Unmanned Aircraft Bistatic LIDAR for CO₂ Column Density Determination

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Abstract—A novel technique for laser remote sensing of aviation-related atmospheric pollutants from Unmanned Aircraft (UA) platforms is presented. In particular, the paper focuses on Carbon Dioxide (CO₂), which is the most important aviation greenhouse gas, and whose column density data can be used for environmental monitoring purposes and to support the development and validation of aircraft engines and Systems for Green Operations (SGO). The proposed measurement techniques are based on a near-infrared bistatic Light Detection and Ranging (LIDAR) system using a modified version of the Integrated Path Differential Absorption (IPDA) technique currently adopted in state-of-the-art (monostatic) remote sensing LIDARs. Target surfaces of known spectral reflectance and Bidirectional Reflectance Distribution Function (BRDF) are irradiated with two laser beams of appropriate wavelengths. The first wavelength is selected in coincidence with one vibrational band of the CO₂ molecule, exhibiting significant absorption phenomena (absorption line). The second wavelength is selected in the same transmission window but outside the absorption line. By measuring the difference in incident energy between the two beams, and inverting the differential transmittance models, it is possible to determine the pollutant column density. Parasite effects include haze, precipitation and dust particulate, which can be modelled as well. In addition to the bistatic LIDAR technique, a monostatic control technique is also proposed in this paper for experimental and calibration purposes.

Keywords—carbon dioxide, bistatic, green-house gas, extinction measurement, IPDA, LIDAR, near-infrared, particle column density, pollutant characterisation.

I. INTRODUCTION

The environmental sustainability of aviation is being challenged by the continuous growth in air transport demand and is currently receiving much attention by scientists and engineers worldwide. Several large scale research initiatives are currently ongoing (Clean Sky, Environmentally Responsible Aviation, SESAR, NextGen, Greener by Design, Omega, etc.) are aiming at reducing the impact of air transport on the environment in a holistic manner. The R&D activities are focusing on several technologies that can attain reduced environmental impacts in current and likely future operational tasks, as well as in manufacturing, logistics, assembly, and disposal chains. This extensive and global endeavour is soliciting, and partly even mandating, a substantial evolution in the measurement techniques both to determine quantitatively these environmental impacts and to assess the effective gains attained by the ongoing R&D activities. An area to which the aviation community and society is very sensitive to, is the level of gas pollution and noise emissions at airports and terminal areas, particularly at large hubs. Legislation is already in place with respect to noise pollution and suitable equipment is currently being used to measure noise levels especially around airports. Given the growing political pressures, it is expected that such initiatives will be extended to carbon dioxide (CO₂) and other polluting gases, where high aircraft density areas will be actively monitored for the overall emissions in the environment. Research interest is therefore gathering around CO₂ measurements at airports and their environs, as well as in other high-density air traffic nodes. CO₂ is a very common greenhouse gas, generated both in man-made and natural processes, and its rising concentration worldwide is a matter of concern for the current and future generations. In aviation, CO₂ is typically generated by the combustion of fossil fuels (organic) with the oxygen present in the air. Fossil fuels are by far the largest energy source for aircraft propulsion at present and no substantial change can be envisaged in the near future, due to the average design and life cycle time frames of aircraft. Although civilian air transport is currently responsible for only about 2% of the overall man-made CO₂ emissions, the global community is working to reduce the relative level of emissions as growth in air transport is forecast to increase such emissions by 50% over current levels by 2050 [1]. In order to better investigate the actual aircraft emissions and their effective improvements attained with new technologies, it is essential to characterise the pollutant concentrations in a quantitative way. In particular, emphasis is on the spatial and temporal variation of macroscopic observables, and on the microphysical and chemical properties of atmospheric constituents and pollutants, including molecular, aerosol and particulate species [2-4]. A valuable input for present and future R&D will be given by the characterisation of CO₂ concentrations in space and time for a variety of aircraft operations. At present, ignoring dedicated test-bench installations, the commonly adopted measuring techniques for pollutant emissions are based on indirect measurements.

