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Development of Rayleigh lidar for clear air turbulence detection

Porteneuve J.¹, Gaudo T.², Hauchecorne A.¹, Cot C.¹, Dalaudier F.¹,

Perrin J.M.³, Planchat. C.², Rialland .V², David .J.M², Cézard N.², Lombard L.², Dolfi-Bouteyre A.²

¹CNRS, LATMOS quartier des Garennes 11, Bd d'Alembert 78280 Guillaucourt France, name@latmos.ipsl.fr

²ONERA, Chemin de la Hunière FR-91761 Palaiseau France, name@onera.fr

³OHP, OHP/CNRS F-04870 St.Michel l'Observatoire France, jean-marie.perrin@oamp.fr

ABSTRACT

The conditions of the Clear air turbulence (CAT) in the atmosphere are due to various phenomena : gravity waves breaking, shears associated with jets, convection etc.... Therefore, we propose systematic investigation from the ground with Rayleigh back-scattering lidar, in order to better characterized this atmospheric phenomenon. Rayleigh lidars are able to measure the vertical profile of light emitted by a pulsed laser and backscattered by atmospheric molecules. The Rayleigh signal intensity variations are proportional to the CAT . This paper describes a new technique developed at The Haute-Provence Observatory (OHP). This technique is based on using of a Rayleigh lidar to detect density at 8-12km height and monitor the index turbulence along the laser beam.

1. INTRODUCTION

Clear Air Turbulence (CAT) refers to turbulences in air without cloud, usually located in high troposphere and low stratosphere. Those CAT are a serious issue for in-flight plane security and are responsible for numerous injuries or even reported deaths every year. Planes crossing such CAT can be strongly vertically shaken and passengers with security belt unfastened can be seriously injured. There is nowadays no alert system able to detect CAT at typical flight height and at a sufficiently range ahead in the plane direction (20 km). Indeed, onboard weather radars are blind to CAT.

The clear air turbulence (CAT) can be retrieved from the molecular backscattering by use of an incoherent Raleigh lidar .

We began to conduct a series of simulations and studies of this Lidar technique. Later concluded that CAT detection performances depending on the dominance of aerosol scattering or molecular scattering. Since aerosol consists of sharp depolarization features [1], the polarization beam-splitter cube been used to discriminate the aerosol content of the backscattering signal.

In this paper, a ground-based incoherent Raleigh lidar system, with a Nd:YAG pulsed laser outputs radiation

at 532 nm, is presented for low-altitude atmospheric CAT measurements.

The feature of this lidar type is its capability to monitor the measurement of the aerosol and molecular scattering. The lidar returns passing through the polarization discriminator can be processed to retrieve CAT profiles under a varied mixture of Rayleigh and Mie scattering.

2. DESCRIPTION OF THE INSTRUMENT

The schematic diagram for lidar transmitter, receiver, is shown in Fig. 1 and the principals instrumental parameters are listed in Tab. 1. The master of the system is the Nd:YAG laser located at 6 m of telescope in off-axis. The 532-nm output of the laser beam is sent to the sky with a pulse repetition rate 50 Hz with power 15 W.

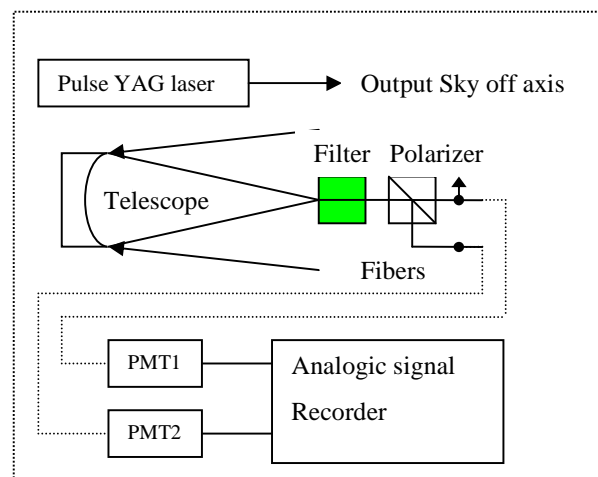


Fig. 1. Optical layout of Raleigh lidar.

The received backscattered light is collected by a Newton telescope with 530-mm aperture, and then passes through a narrowband interference filter (bandwidth=1 nm, peak transmission 61%). As shown in the right of Fig. 1, the collected light polarized component is split by the polarizer into two channels; approximately 99 % of orthogonal component is

detected directly by the photomultiplier tube R7205-01 PMT2 and 95 % of the parallel component by the PMT1. The two PMTs are used in analogic mode, and the signals from the two channels are filtered in bandwidth 3.5 MHz and digitalized by a dual channel 10 MHz, 16 bit analog-to-digital converter (NI5922 board).

