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Bistatic LIDAR System for the Characterisation of Aviation-Related Pollutant Column Densities

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Abstract. In this paper we investigate an innovative application of Light Detection and Ranging (LIDAR) technology for aviation-related pollutant measurements. The proposed measurement technique is conceived for the high-resolution characterisation in space and time domains of aviation-related pollutant gases. The system performs Integral Path Differential Absorption (IPDA) measurement in a bistatic LIDAR measurement setup. The airborne component consists of a tuneable Near Infrared (NIR) laser emitter installed on an Unmanned Aircraft (UA) and the ground sub-system is composed by a target reference surface (calibrated for reflectance) and a differential transmittance measuring device based on a NIR Camera calibrated for radiance. The specific system implementation for Carbon Dioxide (CO_2) measurement is discussed. A preliminary assessment of the error figures associated with the proposed system layout is performed.

Introduction

The principal goal of the research presented in this paper is to investigate new accurate and inexpensive techniques for the measurement of pollutants concentrations in the vicinity of airports and dense air traffic areas. In particular, a growing scientific interest is associated with the measurement of spatial and temporal variation of macroscopic observables, and on the microphysical and chemical properties of atmospheric constituents, including molecular, aerosol and particulate species [1, 2]. Due the advent of powerful tuneable laser sources, a variety of LIDAR systems have been developed for measuring the column density of various important molecular species, both locally and over extended geographic areas [3-9]. Optical absorption spectroscopy was also successfully applied to SO_2 concentration measurements [10]. A variety of ground-based, airborne and spaceborne applications are conceived, including gliders, balloons, parachutes, roving surface vehicles, satellites and interplanetary sondes. The proposed techniques are particularly suited for remote sensing missions performed by Unmanned Aircraft (UA) and satellites. This research is consequential to the PILASTER test range Design, Development, Test and Evaluation (DDT&E) activities, documented in [2, 11-17]. In [18] we introduced the measurement system and discussed the rationale supporting its development. An in situ calibration setup was also introduced.

Atmospheric Laser Beam Propagation

The propagation of laser radiation in atmosphere is affected by a number of linear and nonlinear effects. Assuming a Gaussian profile of the laser beam at the source and an average focused irradiance, the comprehensive expression of the peak irradiance, I_P, accounting for absorption, scattering, diffraction, jitter, atmospheric turbulence and thermal blooming effects is [19]:

$$I_P(z,\lambda) = \frac{b(z)\,\tau(z,\lambda)\,P(\lambda)}{\pi\left(a_d^2(z,\lambda) + a_j^2(z) + a_t^2(z,\lambda)\right)} \tag{1}$$

where z is the linear coordinate along the beam, λ is the wavelength, $P(\lambda)$ is the transmitted laser power, b is the blooming factor, $\tau(z,\lambda)$ is the transmittance coefficient, which accounts for absorption and scattering associated with all molecular and aerosol species present in the path. The

1/e beam radiuses associated with diffraction, $a_d(z,\lambda)$, beam jitter, $a_j(z)$, and turbulence, $a_t(z,\lambda)$, can be calculated as [2, 19]:

$$a_d(z,\lambda) = \frac{Qz\lambda}{2\pi a_0} \tag{2}$$

$$a_j^2(z) = 2\langle \Theta_x^2 \rangle\, z^2 \tag{3}$$

$$a_t(z,\lambda) = \frac{2\, C_N^{6/5} z^{8/5}}{\lambda^{1/5}} \tag{4}$$

where Q is the beam quality factor, a_o is the beam *1/e* radius, $\langle \Theta_x^2 \rangle$ is the variance of the single axis jitter angle that is assumed to be equal to $\langle \Theta_y^2 \rangle$, and C_N^2 is the refractive index structure constant. An empirical model for the blooming factor $b(z)$, which is the ratio of the bloomed I_B to unbloomed I_{UB} peak irradiance, is:

$$b(z) = \frac{I_B}{I_{UB}} = \frac{1}{1 + 0.0625\, N^2(z)} \tag{5}$$

N is the thermal distortion parameter, calculated as:

$$N(z) = \frac{-n_T\, \alpha_m\, P\, z^2}{\pi\, d_0\, v_0\, c_P\, a_0^3} \cdot \left[\frac{2}{z^2}\int_0^R \frac{a_0}{a(z')}\, dz' \int_0^{z'} \frac{a_0^2\, v_0\, \tau\, ''}{a}\, dz''\right] \tag{6}$$

where v_o is the uniform wind velocity in the weak attenuation limit ($\gamma z << 1$), n_T , d_o , and c_p are, respectively, the coefficients of index change with respect to temperature, density, and specific heat at constant pressure. The transmittance coefficient τ depends on the integral effect of absorption and scattering phenomena, both for molecular and aerosol species, on the entire beam length. The expression of Beer's law highlighting such dependences can therefore be written as:

$$\tau(z,\lambda) = e^{-\int_0^z \gamma(z,\lambda)\, dz} = e^{-\int_0^z [\alpha_m(z,\lambda) + \alpha_a(z,\lambda) + \beta_m(z,\lambda) + \beta_a(z,\lambda)]\, dz} \tag{7}$$

where α are the absorption coefficients and β are the scattering coefficients, the subscripts m and a refer respectively to molecular and aerosol contributions. Since for our derivation it is not necessary to distinguish the four contributions, we adopt the following model:

$$\tau(z,\lambda) = e^{-\int_0^z \gamma(z,\lambda)\, dz} = e^{-\int_0^z \sum_i [\psi_i(\lambda) \cdot n_i(z)]\, dz} \tag{8}$$

where:

$\psi_i(\lambda)$ = cross-section of the i^th^ species

n_i = molecular volume density of the i^th^ species

Chemical species with perceivable vibrational modes manifest significant spectral features in their cross-sections. If their molecular volume density in the propagation medium is sizeable, the transmittance spectrum is also significantly affected, and this enables unambiguous species detection.

Bistatic LIDAR Measurement System

The measurement system is based on the Integral Path Differential Absorption (IPDA) technique. The laser source emits beams at two predefined wavelengths. The first wavelength, λ_{ON}, is selected in correspondence of a major vibrational band of the pollutant molecule (on-absorption line), where the molecular cross-section is significantly enlarged. The second wavelength, λ_{OFF}, is selected in proximity of the first, but outside the vibrational band (off-absorption line). The selection of λ_{ON} and λ_{OFF} shall be based on the maximisation of the difference in cross-sections, $\Delta\psi \triangleq \psi(\lambda_{ON}) - \psi(\lambda_{OFF})$, but the limited spectral coverage of compact state-of-the-art laser emitters restricts the possible combinations. Moreover, both wavelengths should be selected in a relatively transparent region in the spectrum of all remaining species, and clear from their transition/vibration features. A number of databases and atmospheric Radiative Transfer Model (RTM) codes are available and allow an accurate estimation of the propagation spectrum at specific wavelength, for the identification of the optimal IPDA wavelengths combination based on the mentioned criteria. From Eq. 8, the fraction between the measured incident laser energy associated with the on-absorption line of pollutant species P and the one associated with the off-absorption line, $R_{ON/OFF}$, can be expressed as [18]:

$$R_{ON/OFF} = \frac{E(\lambda_{ON})}{E(\lambda_{OFF})} = \frac{\tau_{ON}}{\tau_{OFF}} = e^{-[\psi_P(\lambda_{ON})-\psi_P(\lambda_{OFF})]\int_0^D n_P(r)\,dr} \tag{9}$$

where D is the total beam length. The total pollutant column density N_P, which is the integral of the molecular volume density on the entire beam, is therefore:

$$N_P = \int_0^D n_P(r)\,dr = \frac{-\ln(R_{ON/OFF})}{\Delta\psi} \tag{10}$$

The average molecular volume concentration of the pollutant on the path, $\tilde{n}_P$, is therefore:

$$\tilde{n}_P = \frac{N_P}{D} = \frac{-\ln(R_{ON/OFF})}{D\cdot\Delta\psi} \tag{11}$$

As evident from Eq. 9 to 11, the IPDA measurement technique neglects most of the parasite phenomena such as atmospheric visibility, particulate, rain and other precipitations, which would have elsewhere introduced a number of additional uncertainties in the system. The parasite effects, in fact, are assumed to equally affect the off-absorption and the on-absorption transmittances. For the specific carbon dioxide (CO_2) measurement system implementation, a successfully adopted on-absorption wavelength is the centre-line of R-branch at $\lambda_{ON} = 1572.335\ nm$ [4, 6-9, 20, 21], in the Near-InfraRed (NIR). The SO_2 exhibits prominent spectral resonance in the Ultra-Violet (UV) range, and, in particular, in the region of 280 to 310nm, although infrared spectral features are also known, and in particular between 3970 and 4030 nm. As depicted in Fig. 1, the proposed bistatic LIDAR measurement system consists of an airborne LIDAR emitter installed on a UA, and a ground-based receiver. The receiver is composed by a target surface of high and diffuse reflectance, exhibiting Lambertian behaviour, such as Spectralon™, and a NIR camera mounted on a rail. The UA platform flies pre-determined trajectories based on the required space and time frames of the measurement.

