Lidar techniques for a SNSPD-based measurement

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Abstract. LIDAR, Light detection and ranging, is a remote measurement technique used to investigate the properties of the atmosphere. The detectors used in these measurements play a crucial role in the determination of the reached resolution, the maximum reached range and the acquisition time. Superconducting Nanowire Single Photon Detectors (SNSPD) have high performance (high detection efficiency, low timing jitter, low dead time, high maximum counting rate, good SNR) also at infrared wavelengths and they are good candidates to improve the quality of Lidar signals in IR region. To realize a SNSPD – based Lidar measurement, a study of the main Lidar techniques is presented in this work.

1. Introduction

First used in 1963 [1], lidar technique is widely used today in satellite, aircraft and ground-based measurements of the atmosphere and the terrestrial surface [2]. The study of the atmosphere with a lidar can provide not only important meteorological information, as atmosphere temperature, air humidity, clouds height and dimension [3], wind speed [2, 4], but it is also possible to investigate the presence of greenhouse gases and other pollutants[5-6] as ashes, dusts, and suspended particles that have been demonstrate to be a risk of premature death [7].

The investigation of carbon dioxide and other pollutants requires the usage of a lidar working with a laser emitting in the infrared region [8-9]. An infrared laser has also the great advantages of being eye-safe, allowing horizontal and full day measurements, lower atmospheric attenuation, minor disturbance from Rayleigh scattering, and larger particles detection. The critical issue in using such a laser is that the conventional single photon detectors performances drop drastically as the wavelength moves to infrared [10]. Particularly, due to high dark count rate, it is very difficult to distinguish signal to noise, mostly when moving to higher altitudes where the signal becomes lower.

Superconducting Nanowire Single Photon Detectors (SNSPD) indeed, have been demonstrated to be able to detect single photons also in the far infrared region [11], with an excellent signal to noise ratio (SNR) and high detection efficiency [12-13]. For those properties the application of SNSPDs to lidar
acquisition systems is very promising. Nevertheless, there are also some challenges to be overcome, as the coupling with light, complicated by the cryogeny and by the small dimension of the detector sensitive area (around 100\(\mu\)m\(^2\)).

In this work a brief description of the main lidar techniques is provided with a simulation of an acquired signal with a SNSPD.

2. Lidar equation

A basic lidar setup consists in two parts: a transmitter and a receiver. The transmitter includes the laser and a beam expander while the receiver is composed by a telescope that collects the backscattered radiation, the optics needed to select the correct wavelength and to collimate the light on the detector, a detector and a data acquisition and processing system. If a pulsed laser is used, it is possible to calculate the distance \(z\) of a target from the time of arrival of the backscattered photons.

The acquired signal power, \(P\), is a function of the distance \(z\), the light wavelength \(\lambda\) and is described by the lidar equation [2]:

\[
P(z, \lambda) = P_0 \frac{ct}{2} A \eta \frac{O(z)}{z^2} \beta(z, \lambda) \exp[-2 \int_0^z \alpha(z', \lambda) dz']
\]  

(1)

where \(P_0\) is the average power of a single laser pulse, \(c\) is the speed of light, \(t\) is its temporal length, \(A\) is the area of the receiving telescope, \(\eta\) is the system detection efficiency (SDE); the factor \(O(z)/z^2\) is the geometry factor and it contains the overlap function, that takes into account the overlapping between the laser beam and the telescope field of view, over the altitude square. The term \(\beta(z, \lambda)\) is the backscatter coefficient and represents the probability that a target of number density of particles \(N\) emits a returning signal at an angle \(\theta = \pi\). The exponential is the transmission term and it considers the fraction of light that gets lost; the extinction coefficient \(\alpha(z, \lambda)\) indicates the probability that the light that encounters a target of density of particles \(N\) is transmitted and the number two is needed because the transmission process is considered on the two ways. The keys parameters in the study of the atmosphere and of the aerosols are \(\alpha(z, \lambda)\) and \(\beta(z, \lambda)\).

An important feature of the lidar signal \(P(z, \lambda)\) is the very large dynamics that can reach up to 7 orders of magnitude. This implies extremely high specifications for the detection systems in terms of response times, noise and linearity. For that reason, in the most advanced lidar systems the limitations of the detection systems generally used, i.e. high-performance photomultipliers, are overcome by separately detecting the signals produced by limited altitude ranges. The possibility of using SNSPD detectors with response times lower than 10ps and noise of a few Hz, can increase the performance and simplify the design of a lidar device.

3. Lidar techniques

3.1. Elastic – backscatter lidar

Elastic backscatter lidar permits the localization of molecules and particles when the wavelength of the incident radiation remains unchanged during the scattering process. With this lidar it is possible to localize clouds, aerosols and molecules.