Air quality sampling stations in the vicinity of larger airports are the main source of pollution figures, but their measurement is affected by cumulative advection and diffusion of pollutants and is therefore ultimately averaged in time and space. This average measurement is natively incapable of discerning a single aircraft, let alone a particular phase of its flight. Sensors
installed within the aircraft engines and more generally on board aircraft allow an indirect estimation of pollutant emissions based on certain models and assumptions. Most commonly installed sensors are thermodynamic and mechanical sensors, typically measuring Fuel Flow (FF), Turbine Entry Temperature (TET), Exhaust Gas Temperature (EGT), Engine Pressure Ratio (EPR), engine rotation speed \((N_1, N_2, N_n,...)\) and acoustic vibrations. The indirect estimation of pollutant emissions is analytically or heuristically derived from these thermodynamic and mechanical measurements, and is based on nominal conditions. Significantly off-design or degraded conditions of engine, fuel chemical composition, fuel transport or fuel storage conditions may violate key assumptions and hence affect the validity of such indirect measurements. All these motivations support the study, design and development of innovative sensing techniques with improved spatial and time resolutions. These techniques could be based on direct pollutant concentration measurements or, at least, more accurate and reliable indirect measurement. Recent developments in the field of electro-optics have led to innovative sensors, systems and analysis techniques for atmospheric remote sensing. The most widely used electro-optics techniques for Earth atmospheric sounding are passive visible-infrared imaging and active mono-static coherent-detection LIDAR (Light Detection and Ranging). These sensors perform volume scattering measurements and have been previously deployed on satellite and airborne platforms. Both sensor techniques allow accurate measurements of atmospheric components (molecular and aerosol species). However, imaging measurements have the disadvantage of being limited in accuracy, especially if compared with electro-optics coherent and non-coherent detection techniques. Furthermore, some effects, like the influence of turbulence structure constant variations, are difficult to model using these techniques, and any mathematical extrapolation or empiric estimation would add a considerable amount of uncertainty to the measurements performed. On the other hand, LIDAR measurements are more accurate but often limited to shorter ranges than those provided by imaging sensors. This is primarily due to the high concentrations of \(\text{CO}_2\), oxygen \((\text{O}_2)\), nitrogen \((\text{N}_2)\), water vapour and aerosol/particulate species present in the atmosphere, which attenuate the laser signal through a variety of absorption and scattering processes [5]. Atmospheric turbulence also contributes to significant fluctuations of laser energy on the focal plane, and some nonlinear propagation effects, such as bleaching and thermal blooming, may also cause severe attenuations of laser beams propagating in the atmosphere [4]. The advent of powerful laser sources and pointing systems, with low weight and packaged in relatively small casings, allows for different laser sources to be installed on aircraft, satellites or other aerial/surface vehicles. Additionally, due the advent of powerful tuneable lasers, a variety of LIDAR systems have been developed for measuring the concentration/column density of various important molecular species, including carbon oxides \((\text{CO}_2)\), nitrogen oxides \((\text{NO}_x)\), sulphur dioxides \((\text{SO}_x)\), \(\text{O}_3\) and ozone \((\text{O}_3)\), both locally and over extended geographic areas [6, 7]. The propagation characteristics of Near-Infrared (NIR) lasers make them particularly well suited for \(\text{CO}\) and \(\text{CO}_2\) density measurements. In this region of the spectrum propagation is dominated by molecular absorption from \(\text{H}_2\text{O}\), \(\text{CO}\) and \(\text{CO}_2\). Therefore, comparison to recorded \(\text{H}_2\text{O}\) spectra enables the identification of relatively strong and isolated \(\text{CO}\) and \(\text{CO}_2\) transitions for unambiguous species detection [8]. These transitions have formed the basis of NIR sensors for measurements of \(\text{CO}\) and \(\text{CO}_2\) mole fractions in exhaust gases using extraction-sampling techniques and for non-intrusive measurements of \(\text{CO}_2\) in high-temperature combustion environments. Currently, great attention is being devoted to airborne and spaceborne laser sensors for \(\text{CO}_2\) column density measurements [9-13]. The principal goal of this research is to establish the feasibility of a new robust and inexpensive technique that enables local measurements of the \(\text{CO}_2\) and other atmospheric gases/particles concentrations from airborne and ground installations, with a capability of scaling to permit global measurements from satellites as well. The proposed techniques use a combination of NIR laser sources, direct detection electro-optics and passive infrared imaging systems [5, 14], allowing a direct determination of atmospheric extinction and, through suitable inversion algorithms, the indirect measurement of some important natural and man-made atmospheric constituents, including \(\text{CO}_2\) and other pollutants. The proposed techniques are particularly well suited for remote sensing missions performed by unmanned aircraft (UA) and satellites. However, other aerial and ground applications such as gliders/parachutes, roving surface vehicles or permanent surface installations (e.g., at airports) are possible. The various techniques proposed offer relative advantages in different scenarios [3, 15]. All are based on measurements of the laser energy/power incident on target surfaces of known geometric and reflective characteristics, by means of infrared detectors and/or infrared cameras calibrated for radiance. Experimental ground and flight test activities with laser systems operating in the NIR included ground tests performed with 10 Hz and 20 kHz Pulse Repetition Frequency (PRF) NIR laser systems in a variety of atmospheric conditions, and flight trials performed with a 10 Hz airborne NIR laser system installed on a TORNADO aircraft, flying up to altitudes of 22000 ft above ground level [16].

