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Chapter 4

ENVIRONMENTAL MONITORING BY LASER RADAR

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Abstract

Since the discovery of laser, optical radars or lidars have been successfully applied to the monitoring of the three main environments of our planet: lithosphere, hydrosphere and atmosphere. The transmission of light depends on the medium: while in soil it does not propagate, in water and air it can typically travel for meters and kilometers, respectively. Analogously, three theoretical frameworks can be established: lidar equations for hard, dense and transparent targets. Such different behaviors drive the range of lidar applications in the three above mentioned environments. In the lithosphere, laser radars have been applied to three-dimensional scans of underground cavities. In the hydrosphere, lidar fluorosensors have been very effective in the bio-optical characterization of the first layers of sea waters. Such instruments are usually aboard planes and ships and can help filling the gap between in situ measurements and satellite imagery. The medium where lidars are unbeaten, at least for some purposes, is air. Atmospheric applications of laser radars range from troposphere (e.g. pollution monitoring in urban areas and wind speed measurements) to stratosphere (e.g. polar stratospheric cloud detection and ozone hole assessment), and even mesosphere (e.g. profiling of K and Na). The purpose of this paper is twofold: from one hand, the interested reader is introduced in lidar science and technology, to the other one, the researcher familiar with laser remote sensing is faced with some current investigations. The first aim is achieved by introducing the lidar principles, for hard, dense and transparent targets, and by illustrating selected case studies, taken from the experience of the author, in order to exemplify some relevant applications of such principles. The second one is pursued by describing in more detail the most recent results obtained by the author in the field of environmental monitoring by laser radar.

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1 Introduction

Lithosphere, hydrosphere and atmosphere play a major role in sustaining life on our planet. All the biogeochemical cycles take place on them or are part of the matter exchange among them. A thorough understanding of such global processes requires powerful tools.

Remote sensing can support a systematic investigation of natural processes, anthropogenic effects and their interactions. It can be either passive [Elachi 1987], using the Sun as a light source, or active [Measures 1992], being assisted by artificial light sources. The passive technique relies on observing the Earth, i.e. on measuring the sunlight backscattered by the planet surface at different wavelengths. It suits especially satellite borne sensors. The active method is usually based on the optical radar. It is applied mainly to air or ship borne sensors.

The revolutionary capabilities offered to environmental monitoring by light amplification by stimulated emission of radiation (laser) [Hecht 1985, Svelto 1998] have been firstly understood and exploited in the atmospheric field [Fiocco and Smullin 1963, Goyer and Watson 1963, Collis 1966]. Actually, the concept of light detection and ranging (lidar) has been introduced before the laser discovery, in the context of pulsed light detectors of clouds [Middleton and Spilhaus 1953]. Anyway, laser sources, because of high intensity, small divergence, good monochromaticity and the possibility of short pulse emission, are ideal tools for lidar and that word is today synonym of laser radar.

The measurement, up to many kilometers of height, of density, temperature and humidity of air, the detection of trace gases, the study of clouds, the observation of stratospheric aerosols, the probing of high atmosphere and the monitoring of pollutants are some examples among the possible atmospheric applications of lidar [Collis and Russel 1976, Measures 1992, Grant 1995].

Lidar has been successfully used also in the hydrosphere for bathymetric surveys in shallow waters, turbidity measurements, pollution detections, especially in case of oil spills, and phytoplankton mappings [Measures 1992, Grant 1995, Bunkin and Voliak 2001].

As far as lithosphere is concerned, lidar employment has been limited by the lack of light propagation in soil. In this case, the more relevant environmental applications of laser radar are related to the characterization of hollow spaces beneath the terrestrial surface, e.g. the three-dimensional scan of underground cavities by laser range-finder [Fiorani et al. 2000].

2 Lidar Principle

2.1 Hard Target (Lithospheric Applications)

A lidar is essentially composed of a transmitter (laser and beam shaping optics) and a receiver (telescope and signal detection electronics). Its principle of operation is illustrated in fig. 1: the target at the distance R from the system sends back part of the laser pulse toward the telescope surface. Consequently, the analysis of the detected signal as a function of t, time interval between emission and detection, allows one to measure R by the simple relation:

$$R = \frac{c\,t}{2}, \tag{1}$$

where c is the speed of light in the medium where the beam propagates, i.e. air in most cases.

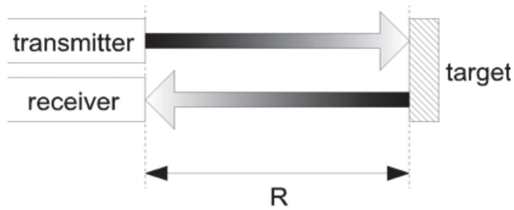

Fig. 1. Lidar principle of operation.