From Eqn. 1 it is also possible to estimate the expected number of photons through the formula [14]:

\[
N(z, \lambda) = P(z, \lambda) \Delta t / \hbar
\]  

(2)

This number represents the photons coming in a time bin \(\Delta t\). The acquired signal is increased by summing up the number of photons coming from different pulses but from the same altitude.
Figure 1: Simulated elastic backscatter lidar signals in the case of clean atmosphere (a) and in the presence of a homogeneous cloud between 10 and 12 km (b).

In Fig. 1 it is shown the expected signal in two cases: Fig. 1a is the molecular signal that is the signal coming from the clean atmosphere (nitrogen and oxygen), Fig. 1b presents the signal in the case of a cloud at 10km. The signals were simulated considering the typical performances of a multiparametric lidar system (MALIA Multiwavelength Aerosol Lidar Apparatus [15, 16]), with a telescope aperture of 30cm, an acquisition time of 15 minutes the repetition rate is 20Hz, the time binning of 100ns and the laser pulse energy of 0.65J at 2µm.

3.2. Raman lidar

The lidar technique based on elastic scattering is generally applied to the study of atmospheric particulate and clouds. Raman lidar can be used for the measurement of the concentration of some atmospheric gas. Raman lidar measurements are based on the weak inelastic scattering light produced by some molecules as water and ozone. The excitation of molecules vibrational and rotational levels causes a shift in the wavelength and, particularly, one refers to Stokes process when the light is red-shifted and to anti-Stokes when it is blue-shifted. The energetic shift depends on the molecule species and on the temperature as the population of the energetic levels follows Boltzmann distribution and it changes with the temperature. Hence, through Raman lidar, it is also possible to determine atmosphere temperature profile at different heights [17-18].

The low value of the cross section of Raman process involves a low signal to noise ratio and typically this type of measurement cannot be operated during daytime because of sunlight and detector noise. Furthermore, the dependence of the Raman cross-section from \( \lambda \) justifies the fact that this technique has been mainly applied in the UV region until now. Nevertheless, the use of SNSPD, due to the high SNR and low deadtime, could extend its application to the near infrared region and also to daylight measurements. In the case of Raman technique, the lidar equation can be rewritten as [2]:

\[
P_R(z, \lambda) = \frac{K_R(d(z))}{z^2} \beta_R(z, \lambda) \exp\left\{\int_0^z \left[\alpha_0(z') + \alpha_R(z')\right] dz'\right\}
\]

where the backscatter coefficient is given by the molecule number density \( N_R \) of the Raman-active gas and the cross section is the one of Raman process. The extinction coefficient is different on the two ways as the wavelength on the way back is shifted.

In general, the Raman technique makes use of two Raman signals: one is the signal of the gas to be detected and the other is due to a reference gas.

The calculation of the signal ratio \( P_R/P_{ref} \) permits the determination of the mixing ratio \( m(z) \) of the two gases

\[
m(z) = C \frac{P_R(z) \exp[-\int_0^z \alpha_{ref}(z') dz']}{P_{ref}(z) \exp[-\int_0^z \alpha_R(z') dz']}
\]

where \( C \) is the calibration constant which considers the differences in the backscatter coefficients and Raman cross section for the two species. The mixing ratio provides the relative concentration of the gas.

3.3. Lidar ratio and depolarization ratio
Simple backscatter signal provides only the localization and the extension of the target. Measurements of the optical parameters such as backscattering and extinction coefficients and of their spectral dependence are needed to gain more information. Among the parameters useful for a characterization of the target, one can analyse lidar ratio and the depolarization ratio.

Lidar ratio is defined as extinction to backscatter coefficients ratio at a fixed wavelength

$$ S(\lambda) = \frac{\alpha(\lambda)}{\beta(\lambda)} $$

and it provides information about target’s refractive index and size of atmospheric particles. The extinction and backscatter coefficients can be measured with a Raman lidar [19].

An analysis of the polarization of the acquired signal can provide further information about the shape of the particles [20-22]. In this case, the radiation emitted by the laser is polarized and the backscatter signal is separated through a beam splitter in parallel and perpendicular polarized signal. The depolarization ratio $\Delta$ is defined as the ratio of the return signal in perpendicular to parallel polarization relative to the emitted laser light, as given by the following equation:

$$ \Delta = \frac{P_\perp}{P_\parallel} $$

Typically, only the backscatter coefficient is polarization-dependent, and one refers also to the coefficient defined as $\delta = \beta_\perp/\beta_\parallel$. The value of $\delta$ is bigger if the scattering particles suspended in the atmosphere are not spherical. That is what happens in the case of dusts, ice crystals, marine salt, crystalized nitric acids etc.