II. BISTATIC LIDAR TECHNIQUE

A new technique is proposed based on NIR bistatic LIDAR irradiance measurements, allowing the \(\text{CO}_2\) column density retrieval by means of the Integral Path Differential Absorption (IPDA) method. In the IPDA technique, the laser emitter fires two beams at different wavelengths for each measurement cycle. The first wavelength is selected in coincidence with one vibrational bands of the measured molecule and is therefore affected by a certain molecular absorption. The second wavelength is selected outside the absorption band, but close to the first one in order to enable a correlation. The system measures the incident energy both on the spectral absorption (on-absorption) line and on a spectral transparency (off-absorption) line. The relationship between on-absorption transmittance \(\tau_{\text{ON}}\) and the one...
relative to the selected off-absorption line $\tau_{OFF}$ in the pollutant spectrum can be written as [3, 4]:

$$\frac{\tau_{ON}}{\tau_{OFF}} = \exp\left\{-\left[\psi(\lambda_{ON}) - \psi(\lambda_{OFF})\right] \int_0^R n_{CO_2}(z) dz\right\} \quad (1)$$

where:

- $R$ = total beam length;
- $\lambda_{ON}$ = wavelength of the vibration spectral line;
- $\lambda_{OFF}$ = wavelength of the off-absorption spectral line;
- $\psi(\lambda)$ = cross-section of CO$_2$ in molecular absorption;
- $n_{CO_2}(z)$ = CO$_2$ molecular volume density.

The transmittance is related to the extinction coefficient $\gamma$ by Beer’s law:

$$\tau = e^{-\gamma z} \quad (2)$$

Therefore, the relationship between the incident energy for the on-absorption wavelength, $E(\lambda_{ON})$, and the off-absorption one, $E(\lambda_{OFF})$, in a one-way path can be expressed as [4]:

$$R_{ON/OFF} = \frac{E(\lambda_{ON})}{E(\lambda_{OFF})} = \frac{\tau_{ON}}{\tau_{OFF}} = \exp\left\{-\left[\psi(\lambda_{ON}) - \psi(\lambda_{OFF})\right] \int_0^R n_{CO_2}(z) dz\right\} \quad (3)$$

Since we are interested in the total pollutant column density, $N_{CO_2}$, which is the integral of the molecular volume density along the entire path length, we obtain [4]:

$$N_{CO_2} = \int_0^R n_{CO_2}(z) dz = -\frac{\ln[R_{ON/OFF}]}{[\psi(\lambda_{ON}) - \psi(\lambda_{OFF})]} \quad (4)$$

An expression of the error affecting the measure of the pollutant column density based only on the IPDA principle as per (4) is therefore:

$$\sigma_{N_{CO_2}} = \frac{1}{\Delta \psi} \sqrt{\left(\frac{\sigma_{R_{ON/OFF}}}{R_{ON/OFF}}\right)^2 + \left(\frac{\Delta \psi}{\Delta \psi^2} \ln R_{ON/OFF}\right)^2} \quad (5)$$

where $\Delta \psi = \psi(\lambda_{ON}) - \psi(\lambda_{OFF})$.

