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Polarization Lidar Calibration Techniques and Sensitivity Analysis

Yiming Zhao [*1], Antonella Boselli [2,3], Libera Nasti [4], Giaunluca Pisani [1,4], Nicola Spinelli [1,4], Xuan Wang [1,5]

[1]China-Italy Laser Remote Sensing Joint Research Center– Beijing Research Institute for Telemetry, Beijing, P.R. China

[2]China-Italy Laser Remote Sensing Joint Research Center– CNISM, Napoli, Italy

[3]CNR-IMAA, Potenza, Italy

[4]Dipartimento di Fisica, Università di Napoli "Federico II", Napoli, Italy

[5]CNR-SPIN, Napoli, Italy

[*1]zym_bird@hotmail.com; [2,3] boselli@imaa.cnr.it; [2,4]pisani@na.infn.it; [2,4]spinelli@na.infn.it; [2,5]wang@na.infn.it

Abstract

Calibrated lidar measurements of linear depolarization ratio provide highly reliable information to discriminate between spherical and non-spherical particles in the atmosphere and to distinguish between liquid and solid phase clouds. In this paper three different calibration techniques are described. For each technique a sensitivity analysis is performed and the different contributions to the total error are evaluated. The stability of atmosphere, the laser source polarization degree, the accuracy of polarization alignment and the background radiation are taken into account in the simulated depolarization measurements. The influence of these parameters and the choice of calibration range and calibration height are studied also. Two calibration techniques were experimentally validated by more than 28 calibration measurements in nearly 5 months. Furthermore aerosol depolarization measurements taken after the calibration are presented.

Keywords

Aerosol; lidar; backscattering; depolarization

Introduction

The aerosol impact on the atmospheric system is a complex task and it is still not perfectly well-known. Minute particles that are suspended in the atmosphere interact both directly, reflecting or absorbing sunlight, and indirectly modifying the clouds' properties and ultimately affecting the Earth's radiation budget and climate.

After the first depolarization Lidar measurements in 1971 (Schotland et al 1971) to characterize Hydrometeor, the Lidar measurement of particles depolarization has proved to be a very useful tool to characterize the shape and discriminate between spherical and non spherical aerosols (Sassen 1991). Particles in water clouds are spherical so they don't change the polarization plane of the backscattering light, while the ice clouds do, because they are strongly asymmetric scattering elements (Sassen 2000). Recent analyses of cirrus clouds used lidar-measured depolarization ratios to derive the effective shape ratios of cirrus cloud particles (Noel et al. 2002). Within the troposphere, polarization-sensitive Lidars are used to detect the presence of dust within the planetary boundary layer (Murayama et al. 2001). Depolarization ratio has also been used to discriminate between volcanic ash and sulphuric acid droplets in the stratospheric aerosol plume produced by the eruption of Mount Pinatubo in 1991 (Winker et al. 1992). Nowadays, there is a growing attention for Lidar depolarization measurements in order to deepen the knowledge of the multiple scattering effect and to correlate depolarization and extinction measurements. In such a context the Cloud Aerosol LIDAR and Infrared Pathfinder Satellite Observations (CALIPSO) mission was launched in April 2006 (Winker et al. 2003).

The key to derive accurate measurements of the depolarization ratio is performing a good calibration of the receiving system. Although in principle the depolarization measurements is relatively simple, the calibration presents a lot of problems. Three different calibration techniques for the polarization lidar will be discussed in detail in this paper and a long term calibration measurement results will be presented. Typical cases of aerosol depolarization measurement after calibration will be also presented.

Lidar depolarization measurements

The depolarization lidar technique makes use of a linearly polarized laser transmitter and a two-channel receiver capable of measuring the components of the return signal polarized parallel and perpendicular with respect to the transmitted beam. The calibrated ratio of these two components is known as the total depolarization ratio.

