Development of an unmanned aerial vehicle to study atmospheric boundary-layer turbulent structure

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Abstract. One of the main challenges in the boundary-layer turbulence research consists in advancing turbulence theory towards describing turbulent regimes over inhomogeneous and irregular surface which is often the case in nature. Novel observational techniques are required to sample turbulence statistics in such conditions. To that aim, a light-weight payload for atmospheric turbulence measurements is designed and used on a vertical take-off and landing (VTOL) fixed-wing unmanned aerial vehicle (UAV). Such an observational platform complements traditional mast observations and makes it possible to sample turbulence statistics over remote and inhomogeneous landscapes. The advantages of the VTOL scheme consist in: i) minimizing the risk of the payload damage during landing; ii) less strict requirements to the surface conditions in the landing area. The turbulence payload consists of a miniature seven-hole probe, inertial navigation system and a fine-wire resistance thermometer. The seven-hole probe and the fine-wire temperature sensor were designed and calibrated as part of this study. In addition, the payload also includes a slow-response temperature-humidity sensor, relatively fast humidity sensor as well as an infrared surface temperature sensor. For the onboard data-logging, a computer based on Raspberry Pi 4 is used. The whole system has been successfully tested at the Tsimlyansk research station, Russia.

1. Introduction

Atmospheric boundary-layer turbulence is in the center of many critically important atmospheric phenomena [1]. Turbulent mixing carries out heat, moisture and momentum exchange between the atmosphere and the underlying surface shaping the near-surface meteorological regime, affecting low-level cloud and fog formation, as well as pollutant dispersion [2]. Thus, it is crucial that turbulent mixing
is adequately taken into account in atmospheric models used in numerical weather prediction and climate simulations [3]. The main challenge consists in that turbulent scales are typically smaller than the horizontal grid step used in such models. Therefore, turbulent mixing has to be parameterized using a turbulence closure and the corresponding similarity hypothesis and semi-empirical relations [4].

The used closures are valid for horizontally-homogeneous and quasi-stationary conditions and employ empirical relations obtained in such conditions [2]. However, many natural surfaces are strongly inhomogeneous with respect to the surface temperature, moisture and roughness [5]. The examples are forest-field transitions, boreal lakes, polynyas and leads in sea ice and many other. The “non-classical” conditions also often occur due to the interaction of turbulence with other physical processes such as gravity waves [6] and mesoscale motions [7]. Further research and novel observational data addressing these problems are needed.

Empirical data on turbulence statistics over heterogeneous surface as well as at different heights in the boundary layer is needed to test the adequacy of the existing closures and to develop new ones. However, traditional observational methods of turbulent research, such as eddy-covariance masts and piloted instrumented aircraft, are often not sufficient [5]. The main drawback of an eddy-covariance mast is its fixed stationary location, while the drawback of using a piloted aircraft is its high cost. An instrumented unmanned aerial vehicle (UAV) is an affordable platform which can provide the needed turbulence data. Such a UAV provides the most cost-effective way to obtain the observations, especially over the difficult to access areas [5].

In recent years, the development of UAVs for turbulence and meteorological research has gained increasing attention worldwide [8]. The International Society for Atmospheric Research using Remotely piloted Aircraft (ISARRA, http://www.isarra.org) has been organizing a yearly conference starting from 2013 often accompanied by a field intercalibration experiment [9]. Also an increased number of observational campaigns has been using UAVs as a main or complementary tool [e.g., 10-13], including one of the most recent ISOBAR (The Innovative Strategies for Observations in the Arctic Atmospheric Boundary Layer) campaigns [14,15] in which several research groups used different types of UAVs to study the mean and turbulent structure of a stable boundary layer over snow/ice in winter.

The UAVs used for turbulent research most commonly have the fixed-wing scheme [15-19]. The advantages of this scheme over the multirotor platform are the longer endurance and larger payload. The vertical take-off and landing (VTOL) scheme has just started being used in the meteorological UAVs [20,21]. It has the advantages of an easier and safer take-off and landing and is also less restrictive to the landing conditions.