Summarising, by performing two spectrally distinct measurements of the energy incident on the receiver, the IPDA-based measurement techniques neglect most parasite phenomena such as atmospheric visibility, particulate, rain and other precipitations, which would have elsewhere required additional measurements and the introduction of the related uncertainties in the system. The parasite effects, in fact, are assumed to equally affect the off-absorption and the on-absorption wavelength measurements. It shall be noted that a strict requirement for the validity of the model is the adoption of relatively low-power pulsed laser systems, to avoid incurring in the thermal blooming effect, associated to significant non-linearity. The vibration-rotation bands at 1.57, 1.6 and 2.1 μm were recommended in the literature as good candidate transitions for unambiguous CO$_2$ detection [8, 17-20]. A number of monostatic IPDA-based measurement systems for pollutant concentrations were successfully adopted and validated for CO$_2$ measurements campaigns from airborne platforms in the R&D activity related to the NASA Active Sensing of CO$_2$ over Nights, Days and Seasons (ASCENDS) mission [9, 21, 22]. The successfully adopted wavelength for on-absorption measurement is the centre-line of R-branch at $\lambda_{ON} = 1572.335$ nm. Assuming a Gaussian beam at the source and an average focussed irradiance, the expression of the peak focal irradiance for a laser beam accounting for diffraction, random jitter and turbulence is [23]:

$$I_p = \frac{P \cdot \gamma}{\pi \cdot (a_d^2 + a_j^2 + a_t^2)} \quad (6)$$

where $P$ is the output power, $\gamma$ is the attenuation coefficient, $a$ is the 1/e beam radius, and the subscripts $d$, $j$, and $t$ refer to diffraction, jitter, and turbulence. The contributions to the focal spot area due to diffraction, jitter, and turbulence are, respectively, given by:

$$a_d^2 = \left(\frac{52\lambda}{\pi a_d}\right) \quad (7)$$

$$a_j^2 = 2 \left(\Theta_j^2\right)^2 \quad (8)$$

$$a_t^2 = \frac{4 \cdot \epsilon^2 \cdot \xi^{16/5} \cdot \xi^{16/5}}{\lambda^{2/5}} \quad (9)$$

where $\beta$ is the beam quality factor (i.e., the observed beam radius divided by the diffraction- limited radius), and $\left(\Theta_j^2\right)$ is the variance of the single axis jitter angle that is assumed to be equal to $\left(\Theta_j^2\right)$. In our proposed measurement system layout, an NIR laser emitter is installed on board of a UA. The airborne emitter fires its beams towards a ground-based receiver. The receiver is made on a movable support and is composed by a target surface and a rail-mounted NIR camera aimed at the surface. The NIR camera is calibrated in radiance using an integrated sphere and the calibration setup described in previous work [4]. The surface is made of a highly reflective material, exhibiting a Lambertian behaviour, and orientated normal to the incident laser beam. The overall bistatic LIDAR measurement system implementation is represented in Fig. 1. The one-way IPDA extinction measurement is defined by (1) to (3).

![Fig. 1. Bistatic LIDAR measurement system layout.](image-url)
III. CALIBRATION TECHNIQUE

In order to enable in-situ calibration of the bistatic LIDAR measurement we introduce a calibration system, represented in Fig. 2.

![Fig. 2. Monostatic calibration system layout.](image)

In particular, an additional co-located NIR laser emitter and detector complex is installed on the ground at known distances from the first target surface and from an additional target surface, of equivalent specifications of the first, but without the NIR camera. The quality of the calibration is directly associated with the relative distance between the target surfaces, as evident from the following equations. As a reference, the assumed relative distances are, in particular, \( \Delta d = d_2 - d_1 \geq 1 \text{ km} \). The anodic voltage at the receiver, \( V \), can be expressed as [4]:

\[
V = R_L \cdot R_S \cdot P_R \quad (10)
\]

where:
\( R_L = \text{anodic load (\Omega)} \);
\( R_S = \text{detector responsivity (A/W)} \);
\( P_R = \text{power reaching the detector (W)} \);

By adopting two identical targets placed at different slant ranges, \( d_1 \) and \( d_2 \), at the same elevation above mean sea level (AMSL) at a similar bearing from the emitter/receiver, we can assume that the extinction coefficient on the absorption spectral line, \( \gamma_{OFF} \), is constant between the two baselines. By detailing \( P_R \), the following expressions can be written for the anodic voltages at the receiver, for the target surface 1, \( V_1 \), and 2, \( V_2 \):

\[
V_1 = R_L \cdot R_S \cdot \left( P_B \cdot \rho \cdot \frac{e^{-2\gamma_{d_1}}}{d_1^2} \right) \quad (11)
\]

\[
V_2 = R_L \cdot R_S \cdot \left( P_B \cdot \rho \cdot \frac{e^{-2\gamma_{d_2}}}{d_2^2} \right) \quad (12)
\]

where:
\( P_B = \text{parameter accounting for the laser emitter power, for the window efficiencies and for the geometric characteristics of the beam} \);
\( \rho = \text{target reflectivity} \).

