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Airflow Characterization by Rayleigh-Mie Lidars

This paper deals with lidar systems applied to airflow measurements. The properties of the two main light scattering processes, Rayleigh and Mie scattering, are presented and correlated to general but important rules for lidar design. The Rayleigh lidar developed at Onera for short-range wind speed measurements is also presented, and the Doppler analysis technique using Michelson fringe imagery is briefly discussed.

Introduction

The principle of LIDAR (Light Detection and Ranging) is very similar to that of RADAR (Radio Detection and Ranging). Radars emit radio wavelengths to detect echoes on targets of a significant size (typically >1 mm) whereas lidars use optical wavelengths generated by lasers to detect signals backscattered by much smaller elements, like dust, particles, or even gas molecules. For aeronautic applications, weather radars are commonly used to locate and characterize clouds, rainfall and storms. Lidar systems can be very useful for determining physical and chemical properties in the atmosphere, especially in clear air (no clouds).

With regard to airflow characterization, lidar systems fall into two main categories:

- Systems that detect or characterize the airflow disturbances imprinted by an aircraft on the atmosphere. These are generally ground-based systems (sometimes airborne), well-suited for ground tests or measurements during take-off and landing phases. These measurements are important because aircraft-generated airflows can be dangerous for the aircraft itself or for neighboring ones (see wake vortices, detailed in paper [6]).
- Systems that characterize the natural state of the atmosphere in front an aircraft. These are airborne systems, as shown in figure 1. For example, a long-range forward-looking lidar could be used to detect hazardous turbulence early enough to avoid it, or at least to secure passengers and crew. Shorter-range lidars could also be used to anticipate atmospheric parameters (such as air speed, temperature, density), so as to improve automatic flight control systems and reduce turbulence-induced stresses [1-5].

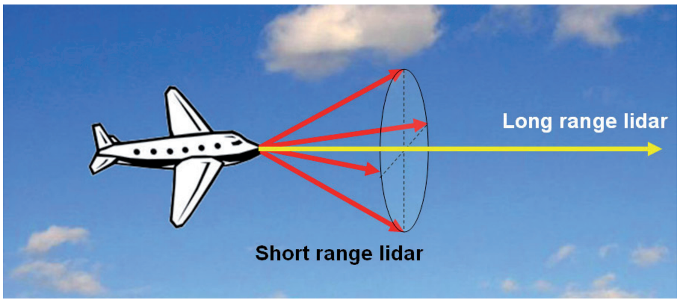


Figure 1 - Long-range lidars could be used for turbulence detection, at least early enough to warn passengers to sit down and fasten their seat belts. Short-range lidars could be used for air data measurements to provide accurate input for automatic flight control systems.

Light scattering in the atmosphere and lidar design

Light scattering in the atmosphere occurs by two main processes: Rayleigh and Mie scattering. Rayleigh scattering involves essentially gas molecules (diameter of about 0.1 nm), while Mie scattering implies airborne aerosols of much bigger size (10 nm to 10 μm). These processes have very different characteristics, which are summarized in Box 1. For lidar design, the particularly important factors are the backscattering coefficient β (m^{-1}.sr^{-1}) and the width γ (m.s^{-1}) of the velocity distribution of scatterers along the lidar line of sight (LOS).

The key role of β and γ for lidar design can be highlighted by considering the example of wind speed measurements with a pulsed laser. The measurable speed u is the wind speed projected on the lidar LOS. It is deduced from the measurement of the Doppler frequency shift $\Delta\nu = 2\mu/\lambda_L$, between the laser spectrum (assumed to be monochromatic of wavelength λ_L here), and the central frequency of the backscattered signal. Because the lidar signal is always corrupted by at least the photon noise, carried by the signal itself, the achievable accuracy of Doppler-shift measurements is fundamentally limited. The minimum error standard deviation ε in m/s is given by:

$$\varepsilon = \kappa \frac{\gamma}{\sqrt{N_e}} \quad \text{with } \kappa>1 \qquad (1)$$

