

Compact Raman lidar for Atmospheric CO₂ and Thermodynamic ProfilING - CONCERNING

Paolo Di Girolamo^{1[0000-0002-7420-3164]}, Davide Dionisi^{2[0000-0003-3854-521X]},
Marco Cacciani^{3[0000-0001-9380-6967]}, Annalisa Di Bernardino^{3[0000-0003-3765-2179]},
Noemi Franco^{1[0000-0001-6605-9847]}, Donato Summa^{4[0000-0002-0867-4144]},
Marco di Paolantonio^{1[0000-0001-6892-2835]}, Anna Maria Iannarelli^{5[0000-0001-7056-7924]},
Tatiana Di Iorio^{6[0000-0001-8872-8917]}

¹ Scuola di Ingegneria, Università della Basilicata, Potenza, Italia,
E-mail: paolo.digirolamo@unibas.it

² ISMAR-CNR, Roma, Italia, E-mail: davide.dionisi@artov.ismar.cnr.it

³ Dipartimento di Fisica, 'Università degli Studi di Roma "Sapienza", Roma, Italia

⁴ IMAA-CNR, Tito Scalo (Potenza), Italia, E-mail: donato.summa@imaa.cnr.it

⁵ SERCO-ESA/ESRIN, Frascati, Italia, anna.iannarelli@gmail.com

⁶ ENEA Centro Ricerche Casaccia, Italia, Email: Tatiana.diiorio@enea.it

Abstract. The research project CONCERNING was funded by the Italian Ministry of University and Scientific Research as part of the "Special Integrative Research Fund (FISR) 2019" Call. The project is aimed at the design and experimental development of an innovative Raman lidar system for measuring the vertical profiles of the two main greenhouse gases present in the atmosphere, i.e. CO₂ and water vapor, as well as temperature and multi-wavelength particle backscatter, extinction, fluorescence and depolarization profiles. The capability to measure this suite of atmospheric compositional and thermodynamic properties represents an important observational potential for improving our understanding of feedback and coupling mechanisms of these two species with the biogeochemical cycles in the Earth system.

The low-weight compact ground-based system has been sized to accurately measure the above mentioned parameters with high time and space resolution to allow for the resolution of convection scales and turbulent processes. Such a system, exploiting both the rotational and vibrational Raman lidar techniques in the UV through cutting-edge technologies for spectral selection, optical signal detection and data acquisition, is hosted in sealed and rugged container, equipped with fused-silica windows, and capable to operate in all-weather conditions. The development of the prototype and the verification of its measurement capabilities, possibly assisted by specific measurement campaigns, will allow to demonstrate the enormous potential impact of a network of these systems.

Keywords: Low-weight compact ground-based Raman and fluorescence lidar, aerosol typing, size and microphysical properties, atmospheric thermodynamic properties.

1 Introduction

Atmospheric CO₂ content has enormously increased in recent decades, from values close to 300 ppm in the 1950s to the current 415-420 ppm, with an annual increase rate of around 2 ppm. About half of the amount of CO₂ produced through the combustion of fossil fuels and other human activities is released into the atmosphere and accumulates there. The remaining half is absorbed by the oceans and the terrestrial biosphere [1]. An adequate quantitative assessment of the various components of the carbon cycle therefore requires accurate measurements of the sink and source mechanisms and, ultimately, an accurate estimate of the Gross Primary Production (or GPP). To quantify the atmospheric CO₂ uptake by forests and its contribution to the carbon cycle, accurate measurements of CO₂ gradients between the forest floor and the top of the canopy are needed [2], as well as measures of their temporal variations. This requires accurate, high vertical and horizontal resolution measurements of the CO₂ mixing ratio profiles. In defining the observational requirements for CO₂, it must be taken into account that its seasonal and annual mean profiles are determined by the combined effect of surface flows and atmospheric mixing. During the summer season in the Northern Hemisphere, atmospheric CO₂ concentrations are typically lower in the Planetary Boundary Layer (PBL) and higher in the free troposphere, due to the prevalence of the effects of photosynthesis over those of industrial emissions [3]. On the contrary, during the winter season, the respiration of the animals and vegetation, the vegetation decay and the use of fossil fuels determine the presence of higher CO₂ concentrations in the PBL and lower in the free troposphere. The amplitude gradients are comparable in the two seasons (of the order of 10 ppm). Additionally, as a result of forest capture, CO₂ gradients between the forest floor and the top of the canopy (~30 m) are between 75-100 ppm during the day and 10-50 ppm at night, in spring conditions, when the development of the leaf area of the canopy is not completed. The above considerations suggest the need for CO₂ mixing ratio vertical profile measurements with an accuracy of 2-5 ppm, with vertical resolutions of the order of 100-200 m (to be increased up to ~10 m in the surface layer) and with temporal resolutions of the order of 1 hour.