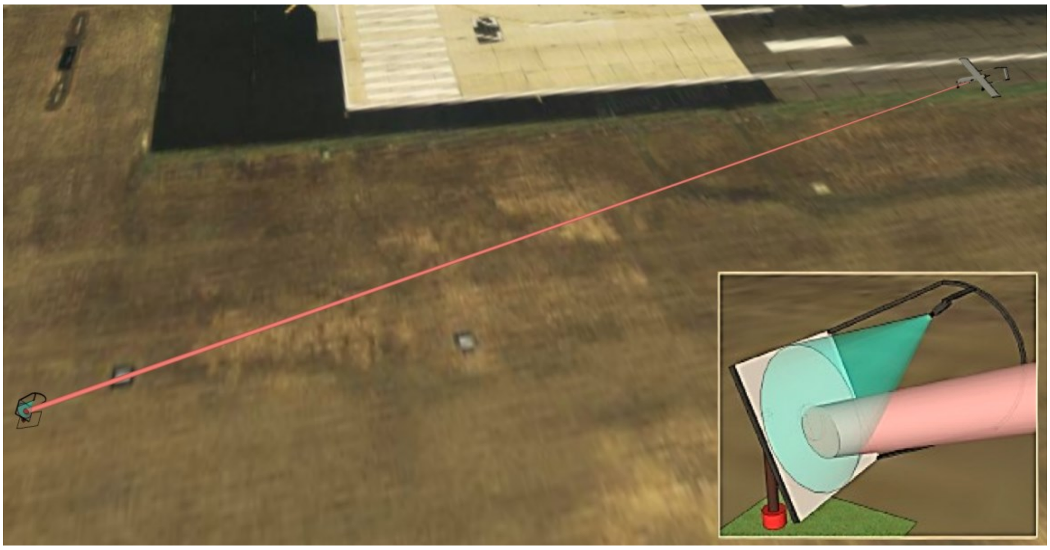

Fig. 1. Representation of the bistatic LIDAR system (not to scale)

The uncertainty associated with the measurement of the molecular volume concentration, derived from Eq. 11, is:

$$\sigma_{\tilde{n}_P} = \frac{1}{D\cdot\Delta\psi}\sqrt{\left(\frac{\sigma_{R_{ON/OFF}}}{R_{ON/OFF}}\right)^2 + \left(\frac{\sigma_D \ln R_{ON/OFF}}{D}\right)^2 + \left(\frac{\sigma_{\Delta\psi} \ln R_{ON/OFF}}{\Delta\psi}\right)^2} \tag{12}$$

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For a preliminary estimation, we introduce representative errors on the first two quadratic terms in eq. 12, specific to the bistatic LIDAR implementation (the third quadratic term can be neglected to a first approximation). A significant variation in the incidence angle of the laser beam between the two IPDA measurements introduces an error in the differential energy measurement, which can be translated in $\sigma_{R_{ON/OFF}}$ by adopting the Bidirectional Reflectance Distribution Function (BRDF) of the target surface [2]. Assuming the worst-case conditions of Table 1 and injecting source errors from Table 2, the resulting relative error for the CO_2 volume density is $\frac{\sigma_{\tilde{n}_P}}{\tilde{n}_P} = 6.77$ %.

Table 1. Assumed worst-case operative conditions.

Parametre	Value
Horizontal distance between the UA and the target surface	1000 m
UA Height Above Ground Level (AGL)	150 m
CO_2 volume density	300 ppm

Table 2. Assumed source errors.

Source	Magnitude	Affected Term	Error
Discrepancy in the incident angle between $E(\lambda_{ON})$ and $E(\lambda_{OFF})$	5° azimuth 5° elevation	$\frac{\sigma_{R_{ON/OFF}}}{R_{ON/OFF}}$	3.04 %
Degraded UA navigation performance	20 m horizontally 15 m vertically	$\frac{\sigma_D}{D}$	2.47%

These preliminary results, associated with the very low error figures of the monostatic LIDAR measurements from experimental campaigns [21] and with the estimated performance of the calibration technique proposed in [18], contribute to supporting the validity of the proposed bistatic LIDAR measurement technique for high accuracy sensing of aviation-related pollutant concentrations. Further research is needed to further corroborate these preliminary findings.

Conclusions and Future Work

This paper presented an innovative application of the bistatic LIDAR technique for the measurement of molecular gas pollutant concentrations. The specific implementation for carbon dioxide measurement is presented. The adopted Integral Path Differential Absorption (IPDA) measurement technique is largely unaffected by parasite effects such as atmospheric visibility, particulate and precipitation, which would have elsewhere introduced additional uncertainties. The estimated overall accuracy of the proposed bistatic LIDAR technique is promising for CO_2 column density measurements and, in future research, will be investigated for possible application to other families of gaseous pollutants such as nitrogen oxides (NO_X) and sulphur oxides (SO_X). These research activities will involve laboratory testing as well as flight testing in various representative conditions. In particular, the development of the airborne component will benefit from the concurrent research activities on UA-based LIDAR systems [22, 23]. The experimental activity will be carried out using a UA equipped with tuneable laser sources and a Differential GPS-based Time-and-Space-Position-Information (TSPI) system [24, 25]. With an increasing maturity level, a possible deployment of the measurement system will be investigated in the next generation Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) context. This will involve, in particular, integration with the Next Generation of avionics Flight Management Systems (NG-FMS) and with the ground-based 4-Dimensional Trajectory Planning, Negotiation and Validation (4-PNV) systems currently being developed for improved safety, efficiency and environmental sustainability of aircraft operations [26, 27].

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