Tab. 1. System Parameters for transmitter and receiver

Instrumental parameters	
Laser	Pulsed Nd:YAG
Average power	$E_0=15$ W at 532 nm
Laser emission	$4 \cdot 10^{19}$ ph/s
Divergence	1 mrd
Off axis	6 m
Pulse repetition rate	50 Hz
Telescope	Newton
Focal	1500 mm -
Diameter	530 mm
Pupil surface	$A_{tel} = 0.22$ m ²
Field	0.67 mrd
Multimode fiber	1 mm -diameter
Interferential filter	61% (BW=1nm)
Polarizer	T>95% R>99%
Photomultiplier tubes PMT	Hamamatsu-R7205-01
Bandwidth	4 MHz
Quantum efficiency	10 %
Noise Factor	1.2
Analogic signal Recorder	NI5922
Frequency sampling	10 MHz
Lidar	
Quantum efficiency	$Q_{lid}=0.1-0.01$
Resolution spatial	$d_z=15$ m

3. METHOD

It is straightforward to show that the detected signal at a range z in the reference channel (aerosol backscattering), N_R , and in the measurement channel N_M are given in Equ. [1] :

$$N(z, z + dz) = E_0 \times \tau_{atm}^2(0, z) \times Q_{lid} \frac{A_{tel}}{z} \times \left\{ (\beta_r(z) n_r(z) + \beta_m(z) n_m(z)) dz \right\} \quad (1)$$

Here (see parameters description on Tabs 1 and 2), dz is the range resolution; β_r and β_m (τ_{atm}) are aerosol and molecular volume backscatter (extinction) coefficients, respectively [3]; n_r and n_m represent the depolarization rate from aerosol and molecular, respectively; and Q_{lid} is the system constants for reference and measurement channel, depending on total laser emission energy E_0 and the efficiency of each optical and electronic component.

In general, these lidars are used to determine the vertical profile of atmospheric density in altitude ranges where air is free of aerosols (for instance above 30 km where it is possible to compute the vertical temperature profile from the vertical density profile [2] or to determine the vertical profile of aerosols by comparison between the lidar profile and a density profile taken from an atmospheric model or a radio-sounding profile. For this application, the lidar signal can be integrated in time and in vertical to reduce the signal to noise ratio (during a few minutes to several hours and over a few 100m to a few km)

For this purpose we can only use data when the Mie signal is negligible compared to the Rayleigh signal. This happens generally in the upper troposphere (5-10 km) when air is prevented the formation of clouds. In a lidar signal it is easy to detect the presence of cloud particles and to eliminate contaminated data. In this case it is necessary to record the signal with a time and vertical resolution adapted to the scale of turbulent structures (at least the largest ones).

Tab. 2. Atmospheric parameters

Parameters	
Altitude	10000 m
Transmission	$\tau_{atm}=0.7$
Molecular backscattering	$\beta_m=4 \cdot 10^{-7}$ m ⁻¹ sr ⁻¹
Aerosol backscattering	$\beta_r=0.1\beta_m$
Aerosol depolarization	$n_r \sim 12-40\%$
Molecular depolarization	$n_m \sim 1-2\%$
Horizontal mean wind	15 m/s
Turbulent structure	
scale	30-200-300 m
Density fluctuation (Tropo)	0.006-0.04-0.06%
Density fluctuation (Strato)	0.024-0.18-0.24%

Assuming an isotropic turbulence layer with external scale equal or greater than 30m and with the hypothesis that turbulent structures are advected by a 15 ms⁻¹ mean wind, the lidar signal should be recorded with a 15m vertical resolution and 1 sec time integration. This is feasible with this lidar data acquisition system but the signal to noise ratio for a single measurement will be high. It is proposed to average the variance of density fluctuations instead of averaging the signal itself. It will give an average value of turbulent fluctuations (see simulation results on Tab. [3]).

Tab. 3. Digital signal processing parameters

Parameters	
Quantum lidar efficiency	$Q_{lid}=0.06, 2\sigma$
Detected photo-electrons	$\sim 28000/\text{sec}$
Fluctuation detectivity limit	
Signal average	0.2% (10 sec)
Variance average	0.08% (1 min)

The comparison between the detectivity limit and the expected fluctuations gives the minimum size of detectable fluctuations (see Tabs. 2 and 3). It corresponds to 300m for a stratospheric and tropospheric temperature. These fluctuations are considered as intense turbulence events by atmospheric specialists but are smaller than the fluctuations experienced by airplanes during severe CAT events.

4. EXPERIMENTAL RESULTS, COMPARISONS, AND DISCUSSION

4.1 Instrumental validation

The purpose of this subsection is to estimate the variance of the signal received 8 August 2008 and compare it to what was projected in the feasibility assessment in the previous chapter.

The processed file is the sequence measured 08/08/2008 at 23H13mn during 300 sec which includes 15 000 shots.