In Tab.1, a collection of data shows how a combined analysis of $S(\lambda)$ and $\delta(\lambda)$ permits the identification of the target species [23].

| Particle        | Lidar ratio [sr] | Depolarization ratio [%] |
|-----------------|------------------|--------------------------|
| Marine salt     | 10-30            | 0-5                      |
| Burning biomass | 35-50            | 8-12                     |
| Pollution       | 45-60            | 0-5                      |
| Smoke           | 45-100           | 0-5                      |
| Dust            | 40-100           | 15-25                    |
| Volcanic ash    | 50-60            | 35-40                    |

3.4. Differential absorption lidar (DIAL)

This technique was developed to detect mostly ozone and industrial emission [2, 9, 29-30]. DIAL lidar operates by using two different wavelengths (UV or IR), one $\lambda_{on}$ where the trace gas has high absorption and another $\lambda_{off}$ where it absorbs less. Correspondingly, there are two detected signals, namely $P_{on}$ and $P_{off}$. Typically, the difference between the two wavelengths is small; this choice is made ensure that the contributions to the two signals due to the particulate and other molecular species are the same at the two wavelengths. If only the extinction coefficient $\alpha$ is affected by $\Delta \lambda$, one can write

$$ \Delta \alpha = N \Delta \sigma $$

where $N$ is the molecule number density of the gas, $\Delta \sigma = \sigma(\lambda_{on}) - \sigma(\lambda_{off})$, and $\sigma$ is the absorption cross section. Considering Eq. 1, the molecular number density can be obtained by the acquired signals by the formula [2,9]

$$ N = \frac{1}{2 \Delta \sigma} \left[ \frac{d}{dz} \ln \left( \frac{P_{on}}{P_{off}} \right) \right] $$

This formula represents the theoretical molecular number density, calculated in the limit of continuous acquisition. In practice, the backscattered photons are counted in time bins $\Delta t$ that
correspond to discrete altitude increments $\Delta z$. By considering also the discrete ranging, the molecular number density can be rewritten as

$$N = \frac{1}{2\Delta \sigma \Delta z} \ln \left[ \frac{P_{\text{off}}(z + \Delta z) P_{\text{on}}(z)}{P_{\text{off}}(z) P_{\text{on}}(z + \Delta z)} \right]$$

The minimum time binning, and the minimum range resolution, are related to $\Delta \sigma$.

Table 2: Wavelength and DIAL coefficient used to detect different gases [9]. The DIAL coefficient, defined as $k = 2.55 \times 10^{19} \sigma$, is provided to compare the absorption cross sections.

| Gas          | Wavelength [\mu m] | DIAL coefficient $k$ [cm$^{-1}$atm$^{-1}$] |
|--------------|---------------------|--------------------------------------------|
| H$_2$O vapor | 0.6944              | 0.00035                                    |
| CO           | 2.3                 | 0.4                                        |
| CO           | 4.74                | 10                                         |
| NO$_2$       | 0.45                | 7.2                                        |
| SO$_2$       | 0.30                | 26                                         |
| SO$_2$       | 7.4                 | 16                                         |
| SO$_2$       | 8.88                | 1                                          |
| C$_6$H$_6$   | 0.25                | 33                                         |
| O$_3$        | 0.29                | 12                                         |
| O$_3$        | 9.48                | 10.8                                       |
| NH$_3$       | 10.7                | 30                                         |
| NO           | 0.226               | 7                                          |
| NO           | 5.2                 | 4                                          |
| NO           | 5.31                | 10                                         |
| NO           | 5.5                 | 1.2                                        |
| CH$_4$       | 3.39                | 15                                         |

Table 2 shows the optimal wavelengths to be used to measure the concentration of each gas with the DIAL technique. In most cases, these wavelengths fall in the near infrared region, where the efficiency of the SNSPD detectors is very high [11-12] and their noise is so low that an improvement of the signal-to-noise ratio by several orders of magnitude compared to the detectors traditionally used in this spectral region is expected.

4. Conclusions

Different lidar techniques have been presented in this work. The use of a Superconducting Nanowire Single Photon Detector for a lidar measurement, due to the high SNR also in IR, can push further the maximum wavelength. This could be very advantageous mostly in the DIAL measurements, as lots of pollutants require $\lambda > 2\mu m$ to be detected. Providing high sensitivity and low dark count rate, also small concentrations of gases can be detected, and this feature can be very incisive in the scenario of environments defence protocols.

