

COMPARATIVE ATMOSPHERIC MEASUREMENTS USING UAV-MOUNTED ULTRASONIC ANEMOMETER AND DOPPLER LIDAR

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Abstract

This paper investigates different systems for atmospheric probing. A portable ultrasonic anemometer, integrated with a GPS, wireless data transmission, and data acquisition systems, is mounted on a quadcopter platform. This configuration provides a mobile measurement unit capable of free movement in the atmosphere, delivering measurements of airspeed, temperature, pressure, humidity, air density, and the system's physical orientation. In parallel, a ground-based Doppler LiDAR system (WindCube) is used as a reference, providing 20 simultaneous measurements at arbitrarily selected heights between 40 and 300 meters above ground level. Additionally, a compact airborne mini-LiDAR system intended for future integration onboard the uncrewed aircraft is investigated. This miniaturized system is designed to provide wind field information ahead of the aircraft, enabling anticipative atmospheric sensing and improved trajectory adaptation in turbulent or energy-harvesting flight conditions.

Keywords: atmospheric probing, ultra-sound anemoemter, LiDAR system, mini-LiDAR in flight

1. Introduction

Understanding atmospheric dynamics is critical for a wide range of applications, from weather forecasting and climate studies to the safe and efficient operation of unmanned aerial systems (UAS). Accurate measurement of wind profiles, turbulence, and other meteorological parameters is particularly important for characterizing the atmospheric boundary layer, where interactions between surface processes and larger-scale flows occur [1]. Traditional measurement techniques, such as meteorological towers and radiosondes, provide valuable data but are often limited in spatial coverage or temporal resolution [2]. Some of our previous studies investigated bio-inspired pressure sensing on the wing to assess the influence of flow perturbations on the aircraft angle of attack [3]. Furthermore, we investigated wind estimation based on quadcopter attitude measurements, which demonstrated good accuracy when compared with ground-based Doppler LiDAR measurements [4]. Accurate knowledge of the wind field is valuable for a variety of applications, as it enables improved situational awareness, flight performance optimization, and decision-making, with particular relevance to atmospheric wind energy extraction concepts for small unmanned aerial vehicles [5, 6, 7]. Small Unmanned Aircraft Systems (sUAS) have emerged as valuable platforms for addressing a broad spectrum of theoretical, methodological, and applied atmospheric science research questions. Their ability to provide flexible, high-resolution, and cost-effective observations has significantly advanced investigations of the atmospheric boundary layer, including studies of boundary-layer transitions, turbulence characterization, turbulent flux estimation, Arctic and Antarctic atmospheric processes, wind field reconstruction, and operational atmospheric monitoring in challenging environments [8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. In this study, we combine multiple complementary measurement approaches to capture a detailed picture of atmospheric dynamics. A ground-based LiDAR WindCube vertical profiler is used to obtain high-resolution vertical profiles of wind speed and direction, offering continuous observations

throughout the lower atmosphere. These remote sensing measurements are complemented by in-situ data from an ultrasonic anemometer mounted on a drone, shown in Figure 1, which allows for precise, localized measurements of wind fluctuations and turbulence at specific altitudes. To further enhance spatial coverage and capture dynamic wind features along complex flight paths, a flying UAV is employed to collect wind data in real-time across multiple altitudes and trajectories. By integrating these three measurement techniques, this work aims to provide a multi-scale characterization of wind fields, from localized turbulence to larger atmospheric structures. The combination of remote sensing, drone-based, and UAV-based measurements not only improves data reliability and resolution but also supports the development of more robust UAS operational strategies in variable wind conditions. Ultimately, this study contributes to both fundamental atmospheric research and practical applications in aerial mobility and autonomous flight.

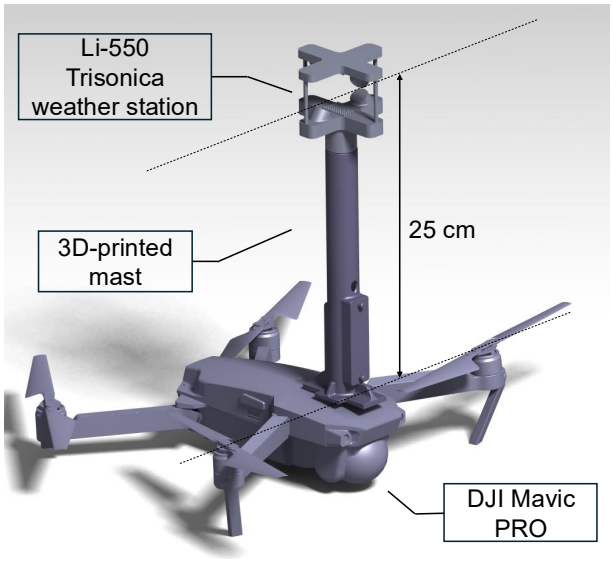


Figure 1 – A portable ultrasound weather station system

Beyond dedicated atmospheric measurement systems, modern UAVs can also estimate local wind conditions using onboard navigation and air data sensors [18]. Wind velocity can be inferred by combining airspeed measurements, angle-of-attack information, and inertial navigation data (IMU angles) with GPS-derived ground speed [19]. The difference between the aircraft velocity relative to the surrounding air mass and its velocity relative to the ground provides an estimate of the ambient wind vector. However, the accuracy of this approach strongly depends on the quality of the navigation measurements, with GPS-derived velocity often representing the largest source of uncertainty in the estimation chain. This limitation is particularly pronounced for the vertical wind component, where the comparatively low accuracy of vertical GPS velocity measurements can significantly affect wind estimation performance.

2. Experimental Measurement Architecture and Sensor Calibration Framework

Accurate characterization of atmospheric wind fields remains a challenging task due to the broad range of spatial and temporal scales involved. Traditional ground-based measurements provide high-quality local observations but are often limited in their ability to capture the three-dimensional structure and evolution of atmospheric flows. In contrast, airborne sensing platforms offer increased spatial flexibility and access to regions that are difficult to instrument using conventional meteorological infrastructure. However, each sensing technology possesses its own limitations in terms of measurement accuracy, temporal response, spatial coverage, and operational constraints.

To address these challenges, the present study employs a multi-sensor measurement architecture combining onboard ultrasonic anemometry, GNSS-assisted navigation measurements, and remote sensing using a Doppler LiDAR vertical profiler. The complementary nature of these instruments enables the characterization of atmospheric phenomena across multiple scales, ranging from local turbulence measurements obtained directly within the flow field to larger-scale wind structures cap-

tured through remote sensing techniques. Particular emphasis is placed on sensor calibration, uncertainty quantification, and cross-validation between independent measurement systems to assess the reliability of the acquired atmospheric data.
The following sections describe the development of the portable airborne measurement unit, the calibration methodology implemented using a controlled wind generation system, and the validation of the resulting measurements against a ground-based Doppler LiDAR reference system.