The analysis procedure is :

- Grouping data by 10 shots in 1500 resulting in profiles grouped
- Removing the sky background estimated on channels 5000-5500 about 36-42 km
- Calculating the square of scale local disturbances $nt * dt, nz * dz$ summing data from 1500 profiles grouped by profiles and nz groups altitude $dt = 0.2s, dz = 12 m$.
- Calculation of a signal profile using the sequence (see Fig. 2.)
- Calculation of a profile on the sequence variance (mean square of local disturbances)
- Comparison of this pattern of variance with that predicted by assuming that the variance from only noise Poissonian photon detection

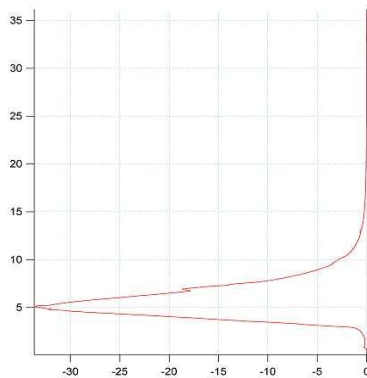


Fig. 2. Average profiles grouped for the sequence.

Under the conditions of the experiment, as expected interval of 1s and 24 m, 3200 photo-elec for $Q = 0.01$ at 10 km in the conditions of the measure. The calculation of variance gives a standard deviation of 3.5% of the signal (see Fig. 3.), which corresponds to 816 photo-elec.

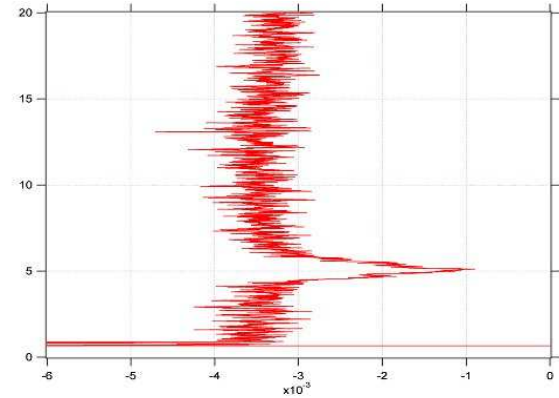


Fig. 3. Variance normalized by the value of the average profile for $nt = 5$ (1 s), $nz = 2$ (24 m). A constant indicates that the variance follows much the law would result if it is due to photon noise. The peak corresponds to the range of altitudes where it saturates.

Assuming that the variance is due solely to the photon statistics. It thus lacks a factor four compared to what is expected.

The causes of the difference can be multiple:

- Energy Laser lower than estimated (in principle verifiable)
- Atmospheric transmission lower
- Setting imperfect optical
- Noise of the analog channel higher than a chain count

4.2 Detection of atmospheric variance

To emphasize the atmospheric variance, we increase the time and vertical integration before calculating the variance. Figure. 4 shows the profile of variance = 50 s (10 s) and $nz = 5$ (60m). Can be seen very strong peaks in the cloud layers and aerosols. If one considers only the peaks above the overlap, we see layers of about 7 km and 13 km which can also occur on the average profile. The aerosol layer around 10 km is much less visible against the variance because it is smoother.

He will then decide how to distinguish a peak variance due to a turbulent structure and due to a cloud layer. Several elements may be taken into account:

- The polarized reference channel (all the particles do not depolarize)
- Is there a peak of distribution on the average profile?
- Stationarity. A turbulent structure should have a duration shorter than a diffusing layer.
- Others ?

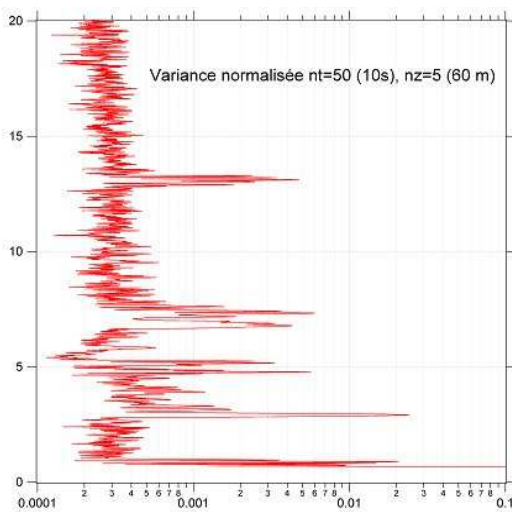


Fig. 4. Variance calculated for $nt = 50$ (10 s) and $nz = 5(60m)$.

5. CONCLUSION

The measurements have a statistical error following a photon counting statistics (variance proportional to the signal). The observed variance on the signal indicates a noise level corresponding to a photon flux of a factor four lower than that estimated for a lidar quantum efficiency $Q_{lid} = 0.01$. It is suggested that the limit detection system is not an intrinsic problem and it can be improved in the future by using UV lidars and signal processing techniques sophisticated.

The variance of the signal in the presence of atmospheric layer of clouds or aerosols is very well detected. It remains to determine how to differentiate an increase in variance due to turbulence from that due to a diffusing layer.

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