References

[1] Fiocco G and Smullin L D 1963, Nat. 199, 1275–76
[2] Weitkamp C, 2005 Lidar, Range-Resolved Optical Remote Sensing of the Atmosphere, Springer, Atlanta
[3] Winker D M, Pelon J and McCormick M P 2003, Proc. of SPIE 4893
[4] Korb C L, Gentry B M, Li S X and Flesia C 1998, *Appl. Opt.* **37**, 3097-104
[5] Fredriksson K, Galle B, Nystrom K and Svanberg S 1979, *Appl. Opt.* **18**, No. 17
[6] Johnson W B 1969, *Journal of the Air Poll. Cont. Ass.* **19**, 176-80
[7] Di Q, Dai L, Wang Y, Zabonetti A, Choirat C, Schwartz J D and Dominici F 2017, *Journal of the American Medical Association* **18**, 2446-56
[8] Baumagartner R A and Byer R L 1978, *Appl. Opt.* **17**, 3555-61
[9] Collis R T H and Russell P B 1976, *Lidar measurements of particles and gases by elastic backscattering and differential absorption*. In: *Laser monitoring of the atmosphere*, Springer-Verlag, New York
[10] Tosi A, Dalla Mora A, Zappa F and Cova S 2009, *Journal of Modern Optics* **56**, 299-308
[11] Marsili F, Bellei F, Najafi F, Dane A E, Dauler E A, Molnar R J and Berggren K K 2012, *Nano Lett.*
[12] Marsili F, Verma V B, Stern J B, Harrington S, Lita A E, Gerrits T, Vayshenker I, Baek B, Shaw M D, Mirin R P and Nam S W 2013, *Nat. Phot.* **7**, 210–14
[13] Dauler E A, Grein M E, Kerman A J, Marsili F, Miki S, Nam S W, Terai H, Verma V B and Yamashita T 2014, *Opt. Eng.* **53**
[14] Zhu J, Chen Y, Zhang L, Jia X, Feng Z, Wu G, Yan X, Zhai J, Wu Y, Chen Q, Zhou X, Wang Z, Zhang C, Kang L, Chen J and Wu P 2017, *Sci. Rep.* **7** 15113
[15] Mona L, Cornacchia C, D’Amico G, Di Girolamo P, Pappalardo G, Pisani G, Summa D, Wang X and Cuomo V 2007, *Q. J. R. Meteorol. Soc.* **133**, 257–71
[16] Garbarino S, Sorrentino A, Massone A M, Sannino A, Boselli A, Wang X, Spinelli N and Piana M 2016, *Opt. Expr.* **24**, 21497-511
[17] Di Girolamo P, Marchese R, Whiteman D M and Demoz B B 2004, *Geophys. Res. Lett.* **31**.
[18] Di Girolamo P, Behrendt A and Wulfmeyer V 2006, *Appl. Opt.* **45**
[19] Ansmann A, Riebesell M and Weitkamp C 1990, *Opt. Lett.* **15**, 746-8
[20] Schotland R M, Sassen K and Stone R 1971, *Journ. of Appl. Meteorol.* **10**, 1011-17
[21] Sassen K 2000, *Lidar backscatter depolarization technique for cloud and aerosol research*. In: *Light Scattering by non-spherical Particles: theory, measurements and geophysical applications*, Mishchenko M L, Hovenier J W and Travis L D, Academic press, San Diego CA
[22] Liou K N and Lahore H 1974, *Journ. of Appl. Meteor.*, **13**, 257-63
[23] Sugimoto N and Lee C H 2006, *Appl. Opt.* **45**, 7468-74
[24] Gross S, Tesche M, Freudenthaler V, Toledano C, Wiegner M, Ansmann A, Althausen D and Seefeldner M 2011, *Tellus* **63B**, 706-24
[25] Kanitz T, Ansmann A, Engelmann R and Althausen D 2013, *Journ. of Geophys. Res.* **118**, 2643–55
[26] Groß S, Freudenthaler W, Wiegner M, Gasteiger J, Greiß A and Schnell F 2012, *Atm. Env.* **48**, 85-96
[27] Sakai T, Nagai T, Nakazato M, Mano Y and Matsumura T 2003, *Appl. Opt.* **42**, 7103-16
[28] Baars H, Ansmann A, Althausen D, Engelmann R, Heese B, Muller D, Artaxo P, Paixao M, Pauliquevis P and Souza R 2012, *Journ. of Geophys. Res.* **117**
[29] Wandinger U, Muller D, Bockmann C, Althausen D, Matthias V, Bosenberg J, Weiß V, Fleibig M, Wendisch M, Stohl A and Ansmann A 2002, *Journ. of Geophys. Res.* **107**
[30] Koch G J, Barnes B W, Petros M, Beyon J Y, Amzajerdian F, Yu J, Davis R E, Ismail S, Vay S, Kavaya M J and Singh U N 2004, *Appl. Opt.* **43**, 5092-99.