Although the space and ground network for CO₂ monitoring has regularly expanded over the past 50 years, it presently does not guarantee the necessary spatial and temporal resolution needed for a quantitatively reliable characterization of CO₂ sources and sinks and the atmospheric component of the carbon cycle. Additionally, presently operational space sensors provide CO₂ measurements above forest canopies, which do not allow to properly estimate Gross Primary Production.

For what concerns the atmospheric thermodynamic properties, it has to be underlined that our current understanding of the Earth's hydrological and energy cycle shows important gaps on all spatial and temporal scales due to the unavailability of accurate measurements with high vertical and temporal resolution of the atmospheric humidity and temperature profiles, especially in the lower troposphere. These measurements are fundamental to improve meteorological forecasts and analyses and are of primary importance for the study of Atmosphere-Earth feedback mechanisms.

The measurement gaps illustrated above can be filled with the development and operation of roto-vibrational Raman lidar systems with the capability to profile measurements of atmospheric temperature, water vapour and CO₂ mixing ratio simultaneously with high accuracy and precision, as well as with high vertical and temporal resolution. By exploiting the three wavelengths emitted by a Nd: YAG laser source in the UV, VIS and nIR and the polarized and depolarized elastic lidar (Rayleigh-Mie) and Raman echoes from atmospheric constituents, the low-weight compact ground-based system developed in the frame of the research project CONCERNING will carry out vertical profile measurements of atmospheric temperature, water vapour and CO₂ mixing ratio, the particle backscatter coefficient at 354.7, 532 and 1064 nm, the extinction coefficient at 354.7, 532 nm, and the depolarization ratio at 354.7, 532 and 1064 nm. A specific channel will measure fluorescence from atmospheric particles and marine chlorophyll to be used for the purpose of aerosol typing [4].

The system is presently under development. A simulation model was applied to simulate the expected performance of the Raman lidar. More specifically, an end-to-end lidar simulator was also applied in the verification of the "instrumental concept" of the lidar system and in the definition of the technical specifications of the laser source, telescope, spectral selection devices and detectors. The possible "trade-offs" between the optical power of the laser source and the telescope aperture were evaluated and different values of the divergence of the laser beam and the field of view of the receiver were considered. Specifically, a solid state laser source (Nd:YAG) was considered with the capability of emitting pulses with a repetition frequency of 100 Hz and a single pulse energy of 100 mJ at 354.7 nm. A telescope with a primary mirror diameter of 0.5 m was considered. The following spectral specifications were also considered for the interference filters: 1) filter for the Raman signal of water vapour (H₂O), central wavelength: 407.5 nm, bandwidth (FWHM): 0.3 nm, peak transmission: 83%; 2) filter for the Raman signal of molecular nitrogen (N₂), central wavelength: 386.7 nm, bandwidth (FWHM): 0.3 nm, peak transmission: 83%; 3) filter for the Raman signal of CO₂, central wavelength: 371.71 nm, bandwidth (FWHM): 0.15 nm, peak transmission: 60%; 4) 354.7 nm elastic signal filter, bandwidth (FWHM): 0.5 nm, peak transmission: 80%; 5) filters for N₂ and O₂ rotational Raman signals, bandwidth (FWHM): 0.3 nm (LoJ) and 0.5 (HiJ), peak transmission: 80%. In the various measurement channels, detectors with quantum efficiency at 354.7 nm equal to 40% and photon count samplers were considered.