The Lidar equation for the depolarization case

The channel aligned with the initial direction of polarization of laser light is called "P-channel", while the orthogonal one is called "S-channel"..
The Lidar signals in the two channels have the following expressions:

$$P(z) = \frac{k_{//}}{z^2}\left[P_{//0}(\beta^a_{//}(z)+\beta^m_{//}(z)) + P_{\perp 0}(\beta^a_{\perp}(z)+\beta^m_{\perp}(z))\right]e^{-2\tau} \quad (1)$$

$$S(z) = \frac{k_{\perp}}{z^2}[P_{//0}(\beta^a_{\perp}(z)+\beta^m_{\perp}(z)) + P_{\perp 0}(\beta^a_{//}(z)+\beta^m_{//}(z))]e^{-2\tau} \quad (2)$$

where P and S refer to the power collected by the P and S channels, respectively. These signals are functions of the components of the initial powers of the laser source $P_{//0}$ and $P_{\perp 0}$, of the aerosol and molecular backscatter coefficients ($\beta^a_{\parallel}$ and $\beta^m_{\perp}$) for parallel and perpendicular components of the ingoing laser radiation, and of the atmospheric trasmissivity $e^{-2\tau}$. In the previous equations $k_{//}$ and $k_{\perp}$ are the efficiencies of the P and S channels respectively, and $P_{//0}$ / $P_{\perp 0}$ is the degree of polarization of the laser source.

In the above equations the effect of the polarization on the signal attenuation has been neglected.

The depolarization ratio is defined as the ratio of the backscattering coefficient for perpendicular and parallel polarization and it can be obtained from the combination of equations (1) and (2):

$$\delta(z) = \frac{\beta^a_{\perp}(z)+\beta^m_{\perp}(z)}{\beta^a_{//}(z)+\beta^m_{//}(z)} = \left(\frac{S(z)}{P(z)}H - k\right)\cdot\left(1-\frac{S(z)}{P(z)}H\cdot k\right)^{-1} \quad (3)$$

In the above equation, $H=k_{//}/k_{\perp}$ represents the calibration constant of the apparatus, i.e. the gain ratio. In normal conditions a single term k can be used to take into account both the not perfect linear polarization of the laser source and the not perfectly aligned receiving system (Biele et al. 2000).

If we suppose a perfect linearly polarized laser source, and a perfectly aligned receiving system, the equation (3) assumes the simplified expression:

$$\delta(z) = \frac{S(z)}{P(z)}H \quad (4)$$

The calibration techniques

The calibration constant H (gain ratio) is a necessary input to obtain the depolarization coefficient, and the accuracy of the calibration method strongly impacts on the quality of the depolarization measurements.

Throughout the paper we refer to the calibration techniques as:

1) Molecular or Rayleigh technique

2) 90° Technique

3) ±45° Technique

In the following paragraphs a detailed analysis of each of them is reported.

Molecular calibration technique

According to the molecular calibration technique, the molecular signal coming from an aerosol-free range is used as the calibration signal. The calibration signals are written as:

$$P_m(z) = k_{//}\left[P_{0//}\beta^m_{//}(z) + P_{0\perp}\beta^m_{\perp}(z)\right]e^{-2\tau} \quad (5)$$

$$S_m(z) = k_{\perp}\left[P_{0//}\beta^m_{\perp}(z) + P_{0\perp}\beta^m_{//}(z)\right]e^{-2\tau} \quad (6)$$

The molecular backscattering coefficients are known from the theory, hence the expression of the gain ratio results:

$$H = \frac{\sum_{i=1}^{n}(P_m(z_i)-b_p)}{\sum_{i=1}^{n}(S_m(z_i)-b_s)}\left(\frac{\delta_{mol}+k}{1+k\cdot\delta_{mol}}\right) \quad (7)$$

where $P_m(z)$ and $S_m(z)$ are the Lidar parallel and orthogonal signals in a free-aerosol range, and they are summed in the reference range to reduce the statistical errors, b_p and b_s are the parallel and orthogonal background components, and δ_{mol} is the molecular depolarization depending on the system characteristics and on the temperature (Behrendt et al. 2002).

This method allows to perform the calibration and the measurements simultaneously. The disadvantages are due to the fact that very often the aerosols are present also at medium altitude, therefore an aerosol free zone can only be found at very high altitude where the lidar signals are weak and the signal-to-noise ratio is very poor.

Orthogonal calibration method

The second method of calibration is obtained in two steps: firstly performing a regular measurement (P_1 and S_1 signals) and then turning the direction of the laser polarization by 90 degrees (P_2 and S_2 signals).
For this method the calibration constant has the following expression:

$$H = \sqrt{\frac{(P_2(z) - b_{2p}) \cdot (P_1(z) - b_{1p})}{(S_2(z) - b_{2s}) \cdot (S_1(z) - b_{1s})}} \qquad (8)$$

This method is based on the hypothesis of a stable atmosphere between the two set of measurements.

