPECIES	kappa (cm-1)	lambdaR (1) (nm)	lambdaR (2) (nm)
Air	0	→ 354,7	532,1
O2	1556	375,4	580,1
N2	2331	→ 386,7	607,4
H2O	3654	→ 407,5	~~660,5~~
Excitation wavelength (lambda0)			
(1)	354,7	nm (Nd:YAG, THG)	
(2)	532,1	nm (Nd:YAG, SHG)	

Cross sections are computed assuming a λ-4 dependency

i.e. higher in the UV than in the NIR

Water-Vapor Mixing Ratio Error

$$\frac{\sigma_w^2}{w^2} = \frac{\sigma_{k^*}^2}{k^{*2}} + \frac{\sigma_{R_w}^2}{R_w^2} + \frac{\sigma_{\Delta\tau}^2}{\Delta\tau^2} \approx \frac{\sigma_{R_w}^2}{R_w^2}; \qquad R_w = \frac{P_H(R)}{P_N(R)}$$



WATER-VAPOR MEASUREMENT (IV)

ERROR SOURCES AND UNCERTAINTIES

- *Water-Vapor Mixing Ratio Error*

$$\frac{\sigma_w^2}{w^2} = \frac{\sigma_{k^*}^2}{k^{*2}} + \frac{\sigma_{R_w}^2}{R_w^2} + \frac{\sigma_{\Delta\tau}^2}{\Delta\tau^2} \approx \frac{\sigma_{R_w}^2}{R_w^2}; \qquad R_w = \frac{P_H(R)}{P_N(R)}$$

- *k^*: Calibration factor → Can be considered to be small*
  - Calibrated using a radiosonde (e.g. VAISALA RS80-A) or a MW radiometer
- *R_w: Signal-induced statistical error dominates the error budget*
- $\boxed{\Delta\tau(\lambda_N, \lambda_H, R)}$ = *Differential Transmission (DT).*
  - λ_N and λ_H experience different amounts of attenuation on their return trips, caused mainly by Rayleigh scattering. The DT can be calibrated by using

    1) A *radiosonde* estimate the molecular number density (i.e, T(z), P(z))

    2) For hazy atmospheres (DT < 0.9 for $\tau_{PBL} > 2$), the *N_2-Raman channel* is used to estimate the aerosol extinction (typ., λ^{-1} dependence)

    See Sec. Inversion of Optical Parameters / Extinction inversion, $\alpha_{\lambda_H}^{aer}, \alpha_{\lambda_N}^{aer}$