2.1 A Portable Aerial Measurement Unit for Drone-Based Atmospheric Sensing

The TriSonica LI-550 (LI-COR, USA) is a compact ultrasonic anemometer designed for high-precision, three-dimensional measurements of wind velocity and direction. The system operates without moving parts, minimizing aerodynamic disturbances and ensuring high reliability for both stationary and airborne applications. The sensor provides additional atmospheric parameters, including air temperature, relative humidity, pressure, and features integrated accelerometer and magnetometer sensors to track orientation and tilt.
Compact ultrasonic anemometers from the TriSonica family have been increasingly adopted for UAV-based atmospheric sensing due to their lightweight design, low power requirements, and capability to provide real-time three-dimensional wind measurements. During the LAPSE-RATE field campaign, Barbieri et al. [20] employed compact UAV-based atmospheric measurement systems incorporating miniature meteorological sensors to investigate boundary-layer processes and evaluate the performance of small unmanned aircraft systems for atmospheric observations. Similarly, Thielicke et al. [21] conducted a comprehensive assessment of a TriSonica Mini ultrasonic anemometer mounted on a multirotor UAV, including wind-tunnel calibration, characterization of rotor-induced flow disturbances, and comparison with Doppler LiDAR measurements. Their results demonstrated the suitability of compact ultrasonic anemometers for airborne wind sensing while emphasizing the importance of dedicated calibration procedures to compensate for platform-induced aerodynamic effects. These studies highlight the growing role of lightweight ultrasonic anemometry in atmospheric boundary-layer research, turbulence characterization, and UAV-based environmental monitoring.
With a sampling frequency up to 40 Hz and low power consumption (5–32 V DC, 400 mW), the LI-550 is suitable for integration on small unmanned aerial systems or fixed meteorological masts. Its lightweight and compact design (approximately 9.1 × 9.1 × 5.2 cm, 50–67 g) facilitates deployment in environments where minimal payload disturbance is critical. The system's capability to measure three-dimensional wind components in real time has been widely exploited in recent UAV-based atmospheric measurement studies, including wind field reconstruction and boundary layer characterization using compact ultrasonic anemometry systems [21]. This makes it particularly valuable for atmospheric research, UAV flight testing, and aerodynamic characterization studies. The TriSonica ultrasonic anemometer used in this study is interfaced with a Teensy 4.1 microcontroller, which serves as the central data acquisition unit. The microcontroller records all measurements provided by the anemometer, including the three-dimensional wind velocity components, air pressure, temperature, air density, relative humidity, and sensor inclination. To complement the atmospheric measurements, the system integrates a u-blox Neo-M8 GNSS receiver, providing position, altitude, ground speed, and time synchronization information. These navigation data facilitate the georeferencing of measurements and enable the correlation of atmospheric observations with the UAV trajectory during flight. An experimental setup consisting of a flying platform and onboard electronics is shown in Figure 2.
In addition, an XBee wireless communication module was included to enable real-time data transmission and visualization on a ground-based computer. The acquired data can be stored locally on an SD card, allowing high-frequency acquisition during flight, and/or transmitted in real time via the XBee module, depending on the operational requirements. The entire measurement system is fully independent of the DJI Mavic platform, both in terms of data handling and power supply, and is powered by a dedicated onboard battery. This architecture ensures platform-agnostic operation and minimizes interference with the flight control and avionics of the carrier UAV.



Figure 2 – TriSonica ultra-sound anemomter mounted on quadcopter in flight in front of a WindShape system.

2.2 Calibration of the ultrasound anemometer with WindShape

This subsection presents the calibration procedure of the Trisonica ultrasonic anemometer mounted on a DJI Mavic quadcopter. The calibration was conducted in front of the WindShape wind generation system to assess the accuracy of the measured wind velocity under controlled and repeatable flow conditions. The presented wind-shape system is located in the indoor flight testing laboratory of ENAC. It is a mobile installation equipped with an optional air-filter grid, which limits the flow velocity to 12–13 m/s in the vicinity of the wind-shape outlet. The objective is to quantify measurement biases induced by the airborne platform and to derive correction factors applicable to in-flight wind measurements. The main sources of measurement disturbance are expected to arise from propeller-induced flow effects.

Prior to flight tests, the quadcopter was fixed at the designated measurement location in front of the WindShape system, corresponding to the position later used during airborne experiments. These stationary tests allowed the characterization of the anemometer response under controlled wind conditions, without the influence of vehicle motion, and provided a baseline for comparison with in-flight measurements. The comparison between multi-hole probe fixed in front of the WindShape and ultra-sound anemometer is shown in Figure 3. The comparison between two systems show that the turbulence intensity of the WindShape system grows with the wind speed. At higher wind speed the fluctuations are on the order of 0.5 m/s.

The results shown in Figure 4 presents a comparison between static hot-wire measurements and anemometer measurements obtained at the same spatial location in front of the WindShape wind generation system. The initial results indicate that as the WindShape system speed increases, the ultrasonic anemometer measurements also rise, but with a slightly higher gradient, leading to an overestimation of the wind speed. This overestimation is attributed to the induced airflow generated by the quadcopter propellers, which rotate faster as the wind speed increases in order to maintain stability, thereby affecting the local velocity measured by the anemometer.

A linear regression analysis shown in Figure 5 was performed to compare the airflow velocity measurements obtained from the multi-hole probe and the ultrasonic anemometer during in-flight experiments conducted upstream of the wind-shape blower. The results demonstrate an acceptable agreement between the two measurement techniques, with a coefficient of determination of $R^2 = 0.9926$,

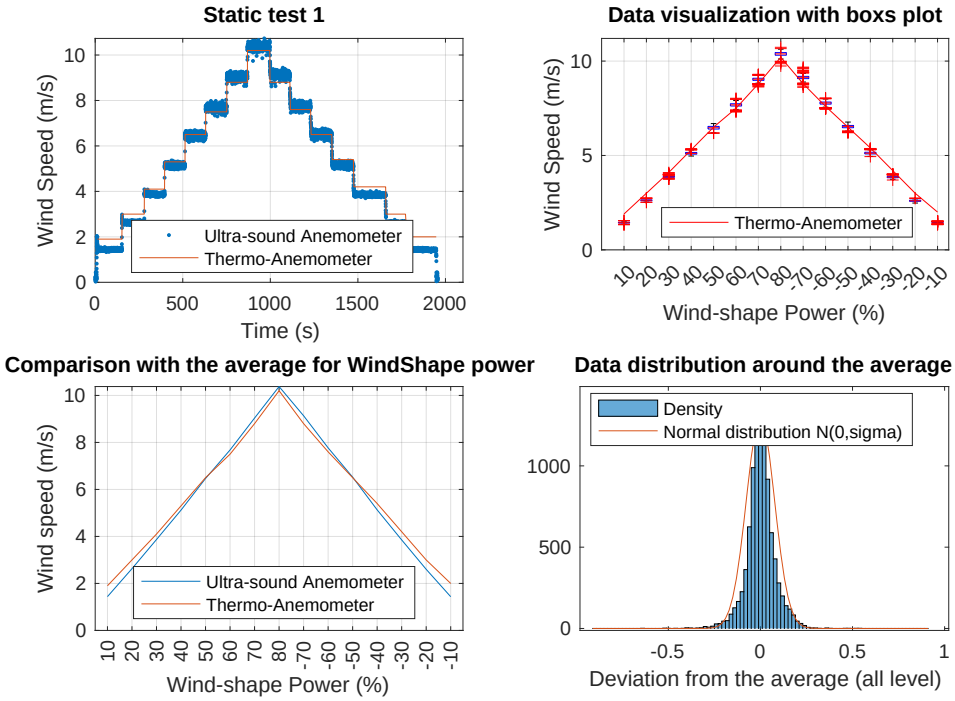


Figure 3 – Results of the first static test of Ultra-sound Anemometer in front of WindShape.

indicating a very strong linear correlation. This high level of consistency validates the reliability of the multi-hole probe measurements under the tested operating conditions and confirms the suitability of both instruments for accurate in-flight flow characterization. The correction derived previously is applied to the system and is considered in the subsequent analysis and comparison with alternative measurement systems.