±45 degree calibration method

The $\pm 45°$ rotation technique is a calibration method recently proposed by Freudenthaler et al. [10]. It consists in the rotation of the laser's direction of polarization of 45° in one direction and 45° in the opposite direction, and in the recording of the signals of P and S channels in both positions.
With this calibration technique the gain ratio has the following expression:

$$H = 0.5 \cdot \left(\frac{P_2 - b_{p2}}{S_2 - b_{s2}} + \frac{P_1 - b_{p1}}{S_1 - b_{s1}} \right) \qquad (9)$$

To reduce the statistical error, the expression of the gain ratio (9) is evaluated as the weighted average, considering the signals at every altitudes in the chosen altitude range.

Sensitivity analysis

Our analysis is based on a simulation of real experimental conditions, supposing a known atmosphere and checking the results of the outputs with respect to the initial hypothesis.

To perform the simulation, the molecular density and the Rayleigh scattering coefficient were calculated by using the U.S Standard Atmosphere model with ground temperature of 20°C and pressure values of 1bar. In the adopted atmospheric profile a typical planetary boundary layer (PBL) of 1.5 km of altitude was considered, with an aerosol backscatter coefficient (β) of 1~5x10^{-6}sr^{-1}m^{-1}, aerosol extinction to backscattering ratio (also known as lidar ratio, LR) of 70~80sr, and an aerosol depolarization ratio of 0.03 (Reichardt et al., 2003) Between 3 and 4Km and between 4.5 and 5.5Km two aerosol layers were simulated, both characterized by a LR of 40sr. The first one was assumed with an aerosol depolarization ratio of 0.05, and the second layer was simulated with an aerosol depolarization ratio of 0.2 (desert dust) (Freudenthaler et al. 2006). Finally, a cirrus cloud is also simulated in the 9~10Km altitude range with β=8x10^{-6}sr^{-1}m^{-1} and LR=30sr and aerosol depolarization ratio of 0.3 (K.Sassen, 1991). A vertical resolution of 60m is considered for the lidar signals. The depolarization ratio of the pure molecular contribution was chosen as 0.00376 (Behrendt et al. 2002), at the supposed laser wavelength of 532nm.

The signals were simulated by choosing the values of the apparatus parameters in order to reproduce real measurements conditions: the energy pulse of the outgoing laser was fixed at 0.03J, considering the losses of the optical elements; the laser repetition rate was fixed at 20Hz, the overall system attenuation at 532 nm was set to 0.01; the overall efficiency of the photomultiplier detector was considered to be 0.05 and 0.1 for P and S, respectively. The radius of the telescope was 0.15m and the depolarization of the laser source was considered to be 0.002. The offset angle (the misalignment of P channel with respect to the laser direction of laser polarization) was fixed at 0.2 degree. The altitude range of the signals was taken from 30m to 40000m. The signals were averaged over 10 minutes.

In general, the depolarization ratio is affected by the error on signals, the laser depolarization, the background, the calibration range , the reference height and the misalignement angle. For the orthogonal and ±45° calibration methods, also the instabiltity of atmosphere represents a source of error. Moreover for the third method also the error of the calibration angles will also contribute to the total error. All of these factors will be analyzed in detail below.

In order to simulate the atmospheric instability the volume backscattering coefficient of the simulated depolarizing layers has been changed by 10%. This introduce an error of the same order in the gain ratio determined with the second method while the first and third methods appeared to be not sentitive to that.

In Fig. 1 the relative error of the gain ratio vs. the depolarization ratio of the laser is reported.

As Fig. 1 shows the relative error of the gain ratio as determine form the first method is much greather that for the second and third metods, moreover for the third method, is almost independent on the laser source depolarization ratio.

Fig. 2 shows the relative error on the depolarization ratio as a function of the the depolarization ratio of the laser souce, evaluated for the simulated layer at 5010m of altitude for all three calibration methods.