    Note: WV absorbs weakly at λ_H=660 nm ⇒ λ_L=355 nm preferred to 532 nm

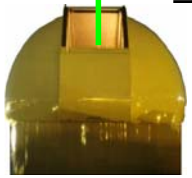
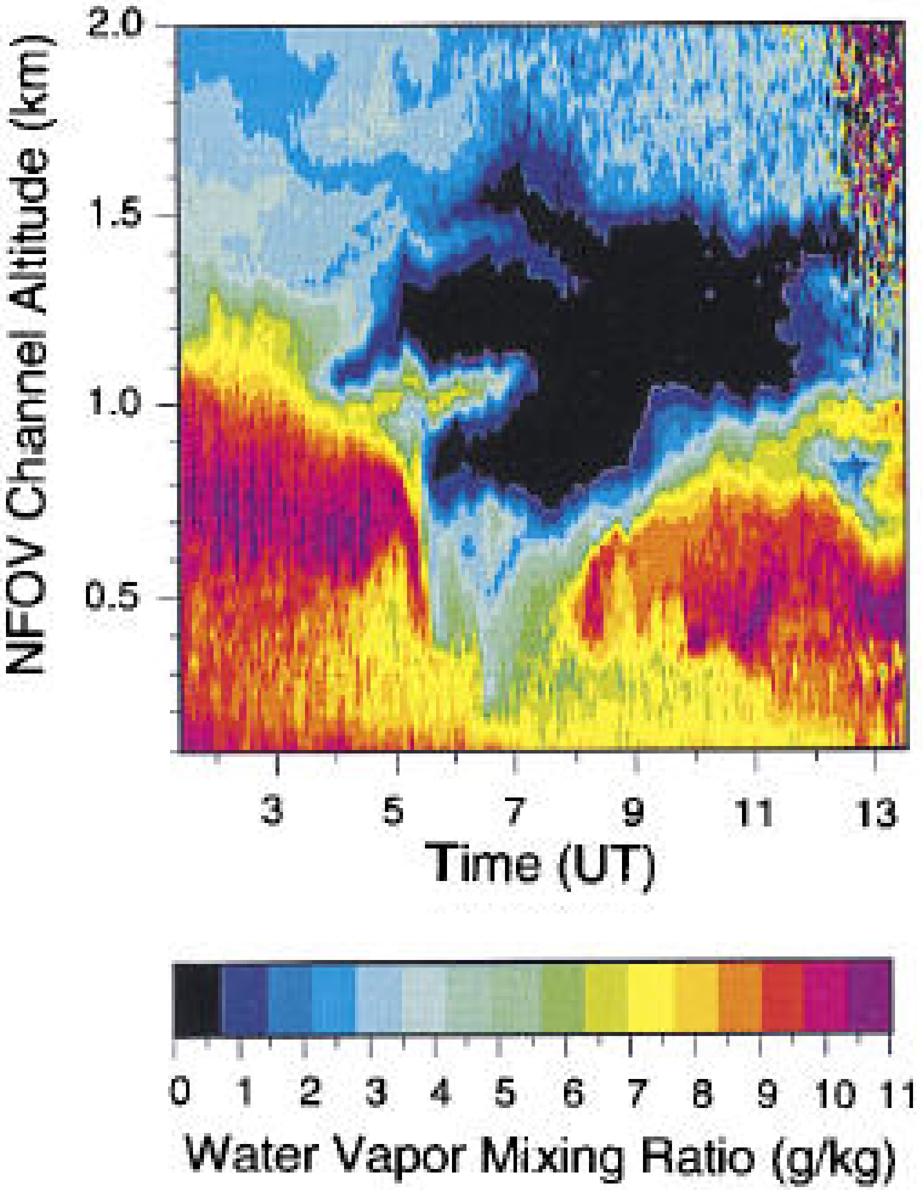
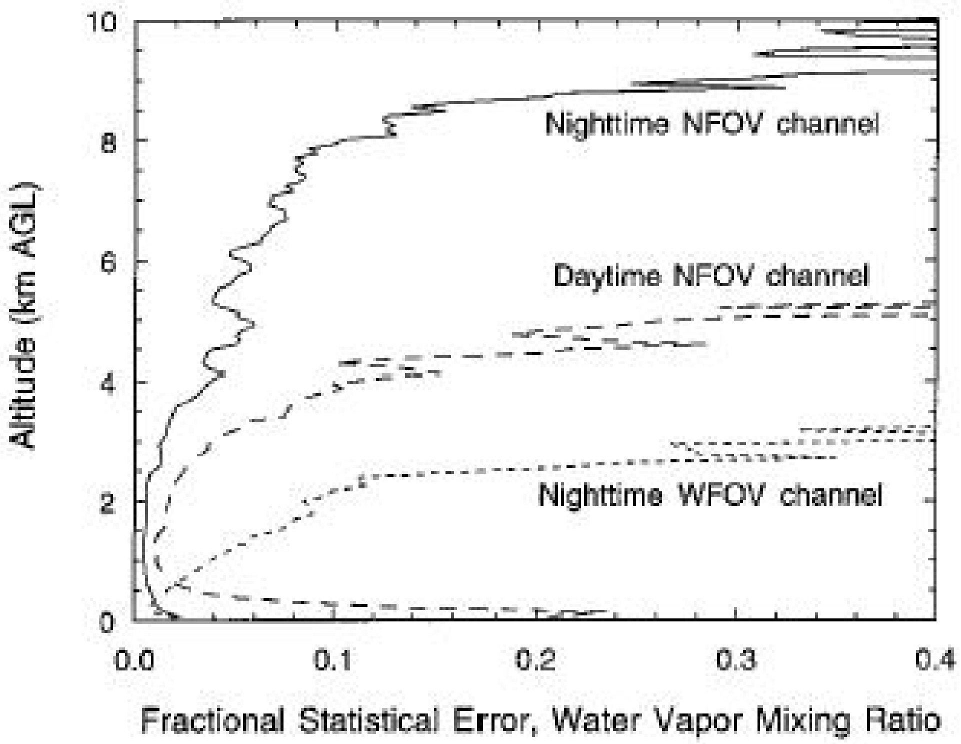