2.3 Wind vertical proflier - Doppler LiDAR

The Vaisala WindCube is a Doppler LiDAR system designed to provide high-precision measurements of wind speed, direction, vertical wind components, and turbulence intensity over a wide vertical range, without the need for a traditional meteorological mast. The system operates by emitting pulsed laser signals into the atmosphere and measuring the Doppler shift of the back-scattered light from aerosols, allowing it to profile wind at multiple altitudes simultaneously (up to 20 measurement levels). The wind vector is reconstructed using a Velocity Azimuth Display (VAD) scanning strategy, in which the laser beam is successively oriented in several directions around the vertical axis. By combining the measured radial velocities, the horizontal wind speed, wind direction, and vertical velocity components can be estimated at each measurement height.

The WindCube offers the equivalent functionality of a tall meteorological mast while minimizing installation constraints: rapid deployment, low ground impact, and flexible positioning. These capabilities make it particularly well suited for wind resource assessment, atmospheric turbulence studies, and applications in aerodynamics or UAV flight testing. Some of our previous works have employed this type of vertical profiler while exploring the feasibility of atmospheric energy harvesting flight with fixed-wing UAVs and can be found here [22]. Compared with in-situ sensing techniques, the LiDAR provides continuous measurements over a large vertical extent and enables the characterization of wind shear, atmospheric stratification, and turbulence structures without requiring airborne instrumentation. However, its performance depends on the presence of a sufficient concentration of atmospheric aerosols to ensure adequate backscatter signal levels.

A comparison between measurements obtained using an ultrasonic anemometer (including correction for propeller-induced flow effects) mounted on a VTOL platform and a LiDAR WindCube at a selected single altitude is presented in Figure 7. The selected altitude was 290 m above sea level

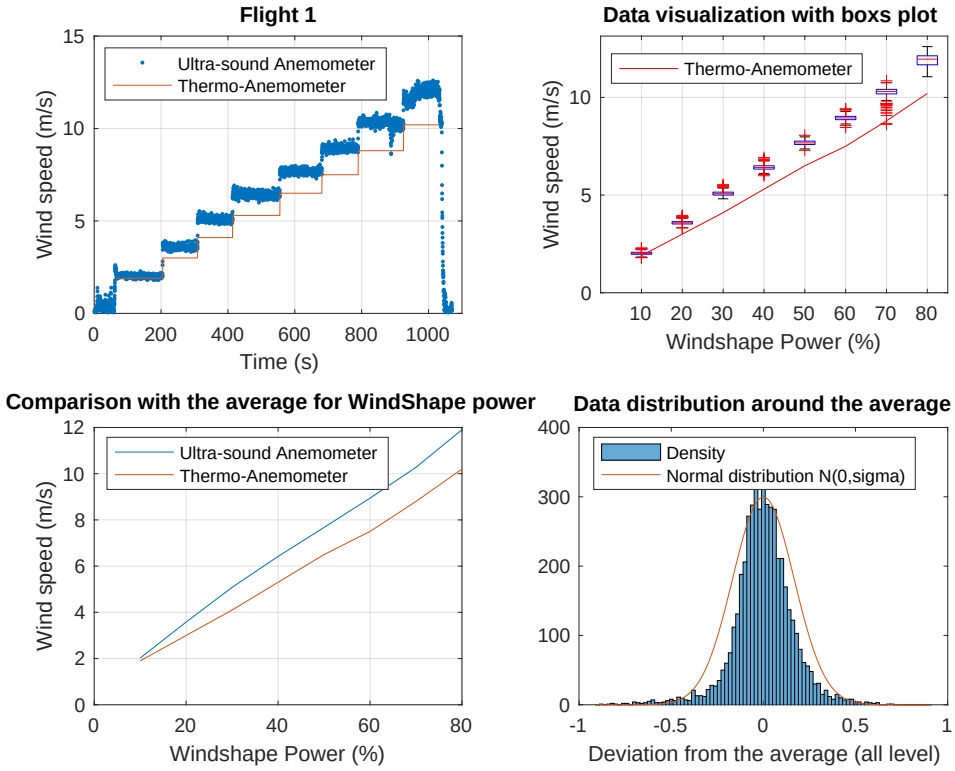


Figure 4 – Results of the first flight of Ultra-sound Anemometer in front of WindShape.

(ASL), while the ground elevation at the test site is 185 m ASL. Consequently, the effective measurement height for both the vertical profiler and the quadcopter-mounted anemometer was 105 m above ground level. The results shown in Figure 7 indicate that, at the selected position, the horizontal ground speed remains stable, with variations not exceeding 0.1 m/s. In contrast, the flying platform exhibits some difficulty in maintaining a constant altitude (error might be coming also from a GPS vertical precision), with deviations of up to 2 m. A representative time interval between 200 s and 800 s demonstrates a very good agreement in the mean wind speed measured by both systems. However, instantaneous discrepancies of up to 1 m/s are observed.

The observed differences between the two measurement systems can be attributed to several factors. First, the WindCube measurement represents a spatially averaged estimate derived from multiple line-of-sight observations, whereas the ultrasonic anemometer provides a local point measurement directly within the flow field. Second, small variations in the UAV position and altitude may result in sampling slightly different air masses, particularly in the presence of vertical wind gradients or

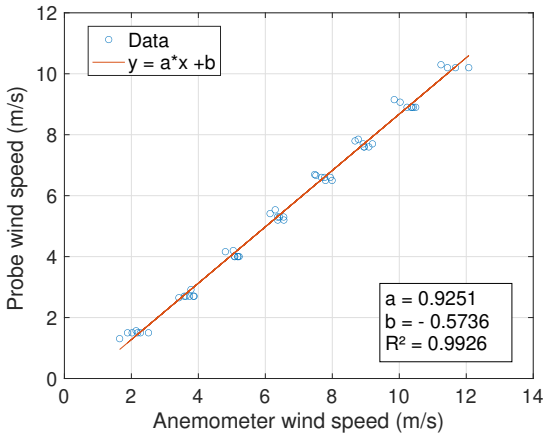


Figure 5 – Linear regression between the multi-hole probe and the anemometer in flight.

