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SET-UP OF A GROUND-BASED RAYLEIGH LIDAR TO DETECT CLEAR AIR TURBULENCE

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ABSTRACT

Atmospheric gravity waves and turbulence generate small-scale fluctuations of wind, pressure, density and temperature in the atmosphere. These fluctuations represent a real danger for commercial aircrafts and are known under the generic name of Clear Air Turbulence (CAT). They are not resolved in weather forecast models and are therefore unpredictable. A ground-based Rayleigh lidar was designed and implemented to remotely detect and characterize the atmospheric variability induced by gravity waves and turbulence in vertical scales between 10m and 1000m. Field measurements at Observatoire de Haute-Provence (France) have shown that the built lidar device was actually able to detect episodes of turbulence. This is to our knowledge the first Rayleigh lidar system able to detect clear air turbulence. The built lidar device may serve as a test bed for the definition of embarked CAT detection lidar systems on board airliners.

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. Indeed, onboard weather radars are blind to clear air turbulence.

Wind and temperature fluctuations in the lower atmosphere can be described over a wide range of scales. In the mesoscale range from a few tens of meters to some kilometers along the vertical and a few hundred meters to a few hundred kilometers along the horizontal, these fluctuations are thought to be due principally to a field of gravity waves. A wide variety of observational techniques have been used to study mesoscale fluctuations in the atmosphere, one will

quote in particular balloon soundings aircraft observations and rocket sonde measurements for in-situ techniques, radar observations and lidar studies] for remote sensing techniques. A common feature of these experimental studies is approximately invariant vertical wave number and frequency power spectra, regardless of season and geographic location. This feature, first recognized by [5] who took as a starting point oceanographic experimental studies [1], led to the concept of a “universal” spectrum of atmospheric Fluctuations constrained to remain with the same shape and same level in the spectral domain everywhere in the world. Several saturation theories have since emerged. Each of them proposes a physical mechanism thought to be responsible to limit wave amplitude and each predicts with a good approximation shape and level of vertical wave number power spectrum.

Turbulence is associated to this wave field, generated when the wave field saturate and then break. It can result from breakdown of stratified shear layers (Kelvin-Helmoltz instability). Turbulence is a chaotic non linear superposition of rotational movement. This vortices, generated by instability, decay into smaller vortices until the vorticity is finally dissipated by viscosity.

Today, Clear Air Turbulences are a serious flight security problem because there exists no ground or onboard detection devices. Besides, the physical phenomenon is far from being clearly understood. The understanding of CAT phenomenon is poor because: 1) it is difficult to measure the CAT atmospheric parameters in situ (relatively low occurrence) 2) the simulations are complex. Therefore, this original project intends to 1) obtain a complete measured data set by remote sensing from the ground 2) join two different know-how to address the theoretical/simulation aspects of CAT.

2. LIDAR SIMULATIONS

Turbulence measurements with lidar

In a turbulent layer, atmospheric density presents 3D fluctuations at different scales. The amplitude of these fluctuations is related to the intensity of the turbulence and has a 3D spectrum depending on its nature. For an isotropic 3D turbulence field a -5/3 slope of vertical and horizontal spectra is observed. It means that fluctuations are expected to be larger at larger than at smaller scales.

A Rayleigh-Mie lidar is a system able to measure the vertical profile of light emitted by a pulsed visible or near UV laser and backscattered by atmospheric molecules and particles. Its signal is the sum of a Rayleigh scattering signal directly proportional to the atmospheric density and a Mie scattering signal depending on the number and the nature of particles.

The lidar equation in elastic scattering mode is:

$$S(z, z + dz) = E_0 \times T_{atm}^2(0, z) \times Q_{lid} \times \frac{A_{lid}}{z^2} \times (\beta_r(z) n_r(z) + \beta_m(z) n_m(z)) dz \quad (1)$$

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] [4] 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). In the present project our goal is to use a Rayleigh-Mie lidar to detect density fluctuations due to turbulence. 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 to prevent 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). 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 1s time integration. This is feasible with modern lidar data acquisition systems 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.

The expected signal with the OHP Rayleigh lidar is estimated using the following characteristics :

- Laser Nd-Yag : - 15W @ 532 nm
- Laser émission : 4. 10¹⁹ ph/s
- Atmospheric transmission : 0.7²
- Lidar efficiency : Q_{lid}=0.01 to 0.1
- Reception telescope area : 0.5 m² (80 cm diameter)
- Altitude z: 10000 m
- Rayleigh backscattering: β_r=4. 10⁻⁷ m⁻¹sr⁻¹
- Detected photo-electrons : N=800 to 8000/m/s

The accuracy of the Rayleigh density lidar is given by :

$$\frac{\Delta \rho}{\rho} = \frac{1}{\sqrt{N_{ph}}} \quad (2)$$

Figure 1 presents the 2-sigma detectivity limit in red expected using Q_{lid}=0.03 for 1s and 1 min time integration and in blue the expected amplitude of density fluctuations (in blue) depending on the external scale of turbulence for troposphere and stratosphere temperature gradient. Turbulent layers thicker than 100m in the stratosphere and 200 in the troposphere can be detected.