To summarize, the mentioned studies where the UAVs were used to sample atmospheric boundary layer (ABL) turbulence demonstrated that such a platform is capable to provide the good quality data resolving turbulent fluctuations in a broad range of scales. At the same time, the uncertainties of the obtained turbulence statistics remain not well known and require further intercomparison and calibration studies. Moreover, no standard commercially-available turbulence payload for UAVs exists. Each research team has to go through the development of their own system using the experience of the previous studies. This is an ongoing iterative process due to the development and testing of new sensors and the UAV components. An essential part of such studies is the comparison of the observations obtained by a developed system with the data from other well-calibrated platforms and theoretical models.

The goal of this paper is to present the newly developed fixed-wing VTOL UAV “Tsimlyanin” and its turbulence payload. Both the UAV and its payload were custom-designed. To validate the system, several test flights were performed during the summer campaign in Tsimlyansk (Southern Russia) in 2020. Here, a first comparison of the observed mean wind speed and direction profiles with the observations from sonic anemometers and sodars is presented.

The structure of the paper is as follows. In section 2, the comparison of the performance of the two different UAV schemes is presented and the meteorological payload and the data acquisition system are described. The results from test flights in Tsimlyansk are shown in section 3.
2. Unmanned aerial system “Tsimlyanin”

The UAV “Tsimlyanin” was designed in collaboration between the Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (IAP RAS, Moscow, Russia) and the Moscow Aviation Institute (MAI). Apart from several commercial sensors, the meteorological payload includes two custom sensors: i) the seven-hole probe designed and calibrated in the Khristianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of RAS (ITAM SB RAS, Novosibirsk, Russia) and ii) the fast-response platinum-wire temperature sensor designed and calibrated in the Central Aerological Observatory (CAO, Dolgoprudny, Russia). The onboard data acquisition system was designed in MAI. In the following subsections, the UAV and its payload are described in more detail.

2.1. Design of the UAV scheme

The key requirements to the UAV scheme were the following: i) the air flow disturbances generated by the aircraft during the flight must not affect the measurements, ii) the installed payload must not shift the center of mass out of the tolerable limits. Furthermore, the UAV design had to meet the characteristics of the flight patterns used for the boundary-layer observations, which are summarized in table 1.

| Characteristic               | Value   |
|-----------------------------|---------|
| Payload mass, kg            | <1.2    |
| Mission endurance, min      | 60-90   |
| Cruising speed, m/s         | 20-22   |
| Cruising altitude, m        | < 2000  |
| Near-surface wind-speed limit, m/s | 8       |

First of all, one had to choose among the most common UAV schemes which are: i) a multirotor (MR), ii) a tilt-rotor, iii) the flying wing (FW), iv) the hybrid “vertical takeoff and landing” (VTOL) fixed-wing scheme. The latter combines the take-off and landing in the multirotor mode and cruising in the fixed-wing mode.

The multirotor and tilt-rotor schemes were not considered due to the likely influence of the propeller-induced disturbance on measurements, as well as due to the short mission endurance of the MR scheme. For the further development, the FW and VTOL configurations were selected.

Concerning the choice of the propulsion type, the electric propulsion was selected as it sufficed the required mission endurance time.

First, the FW scheme and the results of its performance tests are considered. The designed FW UAV and its components are shown in figure 1.

Structurally the UAV is based on the commercially-available Skywalker-X8 model. The fuselage was made of a composite material, the structure of the consoles was reinforced and the weight of the structure was reduced. The FW UAV consists of the following main parts: i) composite fuselage used to accommodate the autopilot system, payload and batteries; ii) a pair of wing-panels; iii) a propulsion system with a folding propeller; iv) electrical battery; v) a parachute; vi) an autopilot.

During the test flights the following results were obtained: the steadiness and controllability of the FW scheme strongly depends on the payload location, which imposes restraints on operation and possible modification of the aircraft; the parachute method of landing cannot provide the safety of the sensors, such as the seven-hole probe and the open-wire temperature sensors. Apart from that, the aircraft performance characteristics (APC) of the vehicle were found to meet the required ones (table 1).
The 90 minutes mission endurance was reached in the combined cycle flight which consisted in an ascent to 2000 m, cruising and a descent to 150 m. The Multistar High Capacity 20000mAh 4S battery was used with the E-max GT4030/06 electrical engine. The parachute system was removed.