Figure 1 illustrates the simulated vertical profiles of the statistical measurement uncertainty (precision), obtained by considering a temporal and vertical resolution of 1 min (3 hours for CO₂) and 50 m respectively and two possible environmental noise conditions (day and night). The figure includes the results for the mid-latitude summer atmosphere model. The simulations show that the statistical uncertainty affecting night-time measurements of the atmospheric temperature profile is smaller than 0.5 K up to an altitude of 10 km and smaller than 1 K up to 15 km, while the statistical uncertainty characterizing daytime measurements is less than 0.5 K up to 7 km and less than 1 K up to 9 km. Simulations also show that the statistical uncertainty affecting night-time water vapor mixing ratio measurements is less than 5% up to 7 km and less

than 20% up to 10 km, while the statistical uncertainty of daytime measurements is smaller than 10% up to 3.5 km and smaller than 30% up to 5 km.

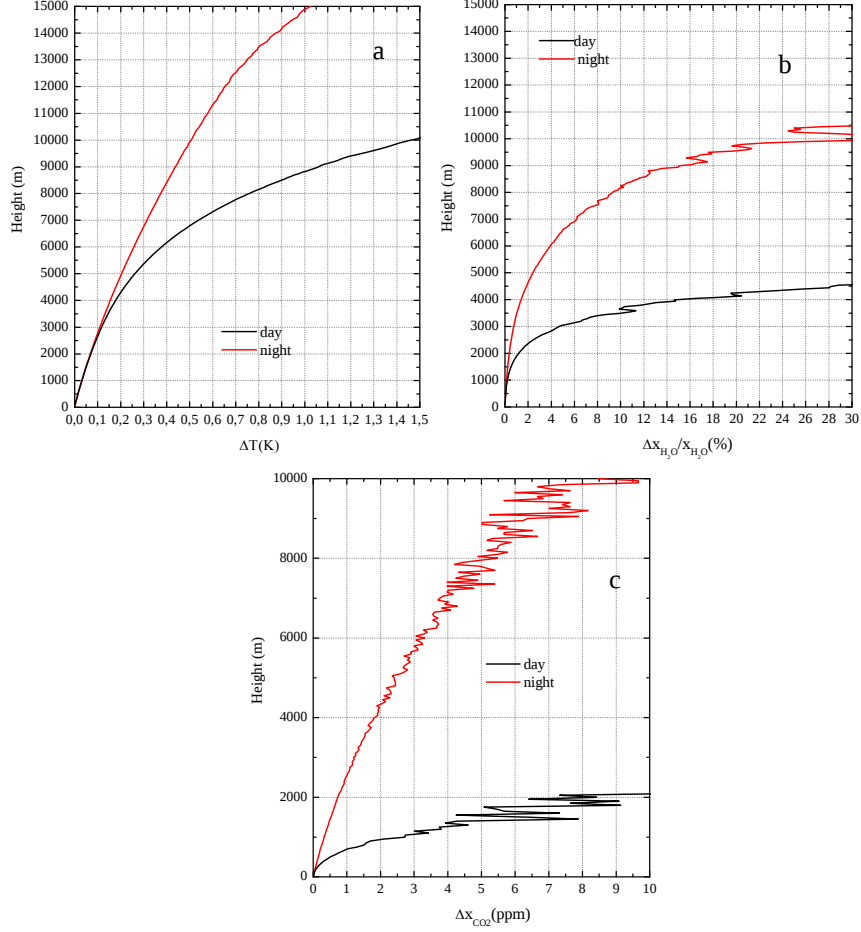


Figure 1: Vertical profiles of the statistical uncertainty for (a) temperature [K], (b) water vapour mixing ratio of [%] and (c) of carbon dioxide [%].