where κ is a constant depending on the Doppler-shift analysis technique (for optimized systems, κ can be as low as 2), γ is the standard deviation of the scatterer's velocity distribution along the lidar LOS, and N_e is the number of charge carriers generated by the lidar signal impinging on the photodetector, given by the so-called "lidar equation":

$$N_e = N_P T \eta \beta \frac{A}{z^2} \Delta z \qquad (2)$$

where N_P is the total number of emitted photons (in one or several laser pulses), T is the global optical transmission factor, η the photodetector quantum efficiency, β the backscattering coefficient, A/z^2

the solid angle of reception (receiver area A at distance z), and Δz the thickness of the atmospheric cell considered as the measurement volume (selected by time gating).

Equation (1) shows that for Doppler measurements, the Mie signal is far more valuable than the Rayleigh signal, because of the ratio between γ_{Mie} and γ_{Ray}. For example, to reach an accuracy of $\varepsilon = 1$ m/s with an instrument working at $\kappa = 2$, the required number of charge carriers N_e would be only 100 for a Mie signal, but 350,000 for a Rayleigh signal (assuming γ_{Mie} = 5 m/s and γ_{Ray} = 295 m/s - see box 1)!

On the ground or at low altitudes, the particle concentration can be high. Since the Mie signal level required to reach a good accuracy is low, it is possible to use lidar systems of moderate powers. Nowadays, using telecom components, compact and efficient infrared Mie Doppler lidars can be built (see paper [6]). These systems are not

Box 1 - Light scattering in the atmosphere

	Rayleigh Scattering	Mie Scattering
Named after	British scientist John W. Strutt, also known as Lord Rayleigh (1842-1919)	German scientist Gustav Mie (1869-1957)
Scatterers *type*	Essentially molecules. In air, the major contributors are O_2 and N_2.	Dust, water droplets, ice crystals, soots… Generally referred to as "particles" or "aerosols"
size	The typical size is about 0.1 nm	Between 10 nm and 10 µm (depending on the particle type)
1-D velocity distribution [(a)]	* Quasi-Gaussian distribution * Average velocity = wind speed * Standard deviation γ_{Ray} depends on temperature T and scatterer mass m $\gamma_{Ray} = \sqrt{k_B T / m}$ (k_B: Boltzmann constant) For air, γ_{Ray} =295 m/s at 288 K	* Lorentzian distribution * Average velocity ≈ wind speed * Standard deviation γ_{Mie} is small because particles are much heavier than molecules γ_{Mie} ≈ a few m/s
Light Polarization	Rayleigh scattering leaves polarization almost unchanged (less than 2 % depolarized)	Mie scattering by spherical particles (e.g water droplets) does not affect polarization, but non spherical particles (e.g ice crystals) can strongly depolarize
Backscattering coefficient β $\beta = \sigma\rho$ σ: backscattering cross-section ($m^2.sr^{-1}$) ρ : scatterer concentration (m^{-3})	* σ is strong wavelength dependent: it is proportionnal to λ^{-4} * ρ decays exponentially with altitude h The decay parameter is called the "scale height" (average value 8 km). → Backscattering coefficient β_{Ray}: $\beta_{Ray} \approx 8.10^{-6} \exp\left(-\frac{h(km)}{8}\right)\left(\frac{355}{\lambda(nm)}\right)^4$	* σ is proportionnal to λ^{-r}, with 1.2 < r < 2.4, depending on the particle type. * ρ varies by orders of magnitude due to a variety of factors, mainly altitude and weather conditions but also local pollution. → Backscattering coefficient β_{Mie} is often expressed in terms of β_{Ray}. A parameter α>1 is defined, called « scattering ratio ». $\beta_{Mie} \approx (\alpha - 1)\beta_{Ray}$

(a) The one-dimensional velocity distribution is the 3D-distribution projected on the lidar line of sight (LOS)

powerful enough to make use of the Rayleigh signal but they do not need to. The Rayleigh signal is then ignored or discarded.