The design of the hybrid VTOL UAV is shown in figure 2. Its main difference from the FW is the presence of the four propeller-engine systems used for the vertical take-off and landing which are not used during the horizontal flight. For a horizontal flight a pusher propeller is used which is set in motion by an electrical motor.

Structurally the aircraft has the frame design in which the central section and the twin-boom tail are tied. On the latter, the propeller-engine systems of the vertical take-off and landing are located. The truss structure fuselage is attached to the frame. The sensors of the payload are located in front of the fuselage. Inside the fuselage there is also an automatic control system and a power battery. The dimensions of both UAVs are shown in figure 3.
In the test flights, the VTOL aircraft used the Multistar High Capacity 20000mAh 6S battery, E-max GT4030/06 motor and the APC 18x10 propeller for the horizontal flight. For take-off and landing, four Sunnysky X4112S KV450 engines were used. The transition to the landing mode was made at 10 m altitude.

![Figure 3. The VTOL and FW UAVs schematic view with dimensions shown in cm.](image)

The test flights showed that the VTOL scheme offers a wider range for the location of the center of mass compared to the FW. Thus, it provides more freedom with respect to the equipment placement inside the fuselage. In particular, it allows placing the payload sensors in front of the nose of the aircraft at a maximum distance from the structural elements. The vertical take-off and landing possibility reduces the probability of the sensors damage.

The automatic control system of both types of aircraft consists of an autopilot of the Pixhawk type, a TBS Crossfire radio control system, a GPS signal receiver based on an M8N chip, and an operator’s video channel. It provides both the manual control mode and the flight according to the preconceived program. The comparative APCs of the considered VTOL and FW schemes are summarized in table 2. The stated payload mass represents the maximal mass of the meteorological payload including sensors, acquisition devices, a controller and a battery powering the payload. It does not include the main battery powering the engines, parachute, autopilot and gps antennas, etc.

**Table 2. Aircraft performance characteristics for the VTOL and FW schemes.**

| UAV type:                          | VTOL  | FW  |
|------------------------------------|-------|-----|
| Gross take-off mass, kg            | 11    | 8   |
| Payload mass, kg                   | 1.7   | 1.2 |
| Peak speed, m/s                    | 32    | 25  |
| Cruising speed, m/s                | 22    | 20  |
| Mission endurance, min             | 60    | 90  |

To conclude, both the VTOL and FW schemes are suitable for the boundary-layer turbulence studies and have specific drawbacks and advantages. The VTOL scheme has a shorter mission endurance time, but has less restrictions with respect to the payload placement, better in-flight dynamics and safer landing. Thus, the VTOL scheme was chosen for the test observational flights during the campaign in Tsimlyansk in August 2020.

2.2. Meteorological payload
The meteorological payload of “Tsimlyanin” is similar to the payloads of the UAVs MASC-3 [15] and ALADINA [17].

It consists of:
- a seven-hole probe (ITAM SB RAS)
- the inertial navigation system Ellipse-2N (SBG Systems)
- a fast-response platinum-wire temperature sensor (CAO)
- the slow-response temperature and humidity sensor HMP110 (Vaisala)
- the humidity sensor P14 Rapid (IST-AG)
- an infrared surface temperature sensor (Melexis).

The seven-hole probe designed at ITAM SB RAS is shown in figure 4a. It has a hemispheric tip with a 10 mm diameter. The 6 holes are placed at 60° angles relative to the axis along the probe. Further along the probe there are 4 holes for static pressure. The probe uses the Honeywell differential pressure transducers HSCMRRD005NDSA5 and the absolute pressure transducers HSCMAND015PASA5. The pressure transducers were calibrated in a laboratory in order to test and further increase the accuracy of the sensors. The wind-tunnel calibration provided the coefficients used to obtain the true air speed, the angle of attack and the sideslip angles. The three wind components can be calculated using the roll, pitch and yaw angles, as well as the aircraft velocities relative to earth obtained from the inertial navigation system, as described in [22,23].

Compared to the most frequently used five-hole probes, the seven-hole probe is expected to have a higher accuracy with respect to the measured attack and side-slip angles. However, the difference becomes significant only for rather high values of these angles. Such conditions are unlikely during typical boundary-layer flight patterns, but we did not study this issue in detail. Another advantage of a seven-hole probe is the redundancy of the obtained data. In case of malfunction of one of the differential pressure sensors, the needed values of the true air speed and the flow angles can still be obtained.