Fig. SOURCE: Inaba, H. Detection of Atoms and Molecules by Raman Scattering and Resonance Fluorescence. In *Laser Monitoring of the Atmosphere,* Hinkley, E. D., Ed.; Springer-Verlag: New York, 1976; Chap. 5, p.162.

WATER-VAPOR MEASUREMENT (V)





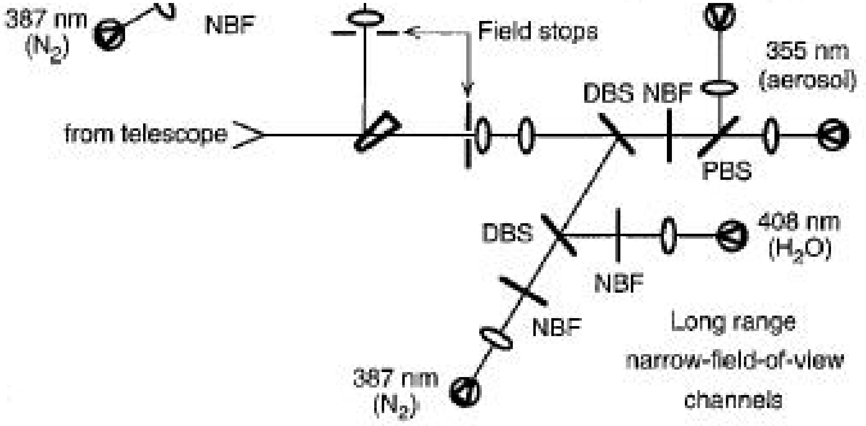
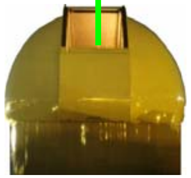


Fig. SOURCE: Goldsmith, J.E.M., et al., "Turn-key Raman lidar for profiling atmospheric water vapor, clouds, and aerosols", *Appl. Opt.* **27** (21), 4979-4990, (1998).



RELATIVE HUMIDITY MEASUREMENT

KEY

- *Water-vapor mixing ratio (wH2O) + Temperature profile* $\Rightarrow$ *RH*
- *Derivation of the RH profile emerges from specific physical refs.1,2*

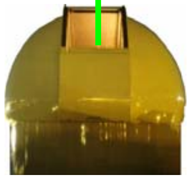
$$RH(z) = \frac{e(z)}{e_w(z)}$$

where e(z) is the WV pressure, and $e_w(z)$ is the saturation pressure,

$$e(z) = \frac{P(z)w_{H_2O}(z)}{0.622 + w_{H_2O}(z)}, \qquad e_w(z) = 6.107\exp\left\{\frac{M_A[T(z)-273]}{M_B + [T(z)-273]}\right\}$$