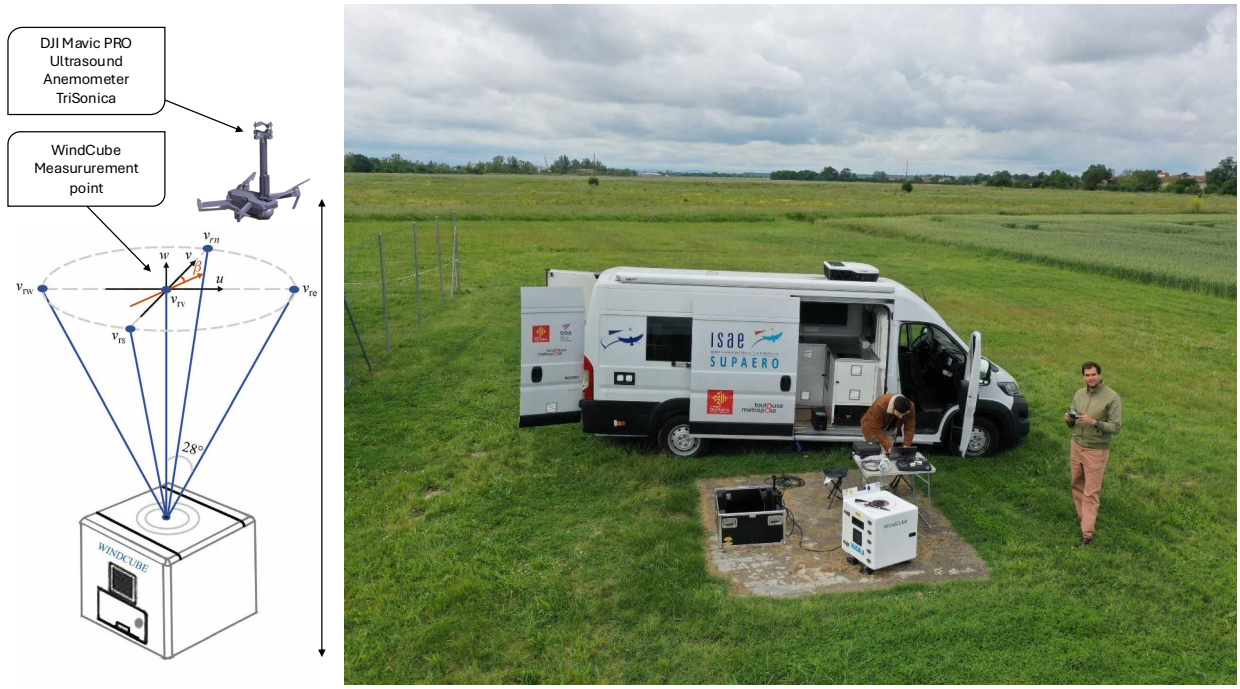


Figure 6 – WindCube LiDAR mobile setup.

localized turbulent structures. Finally, the temporal averaging inherent to the LiDAR reconstruction process differs from the high-frequency sampling of the ultrasonic anemometer, which may contribute to discrepancies in the instantaneous measurements while preserving good agreement in the mean wind speed.

Another test consisted of comparing wind speed measurements obtained from the airborne ultrasonic anemometer with those from a ground-based Doppler LiDAR (WindCube) operating as a reference system. The results are presented in Figure 8 and 9. The LiDAR provided wind measurements at fixed altitudes of 50 and 100 m above ground level, while the quadcopter-mounted ultrasonic anemometer was positioned at corresponding heights.

A direct comparison of the time series reveals that both systems capture similar large-scale wind fluctuations and temporal trends. However, noticeable differences remain in the instantaneous measurements. At an altitude of 100 m, the comparison yields a Pearson correlation coefficient of $R = 0.486$, a mean bias of $-0.13\ \mathrm{m\,s^{-1}}$, and a root-mean-square error (RMSE) of $0.71\ \mathrm{m\,s^{-1}}$. At 50 m, the correlation coefficient slightly increases to $R = 0.536$, while the bias and RMSE are $-0.33\ \mathrm{m\,s^{-1}}$ and $0.81\ \mathrm{m\,s^{-1}}$, respectively.

The relatively small bias observed at both altitudes indicates the absence of a significant systematic offset between the two measurement systems. The moderate correlation coefficients are partly explained by fundamental differences in the measurement principles. The WindCube Doppler LiDAR does not perform a point measurement but reconstructs the wind vector from radial velocity measurements acquired along multiple laser beams distributed on a conical scanning pattern. Consequently, the reported wind speed at a given altitude represents a spatially averaged quantity over a measurement volume surrounding the instrument. As the measurement height increases, the diameter of the scanned cone also increases, resulting in sampling locations separated by several tens of metres. At 100 m altitude, the reconstructed wind field originates from measurements distributed over a horizontal area exceeding 100 m in diameter.

In contrast, the ultrasonic anemometer mounted on the UAV provides a local measurement of the wind at a single position. Therefore, the two systems do not sample exactly the same air mass. In turbulent atmospheric conditions, coherent structures and gusts may exhibit spatial scales smaller than the WindCube sampling volume, resulting in differences between the reconstructed LiDAR wind speed and the local measurement performed by the airborne sensor. Additional discrepancies may arise from residual propeller-induced disturbances, uncertainties in altitude estimation, and slight

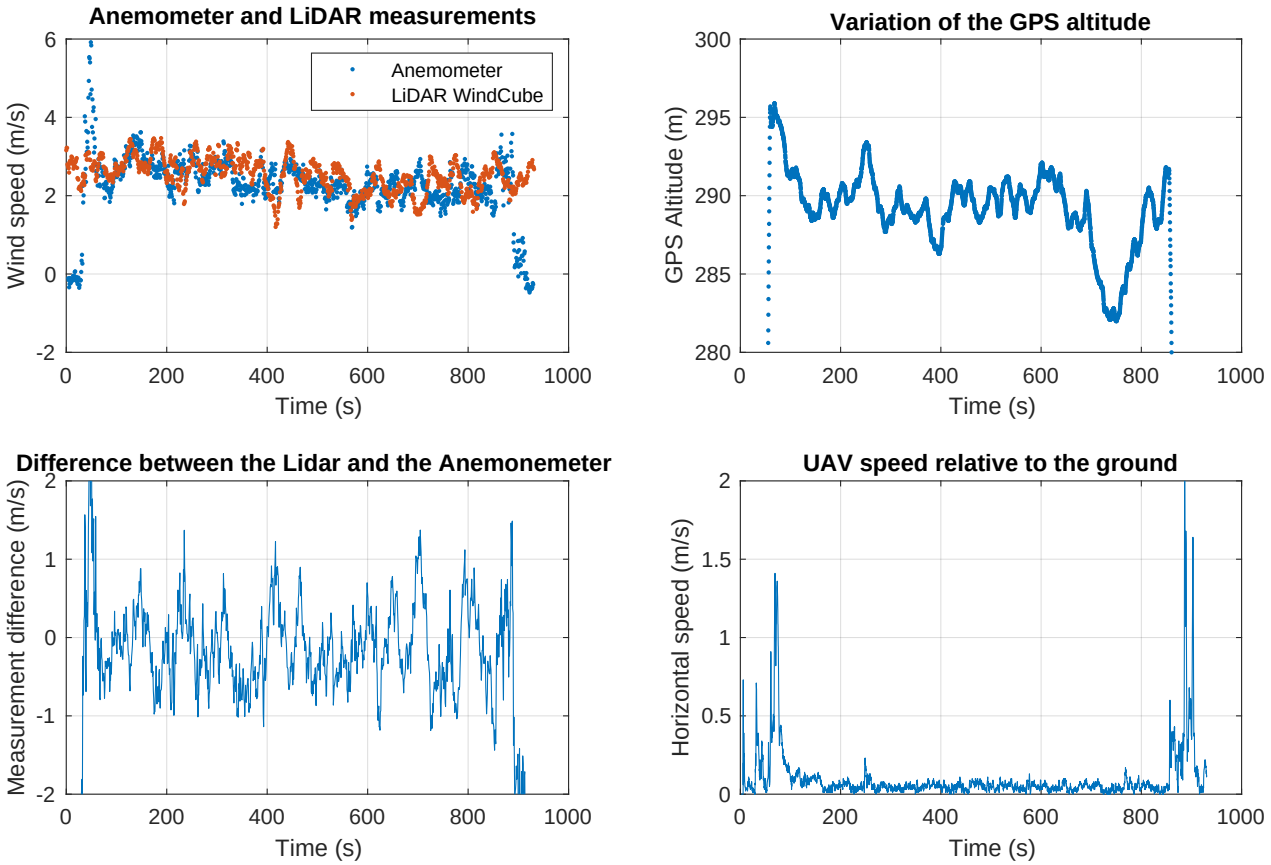


Figure 7 – Comparison between anemometer in flight.