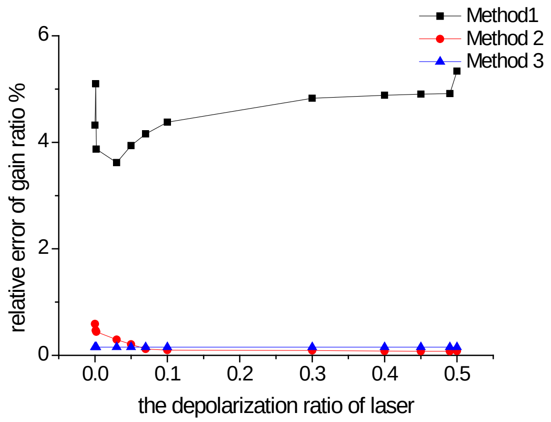

FIG. 1 RELATIVE ERROR ON GAIN RATIO AS A FUNCTION OF DEPOLARIZATION RATION OF THE LASER SOURCE

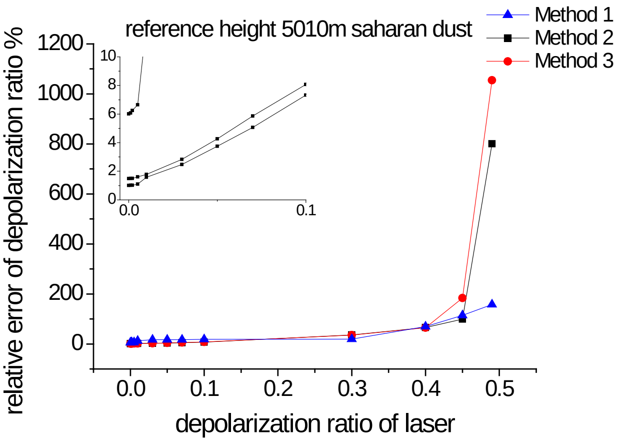

FIG. 2 RELATIVE ERROR ON DEPOLARIZATION RATION AS A FUNCTION OF DEPOLARIZATION OF THE LASER SOURCE FOR THREE CALIBRATION METHODS

The dependence of the relative errors of the depolarization ratio on the background level for each calibration method is shown in Fig. 3, by considering the simulated aerosol layer at 5010m of altitude. For the molecular calibration method the relative error of the depolarization ratio goes up most sharply with respect to the other methods. For the orthogonal and ±45° calibration methods the relative error of the depolarization ratio does not exceed 5%.

For all the three calibration methods a proper range for the calibration must be chosen. For that reason the variability of the relative error of the gain ratio with the altitude and the extension of the calibration range have been studied. Our results show that for the first method the range must be 2000m at least while for the second and third calibtation methods the trend of the relative error of the gain ratio with the range is descendent as a whole, being 0.25%<ΔG<0.8% for the second, and 0.2%<ΔG<0.27% for the third methods, respectively for ranges up to 9000m.

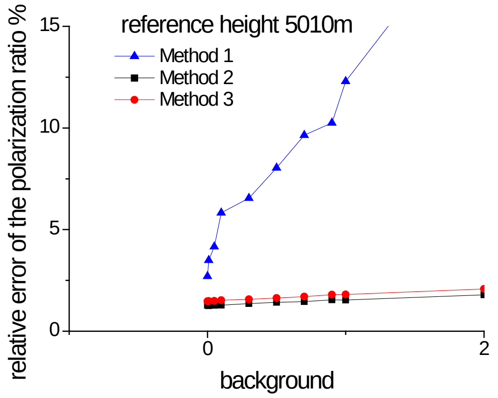

FIG. 3 RELATIVE ERROR ON POLARIZATION RATIO AS A FUNCTION OF BACKGROUND LEVEL

Of course, for the molecular calibration method is mandatory to chose the reference height in a aerosol free layer, where the calibration signal well approximates the pure molecular signal. Moreover, with this calibration method, the errors increase enormously at higher heights also for the gain ratio. The gain ratio relative error varies with the reference height between 0<ΔG<4% for the orthogonal calibration method and between 0<ΔG<3% for the ±45° calibration method. Our results also indicate that the best choice of the reference height is within the mineral dust layer for second and third methods.

For the ±45° calibration method another source of error is the positioning of half wavelength waveplate in order to fix the polarization direction of the laser beam at the calibration angles of ± 45 degree. We evaluated the errors on the depolarization ratio relative error of the three simulated aerosol layers and the gain ratio relative error with respect to the deviation of the positioning angle from 0 to 20 degrees.