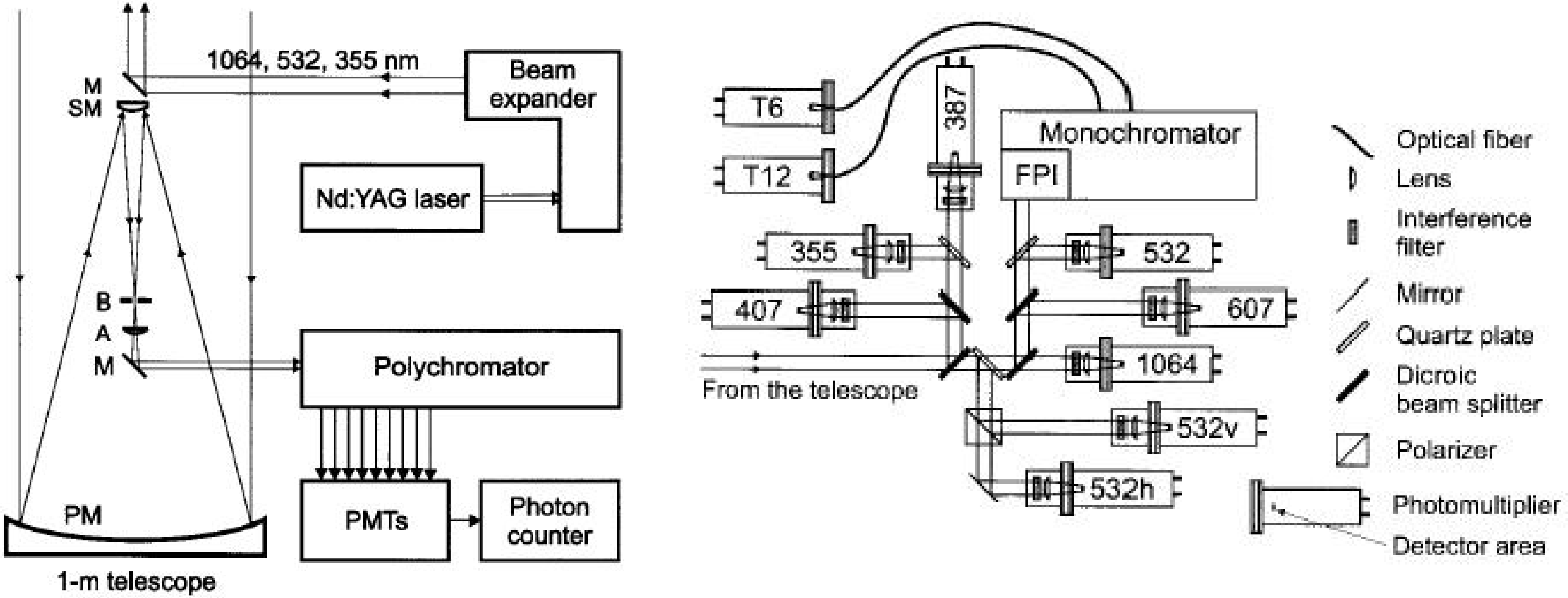
- M_A=17.84, 17.08 and M_B=245.4, 234.2 for T < and > 273 K, respectively.

REFERENCES:
1) R.R. Rogers and M.K. Yau, *A Short Course in Cloud Physics* (Pergamon, New York ,1988).
2) R.J. List, ed., *Smithsonian Meteorological Tables* (Smithsonian Institution, Washington, D.C., 1951).