horizontal offsets between the UAV and the LiDAR measurement volume.
To further evaluate the consistency of the measurements, the power spectral density of both datasets was calculated and is presented in Figure 8. Despite the moderate point-by-point correlation, both systems exhibit a comparable distribution of turbulent kinetic energy across the resolved frequency range, indicating that they capture similar atmospheric motions. This observation suggests that the airborne ultrasonic anemometer reproduces the dominant turbulence scales measured by the reference LiDAR system, even though instantaneous agreement is limited by the fundamentally different sampling volumes of the two instruments.

2.4 Mini LiDAR system - airborne integration

Flight tests of airborne coherent Doppler LiDAR systems have demonstrated their capability to remotely sense wind velocity fields ahead of an aircraft, providing real-time information on atmospheric disturbances and turbulence, thereby improving flight safety and performance [23, 24]. In addition, studies motivated by the prevention of windshear-related accidents have shown that coherent Doppler LiDAR systems can detect windshear hazards several kilometers ahead of an aircraft, enabling early warning capabilities and enhancing operational safety [25, 26].
In addition to the previously presented wind measurement systems, this chapter introduces a miniaturized LiDAR system composed of two optical units and a dedicated control, acquisition, and processing electronic board. The system provides measurements of two wind velocity components (one vertical and one horizontal) at a distance of 12 meters upstream of the installation and is primarily intended for UAV application in this study. Originally, the system was developed to improve the performance of large wind turbines by determining the optimal overall orientation angle of the system. It also shows strong potential for improving the accuracy of vertical wind component estimation compared to conventional GPS-based systems, which often constitute the weakest link in wind estimation algorithms applied to flying vehicles.

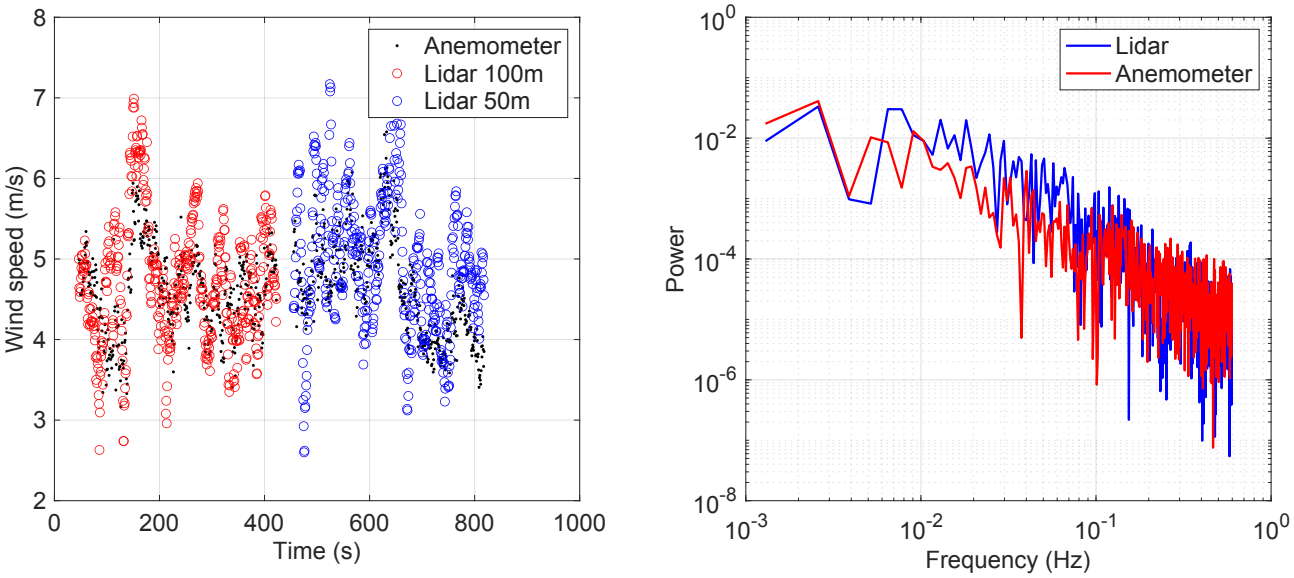


Figure 8 – Comparison between anemometer in flight 2.

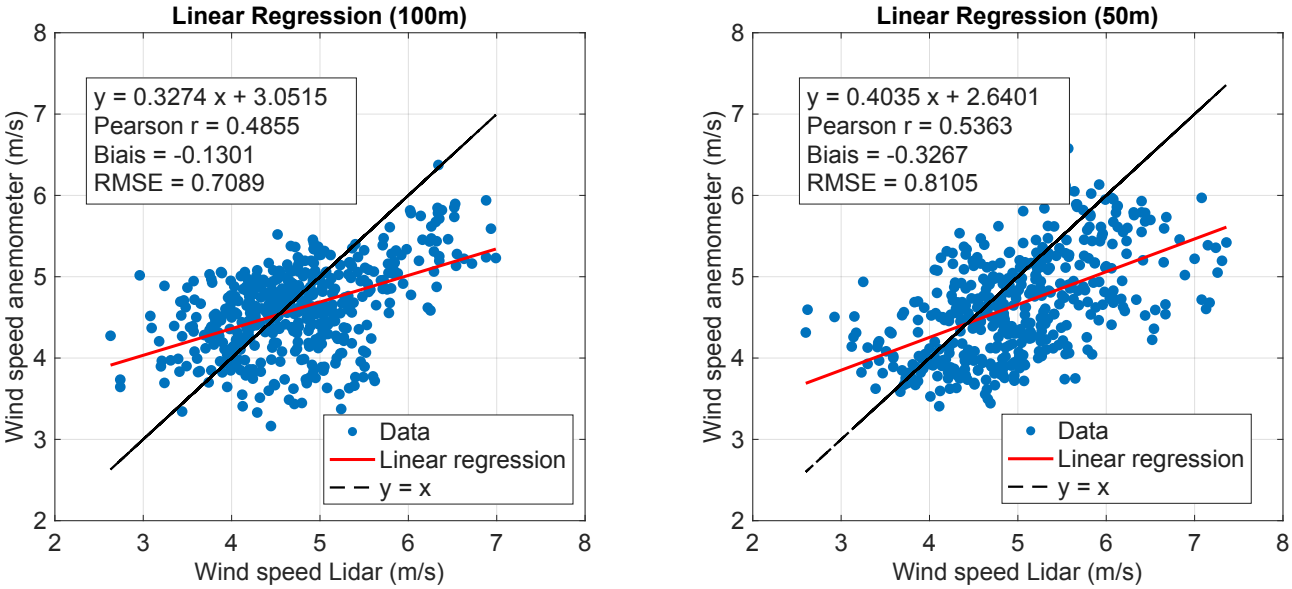


Figure 9 – Comparison of linear regression between two measurement heights.