The optical design includes a diode-pumped Nd:YAG “Master Oscillator - Power Amplifier” laser source configuration. The single pulse energy at 355 nm is 110 mJ and the frequency repetition is 100 Hz (UV radiant power of 11 W). The telescope, in Dobsonian configuration, has a primary mirror with a diameter of 500 mm, a focal ratio equal to 3.6, therefore corresponding to a focal length of 1800 mm. The distance between the primary and secondary mirrors is about 1500 mm, with the secondary mirror having an elliptical shape inclined by 45 ° in order to make it possible to position the telescope focus on a plane placed laterally outside the telescope tube (figure 27). Figure 2 illustrates the optical layout for the lidar receiver. The preliminary

breadboard of the system is shown in figure 3, which shows the instrumental frame including the telescope, the receiving channels and the signal sampling system.

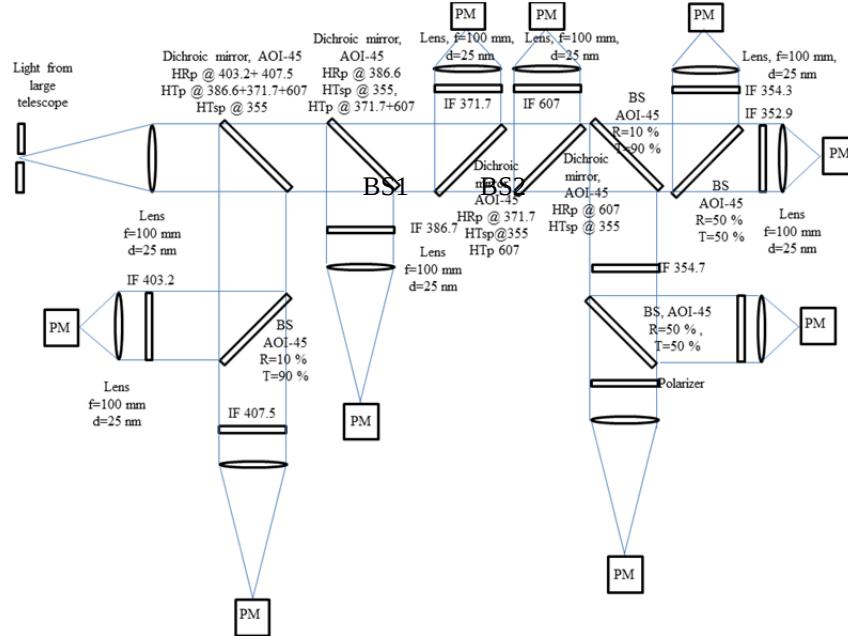


Figure 2: Receiver optical layout.

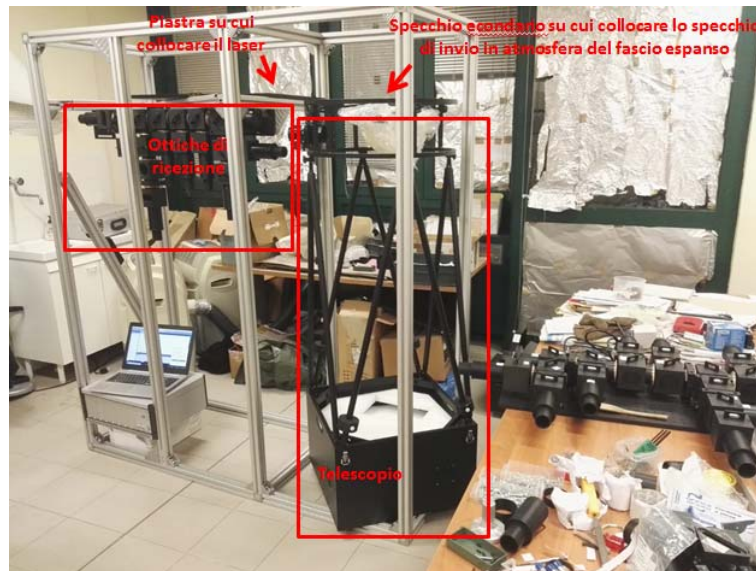


Figure 3: Preliminary breadboard of the system.

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