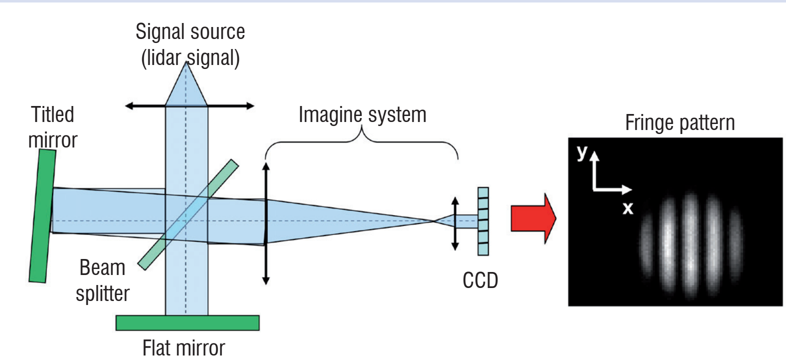
The situation changes at high flight altitudes however, because the particle concentration can drop by several orders of magnitude and becomes unpredictable. The constant availability of Doppler measurements with Mie lidars cannot therefore be guaranteed over a whole flight path. Rayleigh lidars then appear as a possible solution to this problem, inasmuch as molecules are always available in the atmosphere. They are also valuable because they can provide information about the air density and temperature (not measurable with Mie lidars). Today, most Rayleigh lidars operate in the ultraviolet wavelength range to maximize the backscattering coefficient β_{Ray} (proportional to λ_L^{-4}), and reach the high signal levels that are required to obtain satisfactory accuracy. The lidar range is also frequently reduced to gain more signal and to increase accuracy. Long-range applications nonetheless remain possible, but require higher integration times.

An example of a Rayleigh lidar system at Onera

Studies at Onera have covered various applications of Rayleigh lidars, from long-range systems for turbulence detection to short-range systems for air data measurements. We present here as an example a short-range system developed at Onera, demonstrating the feasibility of an all-altitude air speed sensor using a Rayleigh lidar. For this system, it was necessary to design a Doppler shift measurement method that would remain unbiased regardless of the strength of the Mie component. The selected spectral analysis technique uses interferometric fringe imagery, which is an efficient technique at short-range. Michelson interferometry was chosen from among the various possibilities because of its simplicity. The principle is detailed in box 2. In short, the atmospheric backscattered signal generates an interference fringe pattern on a detector, and the phase of the fringes varies linearly with the wind speed.
The lidar built at Onera (laboratory prototype) is depicted on figure 2. It uses a 355 nm laser source. Because the laser frequency can vary slightly from pulse to pulse, the instrument derives the wind speed from a differential phase measurement. With each laser pulse, the fringe patterns produced by the lidar signal and by the emitted laser pulse are recorded with a very small time delay, and their phases are compared. This measurement method has allowed robust daytime

Box 2 - Speed measurement using Michelson fringe imagery

A Michelson interferometer is depicted below:



Michelson interferometer in mathematical terms

The Michelson interferometer "computes" the auto-correlation function of the lidar signal. This latter is equal to the Fourier Transform of the signal power spectrum (Wiener-Khinchine theorem). A Doppler shift in the frequency domain thus naturally translates into a phase variation of its Fourier Transform (= fringe phase shift).

The interference between the waves traveling in the flat mirror arm and tilted mirror arm produces a periodic pattern of straight fringes, which can be imaged on a CCD camera. The fringe phase, which refers to an arbitrary point of the detector, depends on the path difference of the waves at that point, and thus on the mean wavelength of the analyzed spectrum. Consequently, the fringe phase variation is $d\phi$ proportional to the wind speed variation du according to following equation:

$$d\phi = \frac{4\pi\Delta_0}{c\lambda_L} du$$

where Δ_0 is the interferometer path difference, λ_L the laser wavelength, and c the light velocity. Two important characteristics may be noted:

- the phase sensitivity $d\phi/du$ remains unchanged whatever the strength of the Mie component. Thus the fringe phase shift measurement method is unbiased regarding Mie scattering,
- the phase sensitivity is proportional to the path difference Δ_0. However, one cannot increase Δ_0 indefinitely because the fringe contrast decreases with Δ_0. Indeed, the coherence length of the Rayleigh signal is quite short (broad spectrum). Consequently, there is an optimal value of Δ_0 that minimizes the wind speed measurement error ($\Delta_0 \approx$ 3 cm for a 355 nm Rayleigh lidar).

measurements. The Michelson fringe imagery method also allows for unbiased speed measurements regardless of the strength of the Mie signal. Without the Mie signal, pure Rayleigh fringes are obtained, and if a Mie signal is added, fringes with a higher intensity, higher contrast, but the same phase, are obtained. Consequently, rather than being a disturbing effect, the occurrence of Mie scattering is beneficial, though not essential, to this technique.

Conclusion

Lidar systems optimized for Rayleigh or Mie signals are quite different systems, operating with different wavelengths, power levels and spectral analysis methods. Nevertheless, they are complementary instruments to characterize airflows. Rayleigh signals are more reliable, and can provide more information (speed, temperature, density), but generally require high energies. Mie signals require lower energies and are well-suited for speed measurements when the particle concentration is sufficiently high ■

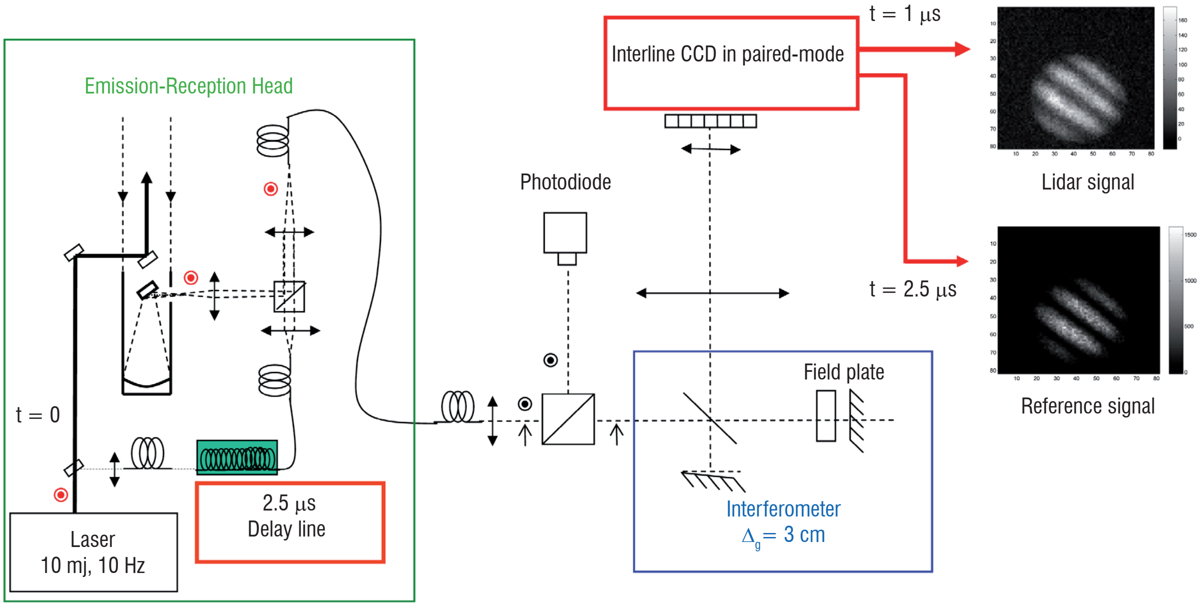


Figure 2 - This 355 nm Rayleigh-Mie Doppler lidar derives the wind speed from the differential phase measurement between fringes generated by the emitted laser pulse fringes and the atmospheric signal. With each laser pulse, the small time delay (2.5 µs using a 500 m fiber delay) between fringe records allows for minimization of the thermo-mechanical disturbances in the interferometer. The interferometer also comprises a field plate to match the fiber field angle at the interferometer input.

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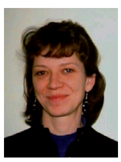

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