The wind vector reconstruction methodology is based on a dual-beam LiDAR configuration, as shown in Figure 10. A direct coordinate system is defined, with the x-axis aligned with the flight direction and the z-axis oriented downward. The two LiDAR channels are symmetrically inclined, one pointing downward and the other upward (or alternatively one pointing left and the other right, depending on the configuration), each forming a known angle with the horizontal. A configuration with one optical head pointing left and the other pointing right, used for ground testing, is shown in Figure 10a). The configuration to be integrated into the aircraft, which provides measurements of the horizontal and vertical wind components, is presented in Figure 10c).

A dual-head LiDAR system shown in 10c) estimates both horizontal and vertical wind components by measuring the wind velocity projected along two non-collinear beam directions. Each optical head emits a laser beam oriented at a known angle with respect to the horizontal reference frame. The LiDAR measures the Doppler shift of the backscattered signal, providing the component of the wind velocity along the beam direction (i.e., the line-of-sight velocity).

Let the two beams be oriented at angles θ_0 and θ_1 with respect to the horizontal. The measured velocities correspond to the projections of the wind vector onto the associated unit vectors. Since the beam directions are not parallel and their relative angle is known (measured on an existing installation

during ground calibration test), the two projected measurements form a system of two independent linear equations. By solving this system, the horizontal and vertical components of the wind vector can be reconstructed analytically.
The accuracy of the reconstruction depends on the angular separation between the beams: a larger separation improves the conditioning of the inversion, whereas small angles increase sensitivity to measurement noise. Additionally, appropriate angular conditions between the wind vector and the beam directions may be required to avoid ambiguity in the sign of the reconstructed components.

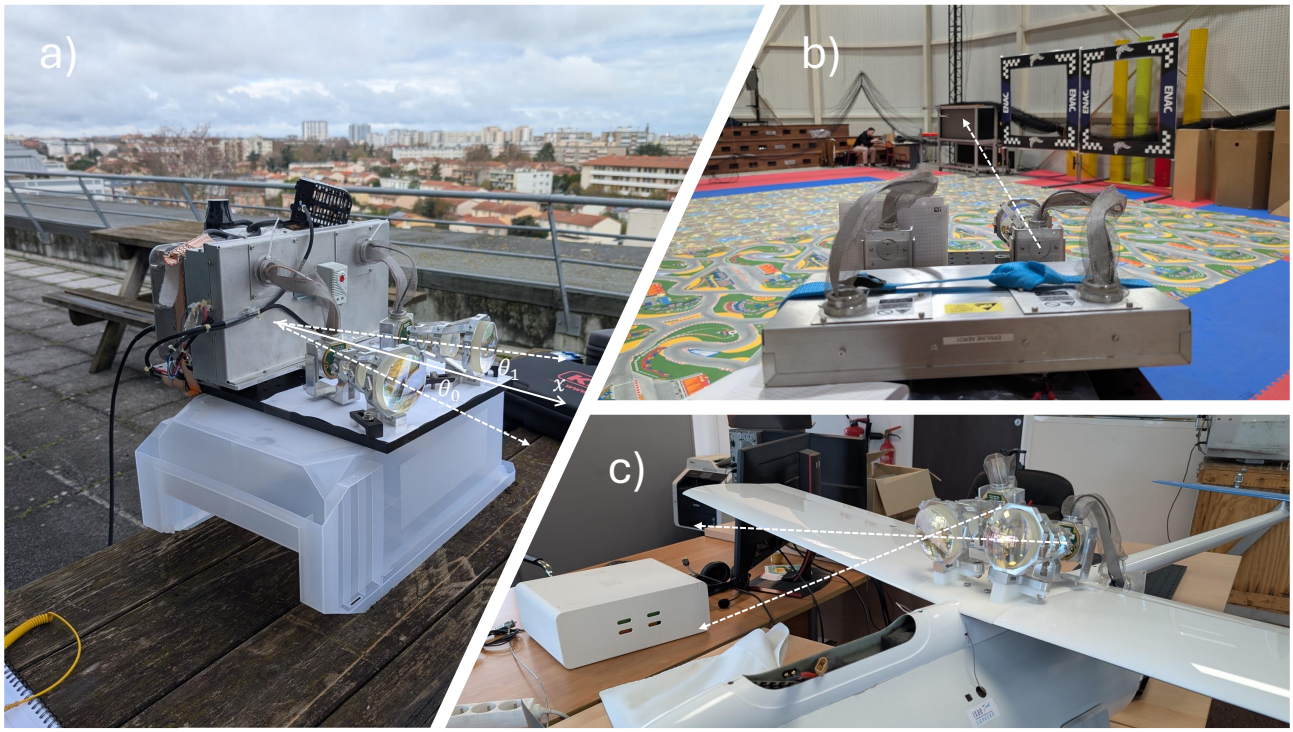


Figure 10 – Mini LIDAR system. a) A required equipment for testing or integration on the aircraft b) A calibration setup with WindShape c) An integrated system on a 4.4 m fixed-wing platform

The initial test campaign perfromed 12 meters in front of WindShape system previously used for anemometer tests is shown in Figure 10b). A comparison between multi-hole measurements with Mini-LiDAR system can be seen in Figure 11. The measurement points obtained by the Mini-LiDAR system depend on the number and size of detected airborne particles, parameters that are not characterized in the present study. It was observed that, as the WindShape system speed increases, the number of acquired measurement points also increases significantly. This indicates that when the flow is accelerated by WindShape, more particles are present in the air, which can be used for LiDAR measurements. At low speeds (e.g., 2–4 m/s), the number of acquisition points is considerably lower. The comparison between the two measurement systems shows higher standard deviation and root mean square error (RMSE) at higher speeds, which can be attributed to the characteristics of the flow generated by the wind-shape system. Turbulence intensity drastically increases with air speed of the WindShape system. Overall, the Mini-LiDAR system appears to be a very reliable airspeed measurement device. However, its performance, particularly in terms of acquisition frequency and particle availability at a given flight test site, cannot yet be determined, as this would require dedicated flight testing of the presented system under representative in-flight conditions. Such flight tests are planned as the next phase of this research activity.
Nevertheless, the integration of the Mini-LiDAR system on a small uncrewed aircraft remains challenging due to the size and mass of the optical hardware. The current configuration requires the installation of two optical heads, each with a diameter of approximately 80 mm and a mass of around 2 kg, in addition to the associated electronics and supporting systems. Such integration constraints may significantly impact aircraft layout, aerodynamic integration, payload capacity, particularly for small UAV platforms. From a practical standpoint, the authors consider that its application should not

be envisaged for aircraft with a wingspan of less than 4 m and a total mass below 12 kg. The authors also consider that a favorable integration location is as close as possible to the aircraft symmetry axis, while avoiding wingtip or under-wing locations due to potential structural dynamic effects.

