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Lighter-than-air particle velocimetry for wind speed profile measurement

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ABSTRACT

The objective of this paper is to consolidate the backgrounds of a method to measure the local wind speed profiles by remotely tracking lighter-than-air bubble clusters, in a way that is efficient, safe and easily implementable. The technologies around remote sensing of atmospheric wind profiles are reviewed, together with those associated with particle image velocimetry. In this case, the targets are light liquid bubbles filled with helium, which are monitored from several locations on ground so that the full trajectory can be reproduced and hence, the wind speed derived at each point along the path. The features of the measurement system are detailed, describing its major components. The different applicable data filtering processes, the core of the operation, are reviewed to find the best options for the estimation of the wind profile in real time. The capability to measure the horizontal wind along the ascending path of the targets has been checked by means of simulated scenarios, indoor campaigns and in-field tests. The synthetic scenarios allowed the tuning of photometric parameters as well as the first estimation of the performance and the limitations. The field test campaigns allowed validating the prototype under different configurations and atmospheric conditions. Initial tests were conducted in a Spanish atmosphere research centre (CIBA), where wind data until 100 m height is continuously recorded, followed by additional experiments in a more realistic environment, near an airport, where these data could be operationally used in the future. The results from these tests are successful, taking into account the fact that the system is still in an early development phase, while still being able to beat initial performance goals (0.4 m/s mean error for wind speed and 15° for wind direction). It is expected that the idea is a reliable and low cost alternative to other remote sensing devices for wind profile measurement in certain applications in the medium-accuracy range.

Contents

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1. Introduction

There are many activities that require a good knowledge of wind speed profiles in the lower part of the atmosphere, like wind energy production, civil engineering, pollutant dispersion or pedestrian comfort amongst others [1–4].

The study of wind speeds and directions is not an easy task, especially if the region of interest is close to the ground because the viscosity governs the air movement near flow boundaries. For the Earth's surface, the boundary layer can be as high as 1000 m over the terrain, changing the wind speed from zero to geostrophic winds [5]. Furthermore, the wind changes its direction with height due to Coriolis forces [6]. Efforts to model the wind speed profile in compact formulations have been continuous over a long period of time, ending up with different mathematic models, the most popular of which is the logarithmic law corresponding to an atmospheric neutral condition, being deduced from a similarity study [7].

But when higher accuracy in the boundary layer knowledge is needed, the standard logarithmic law and its variations are not enough; for the last few decades, new systems have been developed to measure the wind speed values close to the surface. Meteorological towers, LIDAR, RADAR, SODAR, observation balloons or satellites are some examples of these kinds of systems [8].

Meteorological towers are probably the most common resource for measuring the wind speed and direction at a specific place. They are tall (between 40 and 120 m height) and precise, because wind speed and direction can be measured using anemometers and wind vanes at different heights after rigorous calibrations.

RADAR (Radio Detecting and Ranging) can measure the wind velocity by means of the reflection of electromagnetic waves from rain drops, hail or snow. The Doppler velocity is estimated from the phase shift between the return signals of consecutive transmitted pulses [9]. Its limitations are mainly due to anomalous propagation of electromagnetic waves, ground clutter or non-natural interferences like wind farms [10]. There are also limitations on the spatial resolution achieved.

Light Detection and Ranging (LIDAR) uses the reflection of light pulses. This allows high spatial and temporal resolution of the measurements from the ground to more than 100 km, obtaining several atmospheric variables such as temperature, pressure, humidity and, of course, wind speed and direction [11]. Its efficacy has been demonstrated in several applications like measurement of aircraft true airspeed, detection and tracking of clear air turbulence, wind shear, gust fronts, aircraft wake vortices and of course the capture of full atmospheric wind profiles [12].

Sound Detection and Ranging [SODAR] is based on the reflection of sound waves to detect the wind speed and direction at various elevations above the ground [13]. Being more affordable than RADAR and LIDAR systems, one of the most important problems with SODAR is ground clutter, which can severely influence and disturb the echoes. Furthermore it must be located far away from populated locations [14].

Observation balloons have been used for gathering meteorological data for centuries. A lighter-than-air balloon with some meteorological instruments collects data from the desired variables of the atmosphere. Releasing many balloons at the same time allows the acquired data to be compiled into a single scenario at a certain point of time [15]. Also, it the vehicle is large enough, it is possible to include a radar reflector to better measure the wind properties by tracking it from the ground [16].

Satellites are also a valuable tool used to monitor and forecast the movement of air around the globe because they can provide cloud remote sensing and good profiles of temperature and moisture at different levels in the atmosphere by means of special radiometers called sounders [17]. However, measuring wind speed from space is more difficult and there only exist two ways: wind scatterometers [18] and LIDAR devices like Doppler Wind LIDAR [19].

Each technology has its own advantages and drawbacks, many times related to the cost of the equipment or problems with the deployment and installation. For example, should critical locations like airports be the scenarios of interest, where there are severe restrictions related to safety and the height of the structures near the runway is very limited, some of the systems will need to be discarded. The method analysed in this paper is a scaled version of the technique employed with weather balloons, which are usually tracked by radar, radio direction finding or navigation systems in order to obtain wind data from the ground to several kilometres high.

Also, some ideas are borrowed particle image velocimetry (PIV) techniques, where fluid velocity is calculated by measuring the velocity of tracer particles tracked from optical cameras [20]. The most popular technique is the 2D PIV [21,22] although during the last few years more work has been done by capturing the three-dimensional flow fields with a volumetric particle-image velocimetry system (V3V) [23,24]. Like in PIV, the fluid contains small particles which should follow the flow in a good manner. Three sensitive cameras capture the laser light reflected by the tracing particles within a short time interval. Based on the displacements of each particle and the time between the recordings, the velocity of all particles in the measurement volume can be determined. A critical issue to apply this technique is being able to feed the flow in the right way, having an adequate number of tracer particles in the measurement region (the resulting reflection fields should ideally contain about 70,000 source particles [25]). Because of this, PIV techniques are usually limited to enclosed flows with limited test sections.

The bubble tracking method, although inspired by these techniques, has been designed to be used in open air to measure atmospheric boundary layer profiles and some preliminary results have been obtained with this technique in a recent work [26]. Also recently, a similar but more complex and expensive method that consists of small, helium-filled tracer balloons and an instrument that tracks them with high spatial resolution by means of a LIDAR rangefinder has been developed and tested [27]. This method proved to be useful when measuring horizontal wind speed, wind direction, and vertical shear. On the other hand, and also applying a bubble tracking technique, [28,29] are developing a system to quantitatively measure wind flow near the ground surface in both the horizontal and vertical directions (in other words, wind flow in three dimensions) using photogrammetry. In this method, a balloon (a no-lift balloon), with the same relative weight as air, and soap bubbles were released as tracers. The results of the testing proved that the measurement methods were effective.

The initial objective, based on a manual prototype for the bubble generation, is to achieve better accuracy than 0.4 m/s average for wind speeds and 15° average for wind direction in the first 30 m of height. Accuracy using two or three cameras for the bubble tracking is also compared. In further developments, new calibration procedures can be included during the post-processing with the aim of reducing measurement errors to 0.15 m/s and 6°.

In summary, the research work is focused on the development of an affordable wind profile measurement system, which should be able to provide accurate knowledge of the local wind speed profiles by remotely tracking lighter-than-air bubbles. The goal is to achieve a reliable and low cost alternative to the previously referred methods for certain conditions and applications.

2. System overview

The system concept is quite simple and derived from particle image velocimetry techniques. In this case, remote optical sensors