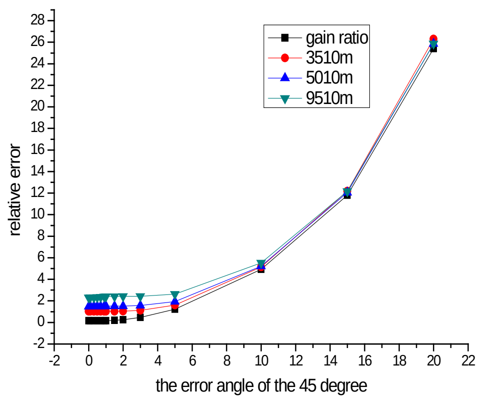

FIG. 4 RELATVE ERROR ON GAIN RATIO AS A FUNCION OF THE POSITIONING ANGLE FOR ± 45 DEGREES CALIBRATION METHOD

Results are shown in the Fig.4. When the deviation of the calibration angle is smaller than 5 degree, the relative error is lower than 2.7%. Above 5 degree the relative error of the gain ratio will increase sharply.

Experimental results

The MALIA (Multi-wavelength Aerosol LIdar Apparatus) system is a multiparametric Raman Lidar system working in Napoli (Italy) since 2000 and equipped with P and S channels for the depolarization measurement at 532nm (Wang et al. 2008).

In the figure 5 the temporal evolution of the gain ratio, obtained by the molecular and ±45° calibration procedures is showed.

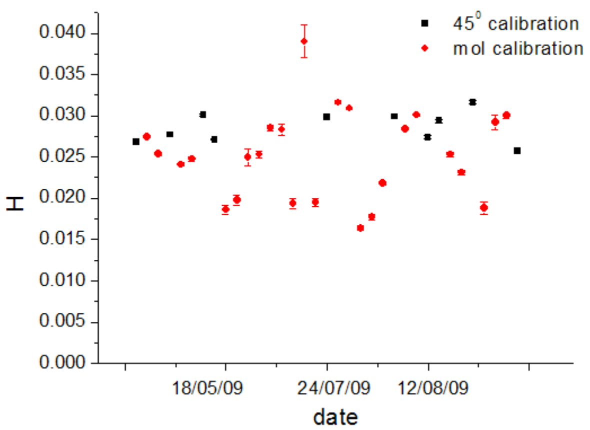

FIG. 5 TEMPORAL EVOLUTION OF THE GAIN RATIO FROM MOLECULAR AND ±45° CALIBRATION METHODS

The gain ratio average values are $2.81\cdot10^{-2} \pm 6\cdot10^{-4}$ and $2.7\cdot10^{-2} \pm 1\cdot10^{-3}$ for ±45° calibration technique and molecular calibration, respectively. Anyway, the molecular technique results to be much less accurate than the ±45° calibration procedure and, in addition, it cannot be applied for every atmospheric condition.
Here after we present an example of depolarization measured performed in Napoli on 08 May 2010 (Fig.6). After the eruption of Eyjafjallajökull volcano on April 2010, the MALIA system was utilized to measure the Eyjafjallajökull ash plume optical properties above the city of Napoli. In that day and according to the backward trajectories, air masses came over Napoli from West, after they were transported over the Iberia Peninsula. This means that volcanic ashes remained several days above the Atlantic Oceans and this could have influence on the optical properties. The volcanic aerosol can be identified by the high value of aerosol linear depolarization, which in these measurements reaches the peak value of 11±5%. It was located between 3.0 and 4.2Km. The measured value of optical depth at 532nm was estimated as $(5.5\pm1.0)\cdot10^{-2}$ and the corresponding lidar ratio was 44 ± 5 sr.

Similarly, OD measured at 355 was $(8.4\pm1.3)\cdot10^{-2}$ with a lidar ratio of 45 ± 5sr. These values of LR are in agrement with those measured over Potenza (Mona et al. 2012) but they are less than those observed over Germany, where Ansmann (Ansmann et al. 2011) and Wiegner (Wiegner 2012) reported on values in the range from 50sr to 60sr. Differences can be due to the longer journey of the particle from the source up to Southern Italy.