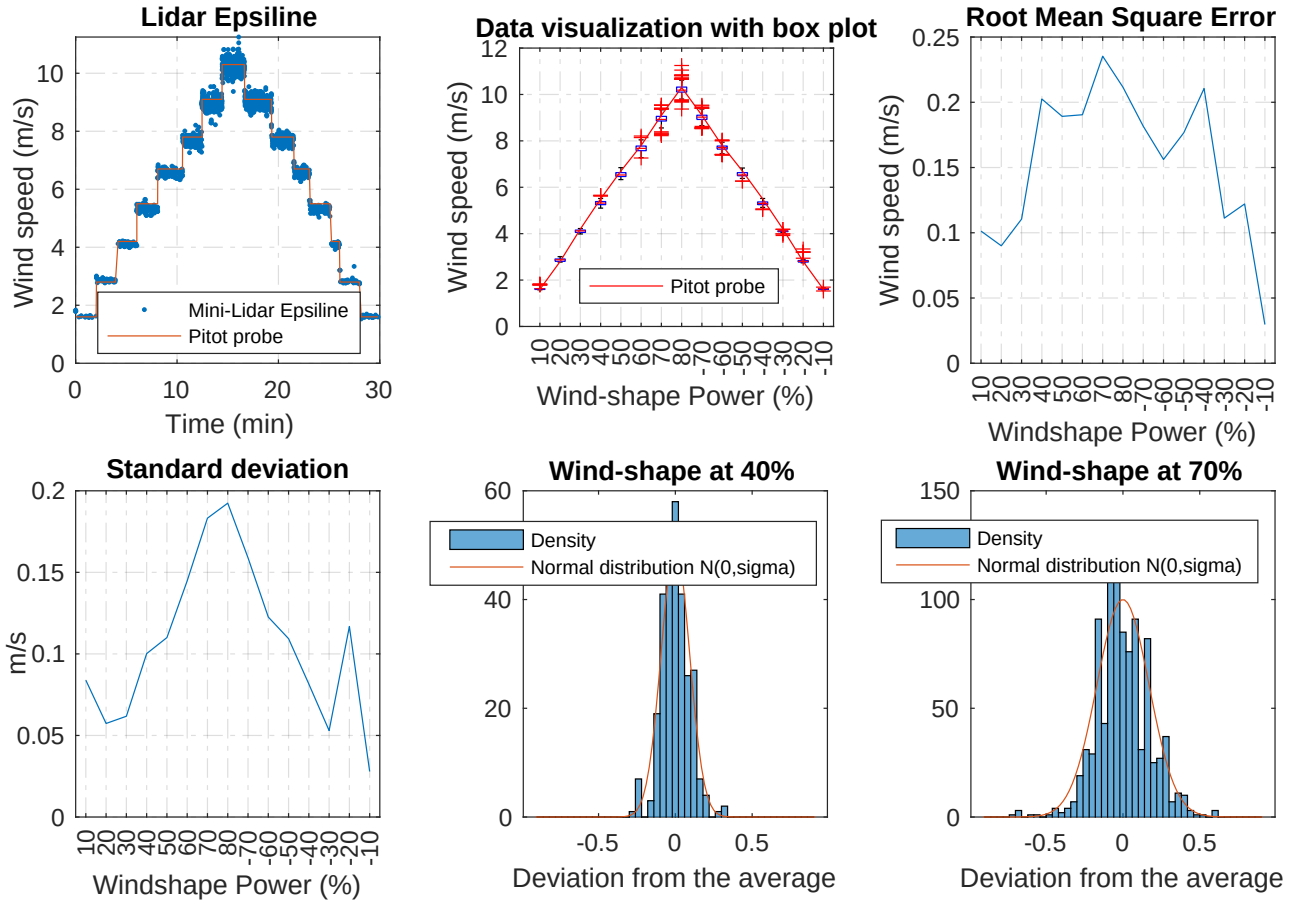


Figure 11 – Mini LiDAR measurements bersus multi-hole probe

3. Conclusion

This study presented a comparative investigation of atmospheric wind measurement techniques using a multi-sensor approach combining a UAV-mounted ultrasonic anemometer, a ground-based Doppler LiDAR system, and a miniaturized dual-beam LiDAR prototype. The objective was to assess the performance, limitations, and operational applicability of each system for atmospheric probing in both controlled and representative conditions.

The results obtained in a controlled WindShape environment demonstrated that the ultrasonic anemometer, when mounted on a UAV, provides reliable wind measurements but remains sensitive to platform-induced effects, particularly propeller-induced flow disturbances. A strong linear correlation was observed between the anemometer and reference multi-hole probe measurements ($R^2 = 0.9926$), confirming the validity of the applied correction methodology. However, increasing flow velocities were shown to amplify turbulence levels and measurement dispersion, highlighting the sensitivity of UAV-based measurements to local flow conditions.

The Doppler LiDAR WindCube system provided high-resolution measurements of the three-dimensional wind field at up to twenty discrete heights within the atmospheric boundary layer. Based on a Doppler Beam Swinging scanning strategy, the instrument reconstructs the horizontal wind components and vertical velocity from line-of-sight Doppler measurements acquired along a conical scanning pattern. Importantly, the sampled measurement points are distributed over an expanding cone whose footprint increases with altitude, meaning that measurements at higher altitudes correspond to increas-

ingly spatially separated atmospheric volumes. This introduces an inherent spatial averaging effect that must be considered when comparing LiDAR data with in-situ point measurements. Overall, the WindCube enabled stable and continuous characterization of the atmospheric wind field and served as a reference for UAV-based measurements at selected altitudes.

The comparison between the UAV-mounted ultrasonic anemometer and the WindCube showed moderate agreement in mean wind speed, with Pearson correlation coefficients of $R = 0.5363$ at 50 m and $R = 0.4855$ at 100 m. Corresponding biases were -0.3267 m/s and -0.1301 m/s, with RMSE values of 0.8105 m/s and 0.7089 m/s, respectively. These discrepancies are attributed not only to UAV altitude fluctuations and atmospheric variability, but also to the fundamentally different sampling volumes of the two systems: a localized in-situ measurement for the UAV-mounted anemometer versus a spatially averaged reconstruction over a conically expanding LiDAR sampling volume.

The miniaturized LiDAR system demonstrated promising capabilities for reconstructing horizontal and vertical wind components using a dual-beam configuration. Nevertheless, its performance remains strongly dependent on particle availability in the flow, which directly affects measurement rate and data completeness. While reliable results were obtained under controlled conditions, further validation under real atmospheric flight conditions is required to fully assess its operational performance.

From an integration perspective, the mini-LiDAR system presents significant challenges due to its size, mass, and optical configuration, requiring two optical heads of approximately 80 mm diameter and 1 kg each, together with associated electronics. These constraints limit its applicability to larger UAV platforms (wingspan $>$ 4 m and mass $>$ 12 kg) and require careful placement near the aircraft symmetry axis to minimize aerodynamic and structural disturbances.

Overall, the presented work highlights the complementarity of ground-based remote sensing, UAV-based in-situ measurements, and compact LiDAR systems for atmospheric characterization. The combination of these approaches provides a multi-scale understanding of wind fields and supports the development of improved sensing strategies for future autonomous aerial systems operating in complex atmospheric environments.

The main outcomes of this paper are:

- Presentation of a portable ultrasonic atmospheric measurement unit mounted on a quadcopter. This section also describes the calibration process, which accounts for the velocity perturbations induced by the proximity of the propellers. The calibration enables accurate wind speed measurements with an error below 0.2 m/s.
- A comparison between measurements provided by a portable ultrasound system and a ground Doppler LiDAR unit at different heights.
- Presentation and initial calibration of a miniaturized LiDAR system that can be mounted on a 12 kg UAV. The objective is to provide forward-looking measurements ahead of the aircraft, enabling anticipatory reaction to atmospheric phenomena.