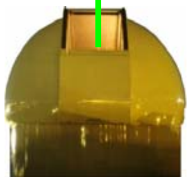
A COMPLETE RAMAN SYSTEM

LAYOUT



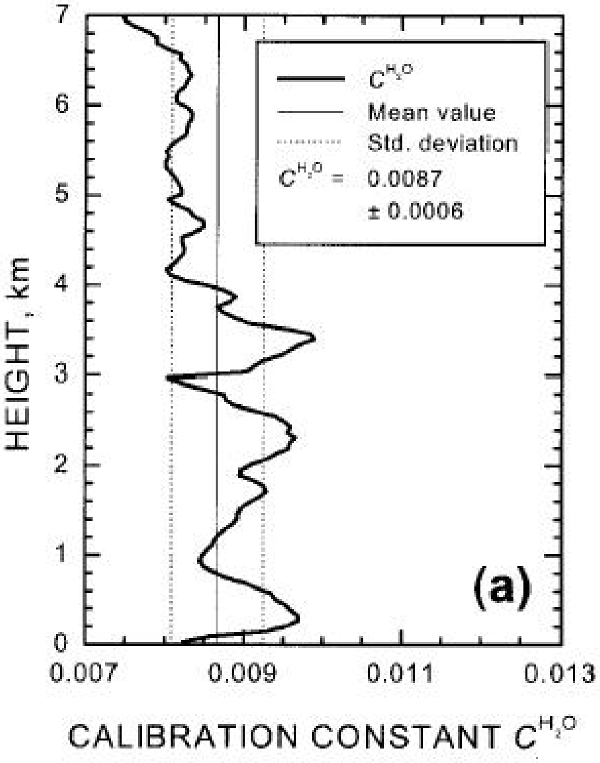
- *3 unshifted returns (1064, 532, 355 nm), NO polarization*
- *4 returns (Stokes and anti-Stokes portions) of the N_2 RR spectrum*
- *3 vibrational Raman returns (N_2 at 387, 607 nm and H_2O at 407 nm)*
- *2 returns from the parallel and cross-polarized unshifted 532 nm*

Fig. SOURCE: Matthis, I, Ansmann, A et al., “Relative-humidity profiling in the troposphere with a Raman lidar”, *Appl. Opt.* **41** (30), 6451-6462, (2002).



A COMPLETE RAMAN SYSTEM

COMPOSITE OUTPUTS



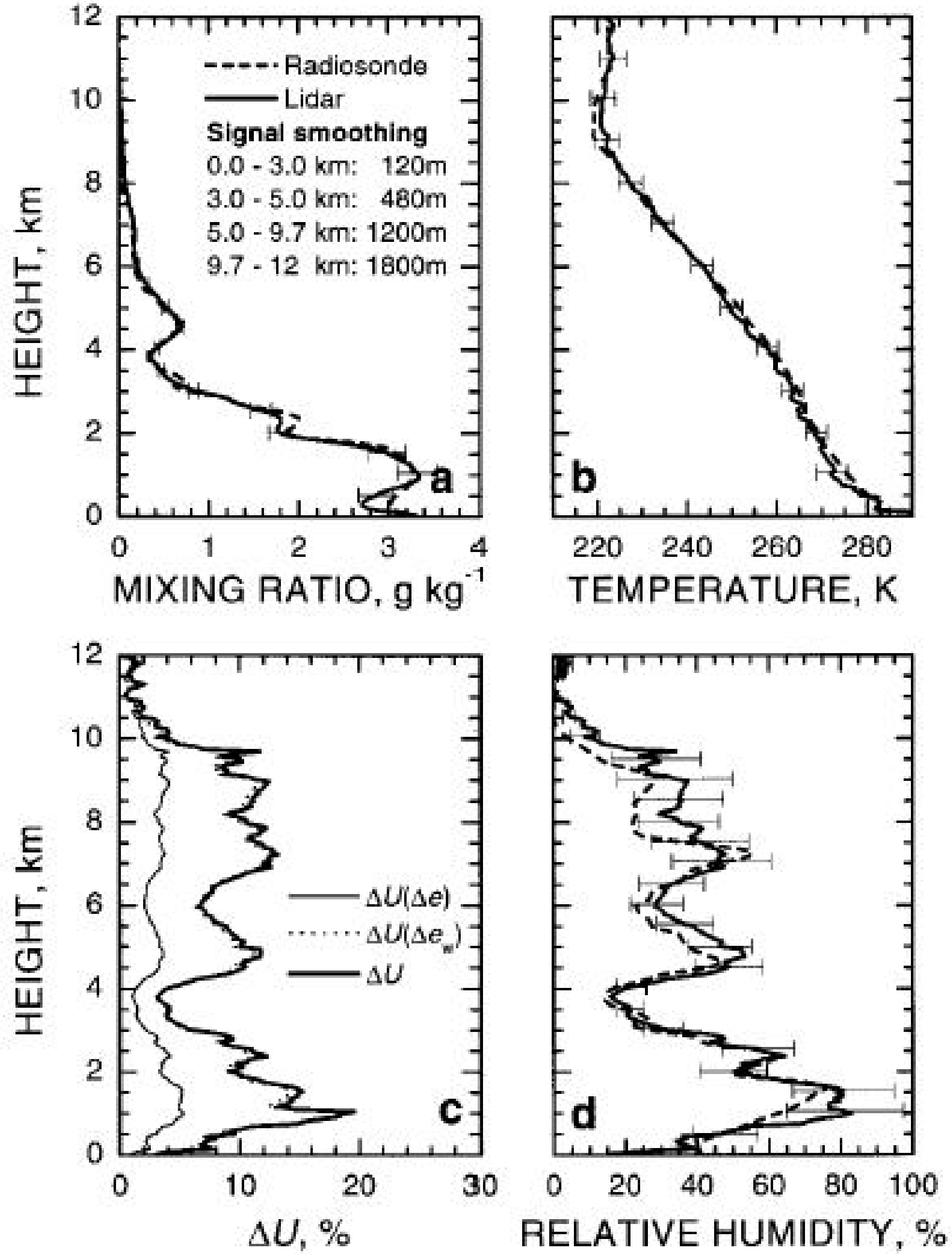
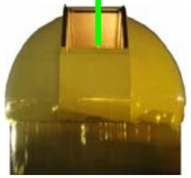