The fast-response temperature sensor is a resistance thermometer with an open platinum wire placed directly into the air flow (figure 4b). The wire has the diameter of 30 μm and the nominal resistance of 100 Ohm. The resistance of platinum is almost a linear function of temperature, while the small diameter of the wire and a rather intense airflow at a cruising speed of about 20 m/s ensure a small response time (<10 Hz). The sensor was first calibrated in a climate chamber where the resistance-temperature calibration curves were obtained. Next, the temperature recovery coefficient was obtained from the wind-tunnel calibration being a function of the true air speed.

The seven-hole probe tip is located 20 cm in front of the nose of the aircraft. Other sensors are located at a distance of about 10-15 cm in front of the nose. Computational fluid dynamics simulations for the considered UAV geometries with the take-off and landing propellers on a metal frame demonstrated that the pressure disturbance at a 20 cm distance is small which is in agreement with [24].

The purpose of the slow-response HMP110 sensor (time constant < 5 s for temperature and < 7 s for relative humidity) is to provide the well-calibrated observations of the mean temperature and humidity. The P14 Rapid relative humidity sensor has a faster response time of about 1.5 s at 20 °C which allows one to capture relative humidity variations due to large turbulent eddies. The purpose of the infrared

Figure 4. (a) Seven-hole probe designed in ITAM SB RAS; (b) fast-response platinum-wire temperature sensor designed in CAO.
surface temperature sensor is to provide data on the spatial variability of the underlying surface temperature which is especially relevant for heterogeneous landscapes.

2.3. **Onboard data logging**

The measurement complex includes the following main elements:

- Sensors which convert some measured physical value into the electrical signal (current, voltage, etc.);
- measurement systems (acquisition devices) which amplify, filter and digitize signals from sensors; in the simplest case, they could be analog-to-digital converters (ADC);
- measurement controller which serves for data collection and logging;
- communication channels.

Modular architecture was chosen to provide flexibility and extensibility. In such an architecture, the measurement and data acquisition devices are separate and independent units. The network bus is used to connect these units with the measurement controller. The bus makes it possible to replace, add or change sensors and acquisition devices. This scheme also allows changing the onboard position inside the UAV in order to choose the best placement. The structure of the complex is shown in figure 5.

![Figure 5. The measurement complex structure.](image)

Measurement controller is the core of the whole complex. It provides control of the measurement process, synchronization and logging. The modularity of the architecture is achieved by the network of acquisition devices. They host ADCs, microcontrollers and auxiliary systems (power supply systems, interface converters, etc.).

The microcontroller configures the ADCs, reads the measurements, buffers and post-processes them and sends them to the data measurement controller by its request. Typically, ADC is connected to a microcontroller via the SPI interface. The number of connected sensors is limited by the number of available SPI. The interface conversion chip is used for the connection of the microcontrollers to the bus. The chip is connected to the free UART interface. Thus, the acquisition devices are independent measuring systems which are set to work with a certain sensor or several sensors of the same type.

The acquisition devices for the 7-hole probe, platinum resistance temperature sensor and the P14 Rapid humidity sensor were designed as part of the meteorological payload.

Currently, a Linux-based single-board computer RaspberryPi4 is used as a measurement controller. It is an arbiter on the RS-485 network. It initiates the exchange, sends a request to the acquisition devices
and receives measurements as a result. The request should include an address of one of the measuring units, a predefined package of data and the current time stamp in milliseconds from the beginning of the program. Timestamps within each request provide time synchronization of different modules.

It should be mentioned that some devices are not supported by the described protocol, namely, the infrared surface temperature sensor, the HMP110 temperature and humidity sensor and the high-precision inertial navigation system (INS).

The INS is the Ellipse-2N series inertial unit. It includes the high-precision strapped-down system, integrated GPS unit, controller and special software and interfaces for connection of additional data sources. It uses serial interface (UART) for connection to the measurement controller and provides the vector of navigation information (position, orientation angles and velocities) at a 100 Hz frequency.

The sample rate for all sensors is the same and is equal to 100 Hz apart from the slow-response HMP110 sensor for which the sample rate is about 1 Hz.