The derived relation between the two sensed voltages is therefore:

\[
\frac{V_1}{V_2} = \frac{P_{O1}}{P_{O2}} \cdot \frac{d_2^2}{d_1^2} \cdot e^{2\gamma(d_2-d_1)} \quad (13)
\]

where:
\( P_{O1,2} = \text{transmitted laser powers (W)} \)

The ground-level extinction coefficient relative to both spectral lines is therefore calculated as:

\[
\gamma = \frac{1}{2\Delta d} \ln \left( \frac{V_{O2}}{V_{O1}} \cdot \frac{d_2^2}{d_1^2} \right) \quad (14)
\]

where \( \Delta d = d_2 - d_1 \geq 1 \text{ km} \), as previously discussed.

The total uncertainty related to the extinction coefficient in eq. 9 is [4]:

\[
\sigma_\gamma^2 = \frac{1}{(\Delta \Delta d)^2} \cdot \left( \left( \frac{\sigma_{V1}}{V_1} \right)^2 + \left( \frac{\sigma_{V2}}{V_2} \right)^2 + \left( \frac{\sigma_{O1}}{P_{O1}} \right)^2 + \left( \frac{\sigma_{O2}}{P_{O2}} \right)^2 \right) + \frac{\gamma^2}{\Delta \Delta d^2} \left( d_2 + \frac{1}{2} \gamma \cdot \frac{d_2^2}{d_1^2} + d_1 + \frac{1}{2} \gamma \cdot \frac{d_1^2}{d_2^2} \right) \quad (15)
\]

By employing the same laser emitter for the ground and airborne systems we may assume constant errors in voltage and power, \( \sigma_{V} / V \) and \( \sigma_{P0} / P_0 \). Considering also the distance \( \Delta d \) several orders of magnitude higher than the extinction coefficient and rearranging the terms we obtain:

\[
\sigma_\gamma = \frac{1}{\Delta \Delta d} \sqrt{\frac{\sigma_{V1}^2}{V_1^2} + \frac{\sigma_{V2}^2}{V_2^2}} \quad (16)
\]

In the calibration system design, it must be ensured that the overall uncertainty is an order of magnitude lower than the one associated with the bistatic LIDAR measurement system. From (3), neglecting the uncertainty in \( \Delta \psi \), the error on the pollutant column density measurement \( N_{CO2} \) for the calibration system layout is:

\[
\sigma_{CALN_{CO2}} = \frac{1}{\Delta \Delta \psi} \cdot \sqrt{2[\sigma_\gamma^2 - \text{cov}(\gamma_{OFF}, \gamma_{ON})]} \quad (17)
\]

By introducing the uncertainty in the extinction coefficient from (16), we finally obtain:

\[
\sigma_{CALN_{CO2}} = \frac{1}{\Delta \Delta \psi} \sqrt{\frac{\sigma_{V1}^2}{V_1^2} + \frac{\sigma_{V2}^2}{V_2^2} - 2 \cdot \text{cov}(\gamma_{ON}, \gamma_{OFF})} \quad (18)
\]

This result clearly supports the selection of large relative distances between the targets, ideally in the range of 1~3 km or more if available. Similar distances are comparable to the typical runway lengths at major airports. Therefore, the calibration system may ideally be collocated parallel and in proximity of a runway, outside of the Instrument Landing System (ILS) sensitive areas where applicable.

IV. MODEL-BASED APPROACH

Analytical expressions of the transmittances were developed for all the atmospheric windows in the Infra-Red spectrum. These expressions depend on a number of additional
parameters such as atmospheric visibility, precipitation and fog. By means of analytical inversion of the transmittance models, and thanks to an accurate sensing of local atmospheric conditions, it is also possible to determine the pollutant concentration without employing the IPDA technique. This process entails the determination of pollutant concentrations by measuring the difference between the actually detected incident energy on the on-absorption line alone, and the model-based prediction for the off-absorption line. Although this technique simplifies the system architecture, its resulting measurement error is heavily dependent on the quality and confidence of the measure of all other factors such as atmospheric visibility, temperature, pressure, humidity and precipitation. The theoretical model is based on comparison with the available extinction models for the $\text{i}^{\text{th}}$ atmospheric window [5]. By introducing the total condensed water along the laser beam path, $w$, the meteorological visibility, $V$, and the rainfall rate $\Delta x/\Delta t$, the estimated atmospheric transmittance values for the 4th atmospheric window in the monostatic case [5]:

$$\tau_{\text{atm}} = k_1 \cdot 0.6432 \left( \frac{V}{w} \right)^{0.222} \exp^{-\frac{3.91}{\sqrt{w}} \cdot 0.3836 \cdot (0.0057V + 1.025)}$$