Fig. SOURCE: Matthis, I, Ansmann, A et al., “Relative-humidity profiling in the troposphere with a Raman lidar”, *Appl. Opt.* **41** (30), 6451-6462, (2002).



INVERSION OF OPTICAL PARAMETERS (I)

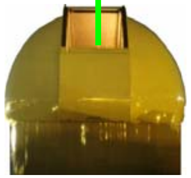
PRINCIPLE

1) Two receiving channels: Besides the ELASTIC receiver, which is only sensitive to the elastic return, another receiver -i.e., the RAMAN receiver- is spectrally tuned to the Raman-shifted wavelength (Q-branch) of any abundant species of known relative concentration (usually N_2).

2) From:

- *radiosoundings or*
- *ground-level measurements of pressure and temperature + assumption of a standard atmosphere,*

the N_2 concentration -as a function of the range to the lidar- is inferred.



INVERSION OF OPTICAL PARAMETERS (II)

Raman-backscattered signal:

$$P_{\lambda_R}(z)=K_{\lambda_R}\frac{O(z)}{z^2}\left[N_R(z)\frac{d\sigma_{\lambda_R}(\pi)}{d\Omega}\right]\times\exp\left\{-\int_0^z\left[\alpha^{mol}_{\lambda_0}(\xi)+\alpha^{aer}_{\lambda_0}(\xi)+\alpha^{mol}_{\lambda_R}(\xi)+\alpha^{aer}_{\lambda_R}(\xi)\right]d\xi\right\}$$

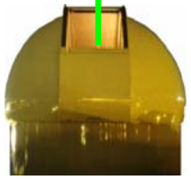
Scattering wavelength dependency: $\lambda^{-\kappa}$

$$\frac{\alpha^{aer}_{\lambda_0}}{\alpha^{aer}_{\lambda_R}}=\left(\frac{\lambda_0}{\lambda_R}\right)^{-\kappa}$$

Raman-channel inverted extinction:

$$\alpha^{aer}_{\lambda_0}(z)=\frac{\frac{d}{dz}\left[\ln\frac{N_R(z)}{P_{\lambda_R}(z)z^2}\right]-\alpha^{mol}_{\lambda_0}(z)-\alpha^{mol}_{\lambda_R}(z)}{1+\left(\frac{\lambda_0}{\lambda_R}\right)^{k}}$$

INVERTED ATMOSPHERIC
OPTICAL PARAMETERS



INVERSION OF OPTICAL PARAMETERS (III)

Backscatter inversion requires:

- *combination of lidar returns from both elastic and Raman channels*

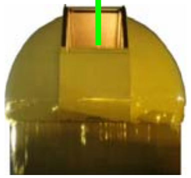
$$\beta^{aer}_{\lambda_0}(z) = -\beta^{mol}_{\lambda_0}(z) + \left[\beta^{aer}_{\lambda_0}(z_0) + \beta^{mol}_{\lambda_0}(z_0)\right] \times \frac{P_{\lambda_R}(z_0)P_{\lambda_0}(z)N_R(z)}{P_{\lambda_0}(z_0)P_{\lambda_R}(z)N_R(z_0)} \times$$

$$\times \frac{\exp\left\{-\int_{z_0}^{z}\left[\alpha^{aer}_{\lambda_R}(\xi) + \alpha^{mol}_{\lambda_R}(\xi)\right]d\xi\right\}}{\exp\left\{-\int_{z_0}^{z}\left[\alpha^{aer}_{\lambda_0}(\xi) + \alpha^{mol}_{\lambda_0}(\xi)\right]d\xi\right\}}; \qquad z \geq z_0$$

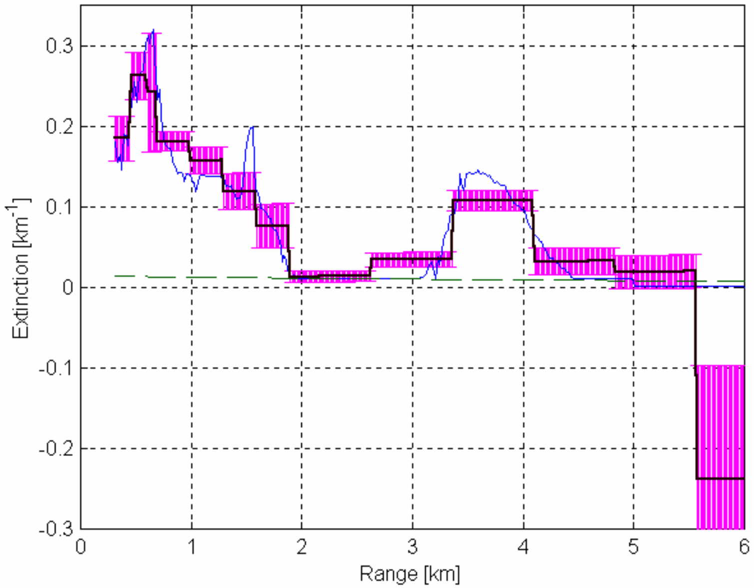
- *a backscatter calibration at some height R_0 so that*

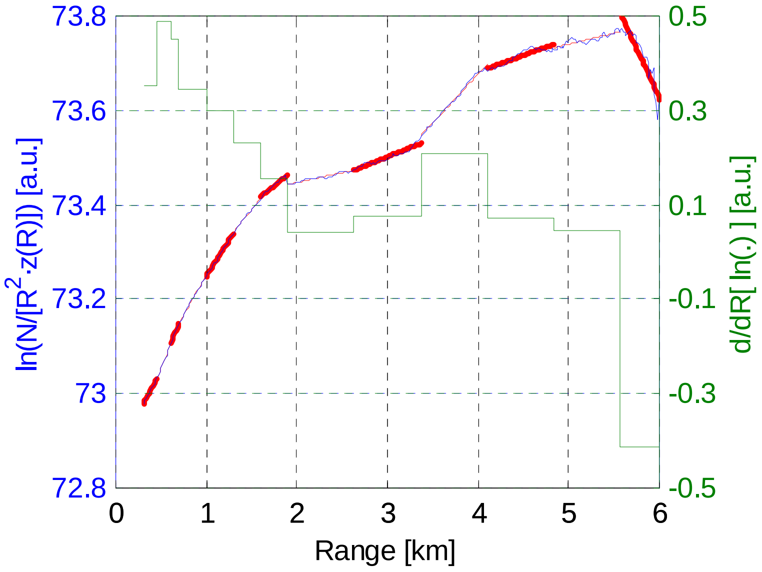
$$\beta^{mol}_{\lambda_0}(R_0) >> \beta^{aer}_{\lambda_0}(R_0) \rightarrow \left[\cancel{\beta^{aer}_{\lambda_0}(R_0)} + \beta^{mol}_{\lambda_0}(R_0)\right] \Rightarrow \boxed{\beta^{aer}_{\lambda_0}(R) = f\left[\underbrace{P_{\lambda_0}, P_{\lambda_R}}_{\text{channel returns}}, \alpha^{aer}_{\lambda_0}, N_R, \underbrace{P, T}_{\text{Rayleigh comp.}}\right]}$$