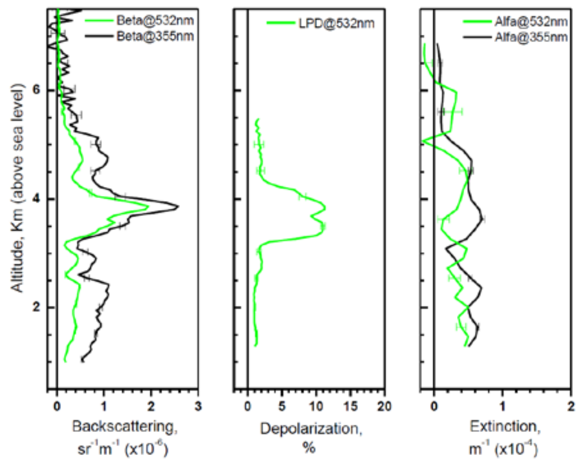

FIG. 6 AEROSOL BACKSCATTERING AT 355 AND 532 NM, LINEAR PARTICLE DEPOLARIZATION AND AEROSOL EXTINCTION AT 355 AND 532 NM MEASURED FROM MALIA ON 08 MAY, 2010. THE INTEGRATION TIME WAS 120 MINUTES, STARTING AT 17:30 UT, CORRESPONDING TO NIGHT-TIME CONDITIONS.

Conclusions

In this paper a comparative analysis of three different calibration techniques to obtain total depolarization ratio from lidar measurements is reported.

The first method performs an instantaneous calibration to the molecular backscattered signal by calibrating the signal on the molecular contribution in an aerosol free region. The advantage of this method is that the calibration is performed at the same time of measurement. The main disadvantage is in the sensitivity to the choice of the molecular range .

The second and the third methods are based on rotation of the polarization direction of the laser source by 90 degree and ±45, respectively. These two methods need additional hardware in the optical path. Moreover, the second method is sensitive to atmospheric instabilities.

The three-steps method results to be the most accurate and reliable in every atmospheric conditions.

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Nicola Spinelli was born in 1947, hee received the Laurea degree in physics from the University of Rome in 1971. From 1971 to 1974 he was postgraduate fellow at the Istituto di Fisica Sperimentale University of Naples. From 1974 until 1982 Assistant of General Physics and teacher on annual contract of experimental physics From 1982 to 1994 he was associate professor of General Physics and from 1994 he has been full professor of Experimental Physics at University of Basilicata and then at University of Naples "Federico II. He has been member of the scientific committees of several Italian institutions and president of the National Interuniversity Consortium for the Physical Sciences of Matter.

He has been active on atomic and molecular physics: electron collision induced ionisation-dissociation of molecules, mass spectroscopy, translational spectroscopy and multiphoton ionisation spectroscopy. Its work has been dealing with the experimental characterisation and modelling of plasma produced by laser ablation of metallic and superconductive targets. Mass spectrometry and electron spectroscopy have been applied to the study of charged species and of their evolution in the laser generated plume and combustion generated particles. His main research interests regard the environmental applications of laser spectroscopy and remote sensing of the atmosphere by active optical methods. He was responsible of the development of several lidar apparatuses using different spectral regions (UV, VIS and NIR) and techniques (Elastic

scattering, Raman scattering and Differential absorption).

Antonella Boselli was born in Naples, Italy, on 1966. She received the Laurea degree in physics from the at University of Naples "FedericoII" on 1994. She is permanent researcher at the Institute of Methodologies for Environmental Analysis (IMAA) of the National Research Council since December 2001.

Her main research interests are in the field of chemical and physical characterization of the atmosphere with laser remote-sensing systems (LIDAR). Her research activity included optical and microphysical characterization of atmospheric aerosol also rising from large scale transport phenomena, with particular reference to Saharan dust and volcanic ash transport events, analysis of multiple scattering processes and depolarization effects on lidar signals, validation of satellite data with lidar data and their integration with model results and in-situ measurement. She was involved in developing several advanced lidar systems for research purpose.

Xuan Wang was born in Kaifeng, Henan, China in 1962. He received his B.S. and M.S. degree in Physics, in 1984 and 1987, respectively, from Nankai University, China. In 2001, he got his Ph.D in Physics from University of Naples "Federico II", Napoli, Italy. Currently, he is permanent researcher in Italian National Research Council (CNR) – SPIN Institute.

His main scientific activity is laser application, including lidar, laser remote sening, and laser ablation.

Yiming Zhao was born in Taiyuan, China, in 1983. She received the B.S. degree in electrical science & technology from Shanxi University in 2004, and Ph.D. degree in physical electronics from Beijing University of Aeronautics and Astronautics in 2009. She is currently a senior engineer at Beijing Research Institute for Telemetry (BRIT). Her main research interests are in the field of application of laser technology, include development of laser radar, atmospheric and ocean environmental monitoring.