If the target is Lambertian [Jelalian 1992], contains the laser footprint and the transmitter divergence is smaller than the receiver field of view, the received power is given by [Mamon et al. 1978]:

$$P = P_0 \frac{A\,\eta_t\,\eta_r\,\rho}{\pi\,R^2} \exp(-2\,\alpha\,R), \tag{2}$$

where P_0 is the transmitted power, A is the receiver area, η_t and η_r are the transmitter and receiver efficiency, respectively, ρ is the target reflectivity and α is the laser beam extinction coefficient of the involved air volume. In this case, α is regarded as constant simply because R is small.

If the laser pulse is Gaussian, the accuracy in the measurement of the distance between lidar and target is given by [Carmer and Peterson 1996]:

$$\sigma_R^2 = \left(\frac{c\,\tau_L}{2}\frac{1.2}{SNR}\right)^2 + \left(\frac{c\,\tau_D}{2}\right)^2, \tag{3}$$

where τ_L is the pulse duration, SNR the signal-to-noise ratio and τ_D the resolution of the device measuring t.

Equation (3) is obtained under the assumption that any bias in the measurement of t has been avoided (as an example of source of bias, let us consider a threshold discriminator: such device measures the occurrence of a higher pulse before that of a lower one).

Typically, the distance between optical radar and target is obtained measuring <R>, mean of R calculated averaging on N laser pulses. The corresponding accuracy is:

$$\sigma_{<R>} = \frac{\sigma_R}{\sqrt{N}}. \tag{4}$$

If, as usual, the signal is detected by a detector coupled to a preamplifier, SNR can be written as [Jelalian 1992]:

$$SNR = \frac{i_s}{\sqrt{i_{sn}^2 + i_{bn}^2 + i_{dn}^2 + i_{an}^2}} , \tag{5}$$

where i_s is the signal current (root mean squared) and i_{sn}, i_{bn}, i_{dn} and i_{an} are the noise currents (root mean squared) due to, respectively, signal fluctuation (shot noise), environmental radiation (background noise), dark current (detector noise) and preamplifier (amplification noise). More explicitly [Mamon et al. 1978]:

$$SNR = \frac{Q\,G\,P}{\sqrt{2\,e\,B\,G^2\left(Q\,P + Q\,P_b + i_d\right) + B\,i_a^2}} , \tag{6}$$

$$Q = \frac{e\,\lambda\,\eta}{h\,c} , \tag{7}$$

$$P_b = A\,\eta_t\,\Delta\lambda\,H\,\Omega\left\{\rho\,\exp(-\alpha\,R) + \frac{1}{4}\left[1 - \exp(-\alpha\,R)\right]\right\}\frac{1}{\pi} , \tag{8}$$

where G is the detector gain, e is the electron charge, B is the receiver bandwidth, i_d is the detector dark current, i_a is the preamplifier noise current, λ is the transmitted wavelength, η is the detector quantum efficiency, h is the Planck's constant, $\Delta\lambda$ is the receiver passband, H is the solar irradiance and Ω is the receiver solid angle.

2.2 Dense Target (Hydrospheric Applications)

Let us consider the case of a fluorescing target, very important for natural waters because it allows one to detect chromophoric dissolved organic matter (CDOM) and chlorophyll-a (chl-a), the main indicator of phytoplankton. In this case, the principle of operation is called laser-induced fluorescence (LIF) and the instrument lidar fluorosensor. In general, the experimental system is above the sea (fig. 2), at a range R_w from its surface, and the laser beam, after propagation in air, probes a water layer characterized by the extinction coefficient α_w. Also in this case, the extinction coefficients in air and water are regarded as constant because the distances are small.

With respect to equation (2), ρ/π has to be replaced by the product of N_F (number density of fluorescing molecules) times σ_F (fluorescence cross section). The effect of the air-water interface on the propagation of forward and backward photons is taken into account with φ, two-way transmission factor, and m, refractive index of water (both can be regarded as constant because their variation with the wavelength is small). Moreover, the dependence of laser emission and transmitter/receiver efficiencies on the wavelength has to be considered but, once the transmitted and received wavelengths are fixed, all the related parameters can be included in the system constant k_F. If the transmitted beam is contained in the receiver field of view, $\alpha_w \times c \times \tau_L > 10$, $\tau_L/\tau_D < 5$ and $\tau_L > \tau$ (fluorescence decay time), hypotheses that usually hold for lidar fluorosensors aimed to CDOM and chl-a detection, the received energy is given by [Measures 1992]:

$$E_F(\lambda_F, R) = E_0 \frac{k_F \; A \, \varphi \, N_F(R) \sigma_F(\lambda, \lambda_F)}{R^2 \; m^2 \left[\alpha_w(\lambda) + \alpha_w(\lambda_F)\right]} \exp\{-[\,\alpha(\lambda) + \alpha(\lambda_F)]R_w\} \quad , \qquad (9)$$

where λ_F is the fluorescence wavelength and E_0 the transmitted energy.