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References

[1] Yubin Li and Jie Tang. Atmospheric boundary layer processes, characteristics and parameterization. *Atmosphere*, 14(4), 2023.

[2] D. H. Lenschow. Probing the atmospheric boundary layer. *American Meteorological Society*, 67(6):765–769, 1986.

[3] Nikola Gavrilovic, Murat Bronz, Jean-Marc Moschetta, and Emmanuel Benard. Bioinspired wind field estimation—part 1: Angle of attack measurements through surface pressure distribution. *International Journal of Micro Air Vehicles*, 10(3):273–284, 2018.

[4] Murat Bronz, Nikola Gavrilovic, Gautier Hattenberger, and Jean-Marc Moschetta. Simultaneous wind field measurements with doppler lidar, quadrotor and fixed-wing uav. *AIAA SciTech 2023 Forum*, 2023.

[5] Murat Bronz, Nikola Gavrilovic, Antoine Drouin, Gautier Hattenberger, and Jean-Marc Moschetta. Flight testing of dynamic soaring part-1 : Leeward inclined circle trajectory. *AIAA SciTech 2021 Forum*, 2021.

[6] W. Manley. The soaring of birds. *Nature*, 28:198, 1883.

[7] J.-M. Kai, T. Hamel, and C. Samson. Novel approach to dynamic soaring modeling and simulation. *Journal of Guidance, Control, and Dynamics*, 42(6):1250–1260, 2019.

[8] G. de Boer, M. Ivey, B. Schmid, D. Lawrence, D. Dexheimer, F. Mei, J. Hubbe, A. Bendure, J. Hardesty, M. D. Shupe, et al. A bird's-eye view: Development of an operational arm unmanned aerial capability for atmospheric research in arctic alaska. *Bulletin of the American Meteorological Society*, 99(6):1197–1212, 2018.

[9] S. T. Kral, J. Reuder, T. Vihma, I. Suomi, E. O'Connor, R. Kouznetsov, B. Wrenger, A. Rautenberg, G. Urbancic, M. O. Jonassen, et al. Innovative strategies for observations in the arctic atmospheric boundary layer (isobar)—the hailuoto 2017 campaign. *Atmosphere*, 9(7):268, 2018.

[10] T. Bonin, P. Chilson, B. Zielke, and E. Fedorovich. Observations of the early evening boundary-layer transition using a small unmanned aerial system. *Boundary-Layer Meteorology*, 146(1):119–132, 2013.

[11] T. A. Bonin, D. C. Goines, A. K. Scott, C. E. Wainwright, J. A. Gibbs, and P. B. Chilson. Measurements of the temperature structure-function parameters with a small unmanned aerial system compared with a sodar. *Boundary-Layer Meteorology*, 155(3):417–434, 2015.

[12] N. Wildmann, G. A. Rau, and J. Bange. Observations of the early morning boundary-layer transition with small remotely piloted aircraft. *Boundary-Layer Meteorology*, 157(3):345–373, 2015.

[13] M. Lothon, F. Lohou, D. Pino, F. Couvreux, E. Pardyjak, J. Reuder, J. Vila-Guerau de Arellano, P. Durand, O. Hartogensis, D. Legain, et al. The bllast field experiment: Boundary-layer late afternoon and sunset turbulence. *Atmospheric Chemistry and Physics*, 14(20):10931–10960, 2014.

[14] J. J. Cassano, J. A. Maslanik, C. J. Zappa, A. L. Gordon, R. I. Cullather, and S. L. Knuth. Observations of antarctic polynya with unmanned aircraft systems. *Eos, Transactions American Geophysical Union*, 91(28):245–246, 2010.

[15] A. van den Kroonenberg, T. Martin, M. Buschmann, J. Bange, and P. Vörsmann. Measuring the wind vector using the autonomous mini aerial vehicle m2av. *Journal of Atmospheric and Oceanic Technology*, 25(11):1969–1982, 2008.

[16] A. van den Kroonenberg and J. Bange. Turbulent flux calculation in the polar stable boundary layer: Multiresolution flux decomposition and wavelet analysis. *Journal of Geophysical Research: Atmospheres*, 112(D6):D06112, 2007.

[17] M. O. Jonassen, P. Tisler, B. Altstädter, A. Scholtz, T. Vihma, A. Lampert, G. König-Langlo, and C. Lüpkes. Application of remotely piloted aircraft systems in observing the atmospheric boundary layer over antarctic sea ice in winter. *Polar Research*, 34:25651, 2015.

[18] N Gavrilovic, A Mohamed, M Marino, S Watkins, J-M Moschetta, and E Benard. Avian-inspired energy-harvesting from atmospheric phenomena for small uavs. *Bioinspir. Biomim.*, 14(1):016006, nov 2018.

[19] Nikola Gavrilović, Murat Bronz, and Jean-Marc Moschetta. Bioinspired energy harvesting from atmospheric phenomena for small unmanned aerial vehicles. *Journal of Guidance, Control, and Dynamics*, 43(4):685–699, 2020.

[20] Lindsay Barbieri, Stephan T. Kral, Sean C. C. Bailey, Amy E. Frazier, Jamey D. Jacob, Joachim Reuder, David Brus, Phillip B. Chilson, Christopher Crick, Carrick Detweiler, Abhiram Doddi, Jack Elston, Hosein Foroutan, Javier González-Rocha, Brian R. Greene, Marcelo I. Guzman, Adam L. Houston, Ashraful Islam, Osku Kemppinen, Dale Lawrence, Elizabeth A. Pillar-Little, Shane D. Ross, Michael P. Sama, David G. Schmale, Travis J. Schuyler, Ajay Shankar, Suzanne W. Smith, Sean Waugh, Cory Dixon, Steve Borenstein, and Gijs de Boer. Intercomparison of small unmanned aircraft system (suas) measurements for atmospheric science during the lapse-rate campaign. *Sensors*, 19(9), 2019.

[21] W. Thielicke, W. Hübert, U. Müller, M. Eggert, and P. Wilhelm. Towards accurate and practical drone-based wind measurements with an ultrasonic anemometer. *Atmospheric Measurement Techniques*, 14(2):1303–1318, 2021.

[22] Murat Bronz, Nikola Gavrilovic, Antoine Drouin, Gautier Hattenberger, and Jean-Marc Moschetta. Flight testing of dynamic soaring part-2 : Open-field inclined circle trajectory.

[23] R. Targ, B. C. Steakley, J. G. Hawley, et al. Coherent lidar airborne wind sensor ii: flight-test results at 2

and 10 μm. *Applied Optics*, 35(36):7117–7127, 1996.

[24] Nikolaus Peter Schmitt, Wolfgang Rehm, Thomas Pistner, Paul Zeller, Hermann Diehl, and Peter Navé. The awiator airborne lidar turbulence sensor. *Aerospace Science and Technology*, 11(7):546–552, 2007.

[25] R. Targ, M. J. Kavaya, R. M. Huffaker, and R. L. Bowles. Coherent lidar airborne windshear sensor: performance evaluation. *Applied Optics*, 30(15):2013–2026, 1991.

[26] Patrick Vrancken, Martin Wirth, Gerhard Ehret, Hervé Barny, Philippe Rondeau, and Henk Veerman. Airborne forward-pointing uv rayleigh lidar for remote clear air turbulence detection: system design and performance. *Appl. Opt.*, 55(32):9314–9328, Nov 2016.