(when $V \geq 6 \, \text{km, } w \geq 1.1 \, \text{mm}$) (19)

$$\tau_{\text{atm}} = k_2 \cdot 0.6432 \left( \frac{V}{w} \right)^{0.222} \exp^{-\frac{3.91}{\sqrt{w}} \cdot 0.3836 \cdot 0.585 \sqrt{w}}$$

(when $V < 6 \, \text{km, } w \geq 1.1 \, \text{mm}$) (20)

$$\tau_{\text{atm}} = k_3 \cdot e^{-0.422/\sqrt{w}} \left( \frac{V}{w} \right)^{0.3836 \cdot (0.0057V + 1.025)}$$

(when $V \geq 6 \, \text{km, } w < 1.1 \, \text{mm}$) (21)

$$\tau_{\text{atm}} = k_4 \cdot e^{-0.422/\sqrt{w}} \left( \frac{V}{w} \right)^{0.3836 \cdot 0.585 \sqrt{w}}$$

(when $V < 6 \, \text{km, } w < 1.1 \, \text{mm}$) (22)

$$\tau_{\text{atm}} = k_5 \cdot e^{-0.422/\sqrt{w} \cdot 0.365 \sqrt{w}} \left( \frac{V}{w} \right)^{0.63}$$

(in presence of rain and when $w \geq 1.1 \, \text{mm}$) (23)

$$\tau_{\text{atm}} = k_6 \cdot e^{-0.422/\sqrt{w} \cdot 0.365 \sqrt{w}} \left( \frac{V}{w} \right)^{0.63}$$

(in presence of rain and when $w < 1.1 \, \text{mm}$) (24)

where $k_1, k_2, \ldots, k_n$ are experimentally determined as in [4]. The numerical coefficients in (19)-(24), in particular, are valid at mean sea level only. In order to extend the validity of the models, the dependency on altitude $h$ Above Mean Sea Level (AMSL) shall be introduced. A number of empirical relationships for the altitude correction have been experimentally determined for NIR lasers depending on the grazing angles [4, 5]. The regression resulting from these experimental activities is the general form:

$$\gamma_{\text{atm}} = J_0 + J_1 \cdot h$$

where $\gamma_{\text{atm}}$ is the extinction coefficient of the slant path, $\gamma_{\text{atm}}$ is the extinction measured at ground level (QFE altitude), $h$ is the altitude above ground level (AGL), and $J_0$, $J_1$ are linear regression coefficients varying as a function of weather conditions and grazing angle, being progressively refined as a result of experimental flight test activities as described in [4]. Future research activities will be performed to further characterise the grazing angle dependency for a possible implementation in the UA bistatic LIDAR.

V. CONCLUSIONS AND FUTURE WORK

The proposed NIR bistatic LIDAR measurement layout, based on the Integral Path Differential Absorption (IPDA) principle, has the potential to provide very accurate characterisation of aviation pollutant concentration data, with high spatial and time resolution around selected sensing locations. Compared to monostatic implementations, the bistatic layout enables the adoption of significantly reduced laser emitter power, or effectively doubled maximum operating ranges. Further R&D activities will address the accurate error modelling and analysis, with laboratory test-bench validation. Flight testing in various conditions will be subsequently carried out using a UA platform equipped with tuneable laser sources and a Differential GNSS Time-and-Space-Position-Information (TSPi) system [24], as well as with other integrated navigation and guidance systems (NGS) [25-29], and related integrity monitoring and augmentation technologies [30, 31].

The research will benefit from the concurrent development activities of scaled Laser Obstacle Avoidance and Monitoring (LOAM) for UA [32, 33]. With an increased level of maturity, further investigations will be carried out to address the potential adoption of this new bistatic LIDAR technique in the Australian aviation context and on a global scale. This will involve the integration with the Next Generation Mission Management Systems and Flight Management Systems (NG-MMS and NG-FMS), as well as ground-based ATM systems in the future intent-based CNS/ATM operational domain [34, 35].

REFERENCES