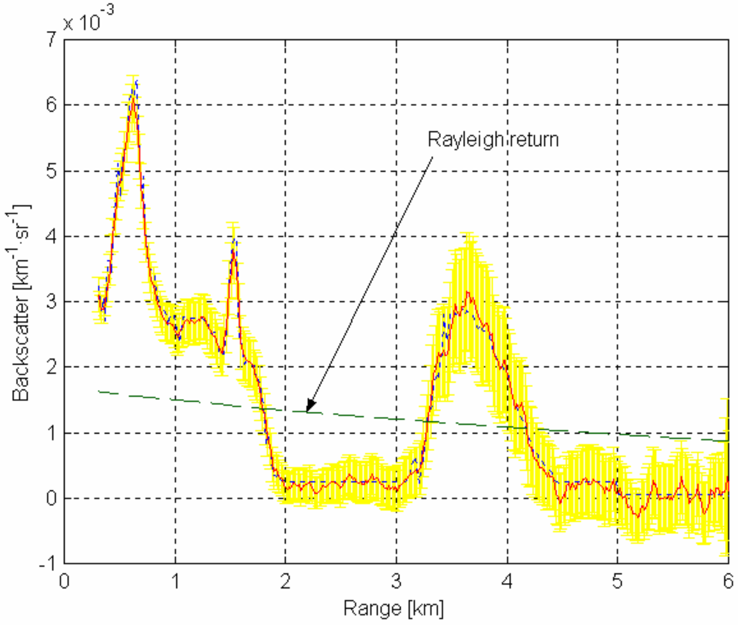
The lidar ratio is found as $$S^{aer}_{\lambda_0}(z) = \frac{\alpha^{aer}_{\lambda_0}(z)}{\beta^{aer}_{\lambda_0}(z)}$$

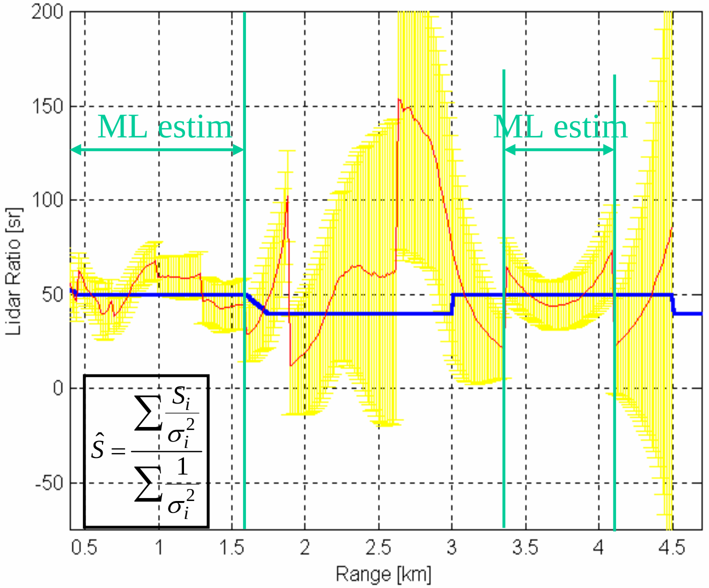


4. INVERTED OPTICAL PARAMETERS









$$\hat{S} = \frac{\sum \frac{S_i}{\sigma_i^2}}{\sum \frac{1}{\sigma_i^2}}$$