The measurement data are written into separate files for each module (sensor) in text format.

3. Test flights in Tsimlyansk

Test flights were performed during the IAP RAS field campaign in Tsimlyansk in August 2020. The site represents a rather homogeneous steppe landscape in the Southern Russia, which has been used by IAP RAS as the main polygon for many turbulence studies [e.g., 25]. It is interesting to note, that there were attempts to use a UAV for turbulence research in Tsimlyansk already more than two decades ago [26]. However, those efforts were discontinued.

The IAP RAS ground observations in Tsimlyansk included a 30-m mast with sonic anemometers installed at 2, 10 and 30 m heights, two sodars, a gradient mast and the microwave temperature profiler MTP-5. Thus, the mean atmospheric boundary layer structure, as well as turbulence statistics sampled by the UAV “Tsimlyanin” could be compared with observations from other platforms. On the other hand, the sodar and MTP-5 data can be validated by the in-situ UAV observations.

![Figure 6. Typical flight patterns performed during the Tsimlyansk 2020 campaign.](image)

Several flight patterns of the UAV “Tsimlyanin” are shown in figure 6, namely, the “spiral”, “racetrack” and “box” patterns. These flight patterns allow using different methods to calculate wind speed and direction [23]. Also, parallel segments of the “box” and “racetrack” patterns flown in opposing direction can be used for the in-flight calibration of the 7-hole probe [27]. Overall 10 flights were performed in different wind conditions without any damage to the payload.
Figure 7. Air temperature during the box flight pattern as measured by the fast platinum wire sensor (orange curve) and the HMP110 Vaisala sensor (blue curve).

The ability of the fast platinum wire sensor to resolve turbulent temperature fluctuations is shown in figure 7 in comparison with the slow-response HMP110 measurements. The temperature time series are obtained during the box flight pattern performed at 100 m height in convective conditions in the early afternoon. Thermals, typical for the convective boundary layer, are clearly visible in the platinum sensor measurements, while in the HMP110 measurements the thermals are filtered out due to the slow response time of HMP110.

Figure 8. Vertical profiles of wind speed and direction at 9:40-9:50 UTC on August 13, 2020 according to the UAV observations, LATAN and Scintec sodars and the three sonic anemometers on a mast. Whiskers show the standard deviation of wind speed and direction within each interval of heights.

Figure 8 shows the vertical profiles of wind speed and direction in the lower 200 m as observed by the UAV during the “racetrack” flight pattern in comparison with observations from the two sodars and sonic anemometers. The Scintec sodar was set up to observe the profiles below 100 m height. The LATAN Doppler sodar designed in the IAP RAS provided observations up to 200 m. Clearly, the UAV
observations are in a good agreement with the data from the two sodars and sonic anemometers. The vertical profiles are quite uniform with height above the surface layer which is typical for a well-mixed convective boundary layer.

4. Conclusion
The UAV “Tsimlyanin” and its meteorological payload are designed for the application to the atmospheric boundary-layer turbulence research. Two fixed-wing UAV schemes are tested: the flying wing (FW) and the hybrid “vertical take-off and landing” (VTOL) schemes. It is concluded that both schemes can be used in meteorological applications. The VTOL scheme proved to have more advantages over the FW scheme, such as a larger payload weight, flexibility with respect to the payload placement, safer landing, as well as being less demanding with respect to the landing/take-off infrastructure and surface conditions. The only drawback of the VTOL scheme is the smaller mission endurance time, as compared to FW.

The turbulence payload consists of the custom-designed fast-response 7-hole probe and platinum resistance temperature sensor, as well as of a commercially available inertial navigation system. Several acquisition devices were also custom-designed for particular sensors. The whole measurement complex has a modular structure which provides flexibility and extensibility. The data acquisition and logging is controlled by the single-board RaspberryPi-4 processor.

Test flights during the field campaign in Tsimlyansk in August 2020 demonstrated a robust performance of the whole system. The first analysis of the data shows a good agreement of the vertical profiles temperature, wind speed and direction as observed by the UAV with the data from other platforms. Further analysis will be focused on turbulence statistics and spectra obtained by the UAV. The presented preliminary results show the potential of using the UAV “Tsimlyanin” for studying the atmospheric boundary-layer mean and turbulent structure.

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