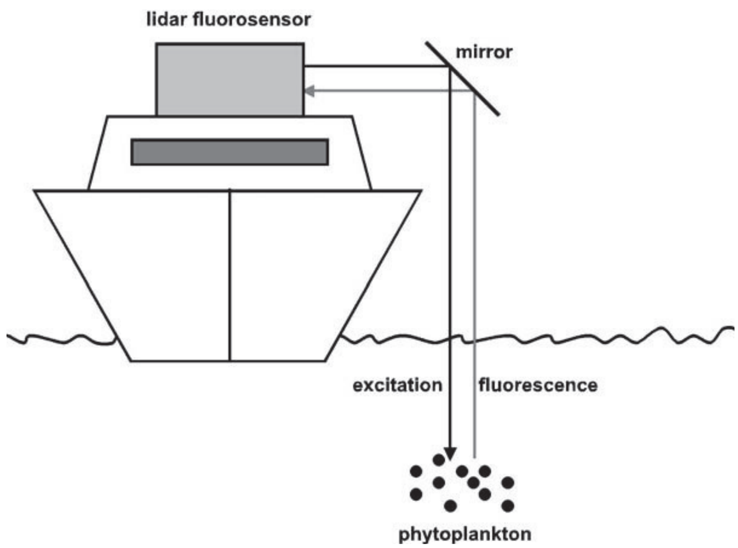

Fig. 2. Lidar fluorosensor principle of operation.

A similar equation can be written for the signal coming from Raman scattering of water [Measures 1992]:

$$E_R(\lambda_R, R) = E_0 \frac{k_R \; A \, \varphi \, N_R \; \sigma_R(\lambda, \lambda_R)}{R^2 \; m^2 \left[\alpha_w(\lambda) + \alpha_w(\lambda_R)\right]} \exp\{-[\,\alpha(\lambda) + \alpha(\lambda_R)]R_w\} \quad , \qquad (10)$$

where λ_R is the Raman-shifted wavelength, N_R the number density of water molecules (practically constant) and σ_R the Raman scattering cross section for the OH stretching vibrational mode of liquid water.

If fluorescence and Raman signal are acquired simultaneously, the following ratio (also called fluorescence in Raman units) can be calculated:

$$E^*(R) \equiv \frac{E_F(\lambda_F, R)}{E_R(\lambda_F, R)} = \frac{k_F \; N_F(R)\, \sigma_F(\lambda, \lambda_F)\, [\alpha_W(\lambda) + \alpha_W(\lambda_R)] \exp\{-[\alpha(\lambda) + \alpha(\lambda_F)] R_W\}}{k_R \; N_R(R)\, \sigma_R(\lambda, \lambda_R)\, [\alpha_W(\lambda) + \alpha_W(\lambda_F)] \exp\{-[\alpha(\lambda) + \alpha(\lambda_R)] R_W\}} \,. \quad (11)$$

If, as usual for CDOM and chl-a detection, the extinction coefficients ratio changes slowly and the exponentials ratio is close to unity, E* can be written as:

$$E^*(R) = k \frac{N_F(R)}{N_R} \,, \quad (12)$$

where k is a new system constant including also the cross sections. This latter formula implies that, in the above mentioned hypothesis, the fluorescence in Raman units is proportional to the density of fluorescing molecules. As a consequence, the absolute concentration of fluorescing molecules can be obtained calibrating the lidar fluorosensor with in situ measurements. The measurement error of the final result can be derived by the statistical parameters of that fit.

2.3 Transparent Target (Atmospheric Applications)

In case of atmospheric applications, the target and the medium before it are of the same nature. Usually, the target at range R is defined as the air layer defined by τ_D, i.e. delimited by the distances R and R+c×τ_D/2, because the photons detected in the time interval defined by t and t+τ_D come from that layer (fig. 3). Their number n is proportional to the thickness cτ_D/2 and to the laser beam backscattering coefficient β of the involved air volume [Measures 1992]: in fact, their product take the place of ρ/π in equation (2):

$$n(R,\lambda) = n_0(\lambda)\, \zeta(\lambda) \frac{A}{R^2}\, \beta(R,\lambda) \frac{c\tau_D}{2} \exp\left[-2\int_0^R \alpha(R',\lambda)\, dR'\right], \quad (13)$$

where n_0 is number of photons of the original pulse and the system efficiency ζ includes η_t and η_r.

Note that, in this case, α can not be regarded as constant because we are interested in long distance remote sensing and atmospheric layer with different optical density can be encountered by the laser beam.

The measurement errors will be discussed in section 5.