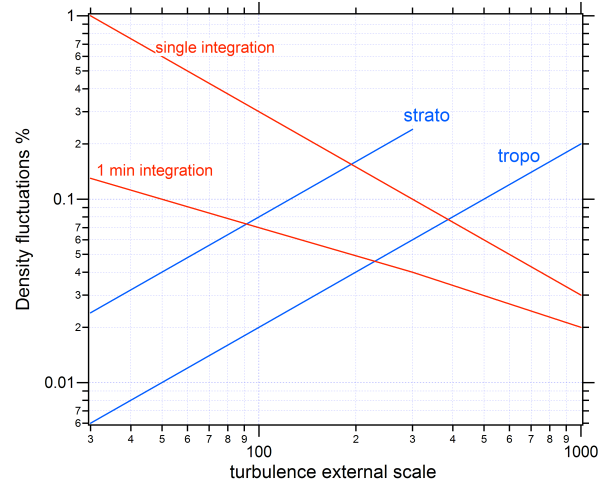


Figure 1. Detectivity limit

3. SET-UP OF THE LIDAR EXPERIMENT

A CAT detection instrumental system has been added to the Rayleigh lidar installed at Observatoire de Haute-Provence (OHP, 44°N, 6°E). This lidar is part of the Network for Detection of Atmospheric Composition Changes (NDACC) station at OHP and measures routinely density and temperature profiles from 30 to 80 km [3]. It uses the second harmonic of a Nd-YAG laser at 532 nm firing at 50 Hz. The CAT detection reception system consists in two 53cm diameter telescopes for the reception distant 6m distant from the laser emission to

avoid the signal coming from the lower altitude. One telescope received the signal with a polarisation parallel to the laser polarisation and the other telescope receives the perpendicular polarisation. This allows detecting the presence of solid particles (cirrus clouds or aerosols) that prevent to use the data contaminated by Mie scattering. Fast photomultiplier tubes receive the signal. Data are acquired shot by shot in analogic mode with a vertical sampling of 15 m (100 ns time sampling) and 4 MHz band- pass corresponding to a 35m vertical resolution.

4. POSSIBLE DETECTION OF A TURBULENT LAYER

Density fluctuations associated with turbulent layers are in the order of tenths of a percent and cannot be detected on a single density profile. In order to detect them, the signal is first binned by 400 shots (8s) and squares density fluctuations are computed using 150 m vertical layers. The result is convoluted in time with a 240s Hanning filter, providing the variance of the lidar signal. Figure 2 shows one example obtained during one hour during the night 8 to 9 December 2008. It clearly shows the presence of a layer with enhanced variance oscillating between 7 and 8 km.

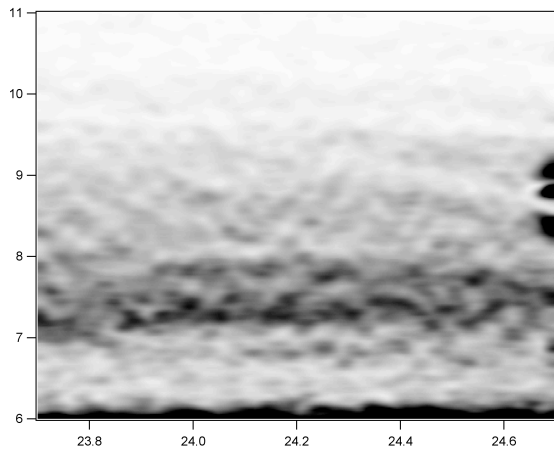


Figure 2. Variance of lidar signal from 23h42 to 00h42 UT during the night 8 to 9 December 2008

The VHF radar installed at OHP was operated during the same night. It provides vertical profiles of wind and reflectivity from 2 to 8-10 km [6]. The reflectivity is proportional to the square of the turbulent energy at 2 m scale characterize by the C_n^2 (square of perturbations in index of refraction). Figure 3 indicates the presence of a turbulent layer with enhanced reflectivity descending from 7 km at 00h30 to 5 m at 03h00 UT. The altitude of the layer at the beginning of the sequence corresponds

well with the altitude of the layer with enhanced variance observed at the same time by lidar. We can conclude that the two systems are observing the same turbulent layer.

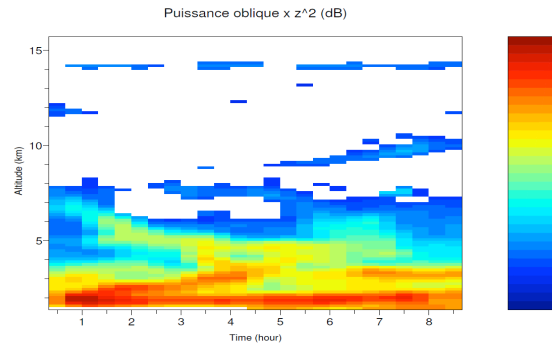


Figure 3. Reflectivity observed by the VHF ST radar on 9 December 2008 from 00h:00 to 08h:35 UT. The vertical resolution is 150m and the horizontal resolution 20 min. Color bar : C_n^2 in dB.

5. CONCLUSION

A ground-based Rayleigh lidar was adapted and implemented to remotely detect the presence of turbulent layers in the upper troposphere. Field measurements performed at Observatoire de Haute-Provence (France) in December 2008 have shown that the built lidar device was actually able to detect episodes of turbulence simultaneously observed with a collocated VHF radar. This is to our knowledge the first Rayleigh lidar system able to detect clear air turbulence. The built lidar device may serve as a test bed for the definition of embarked CAT detection lidar systems on board airliners.

6. ACKNOWLEDGMENTS

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