Meteorological multi-rotor unmanned aerial complex and its application for monitoring of the atmosphere

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Abstract. A design of a meteorological complex based on multi-rotor aeromobile platforms of unmanned aerial vehicles and its possible application for measuring vertical profiles of the main meteorological parameters of the atmosphere, including the air temperature, humidity, and pressure are considered. An example of a comparison of multicopter measurements with the data obtained using an MPT-5 meteorological temperature profiler is given.

1. Introduction

Recently manufacture and use of unmanned aerial vehicles (UAVs) for various applications [1–13] has become one of the fast developing scientific and technical directions. An explosive growth of the market of the unmanned aerial vehicles is observed all over the world. In addition to solving traditional problems of video registration and photographing of various localities [1, 2], the UAVs (or in other words, the drones) can also solve geophysical [3, 4, 7] and meteorological problems [4-13], in particular, they can measure the parameters of the atmospheric state [5–13]. The aircraft-type UAVs have a higher flight resource stock and, as a rule, a higher load lifting capacity for the same masses and sizes. However, it is sufficiently difficult to automate the measurement process for the aircraft-type UAVs. The existing accessible autopiloting systems with automatic takeoff and control of the UAV flight route do not allow the aircraft-type UAVs to land automatically. As a rule, a parachute is used to land these UAVs, which is obviously inconvenient for their use in measurements of the vertical structure of the atmosphere. The aircraft-type UAVs [4, 10] are well suited for measurements along horizontal paths, but they do not provide strictly vertical ascent over the start point. The dynamic characteristics of these UAVs do not allow high-sensitive low-inertia sensors to be placed onboard, which inevitably limits their measurement accuracy.

For the UAVs with vertical ascent and descent, it is possible to automate completely the measurement process. Takeoff, rising, flight along a selected trajectory, and landing of the UAV can be performed according to a preset program. In this case, the operator only gives the command to ascend. The flight, measurements, and descent can be performed in completely automatic mode. Such systems are best suited for monitoring of the vertical structure of the atmosphere [4–13]. Therefore, in our opinion, such multi-rotor UAVs based on aeromobile platforms (MUAVs or multi-copters) are most promising for measuring the vertical profiles of the meteorological parameters in the atmospheric boundary layer (ABL). At present, the multicopters are widespread. The UAVs of these types are universal bearing platforms with a wide range of applications. Their high stability in flight, stability...
against wind loads, and availability of programmable onboard navigating devices allow the MUAVs to be used in a wide variety of weather conditions, round the clock, in manual control mode, and in independent flight. The MUAP equipped with meteorological sensors allows contact measurements of vertical profiles of the main meteorological parameters to be performed in the ABL during each ascend and descent, which is important for the study of the ABL and verification of ground-based systems of remote measurements of the atmospheric parameters. The maximum altitude of measuring the vertical profiles of the meteorological parameters can reach several kilometers and depends on the capabilities of the employed device and weather conditions. The special features of the design and application of the MUAVs allow one to increase the volume of reliable measurements of meteorological parameters and to verify in real time remote sounding data on new qualitative level.

In contemporary scientific publications [1–13], immediate prospects for UAV application in solving meteorological problems and their advantages and disadvantages are widely discussed. Technologies of meteorological measurements with the use of multicopters are developed by a number of scientific groups [3, 5-13]. They are used not only to measure the profiles of meteorological parameters, but also to verify the meteorological parameters measured remotely by other instruments. This is caused by the fact that the data of remote sounding of the atmosphere are gradually more and more involved in weather forecasting. Moreover, they are used by weather forecasters in their work and as input data for prognostic models. It is obvious that as any meteorological data, they need testing and calibration. From this point of view, the UAV is a universal and very mobile system; it can be used for acquisition of data on the state of the atmosphere in the gaps between measurements with aerologic or any other meteorological stations and in hard-to-reach regions. An additional equipment of the UAVs with meteorological sensors of various designations will allow one to carry out multipurpose measurements and to reorient fast the platform for solving specific problems. The development of sounding techniques using meteorological UAVs allows one not only to obtain a large volume of data, but also to solve problems of fundamental study of the atmosphere on qualitatively new level.

The present work generalizes results of our work on the development of unmanned instruments of measuring the meteorological parameters in the ABL based on multicopters and their application for verification of data measured with the MTP-5 temperature profiler. Design of the meteorological complexes based on multicopters of different types is considered. Requirements are given to meteorological sensors, design of the measuring complex, and aerial platform. The developed models and their possibilities are described. Results of their outdoor testing and verification of the data measured with the MTP-5 temperature profiler are given. The verification of remote instruments intended for measuring the meteorological parameters, especially passive ones, of the MTP-5 type, is an urgent problem, because it allows one to calibrate measurements and to improve data processing algorithms.

2. Design of the meteorological complex based on a multi-copter

Technologies of manufacture of modern UAVs and their electronics make it possible to carry out contact measurements of the meteorological parameters in the ABL at altitudes from 10 to 2000 m and higher with high temporal and spatial resolutions depending on the UAV type. The multicopter UAVs are best suited for solving this problem. The multicopter strictly follows a preset trajectory, hangs over preset places, and ascents and descends strictly vertically with a chosen velocity. Reusability of these UAVs reduces expenses on their operation and allows one to increase significantly the frequency of their launch, whereas their controllability makes it possible to change the flight program or to stop the flight depending on circumstances.

Thus, the meteorological UAVs should involve a meteorological complex with a number of meteorological sensors (a portable electronic meteorological station for onboard measurements of the meteorological parameters) capable of measuring the air temperature, pressure, and humidity in the atmosphere and to calculate the wind speed and direction.
The requirements to and the principles of designing the onboard measuring complex (OMC) intended for measuring the meteorological parameters, placed onboard the rotor-type unmanned aerial vehicle (UAV), and capable of recording spatial distributions of the fields of the main meteorological parameters, involving the air temperature, humidity, and pressure of the atmosphere (their vertical or horizontal profiles) are considered below.

2.1 Requirements to meteosensors intended for measuring the air temperature, humidity, and pressure

The characteristics and the design of the individual OMC sensors placed onboard the UAV should meet the requirements to the stationary meteorological stations. This concerns protection against solar radiation. Additional requirements are imposed on meteosensors and conditions of their placing onboard UAVs. Thus, hot airflows from the UAV propellers and engines are sources of errors.

2.1.1 Temperature sensor. To eliminate measurement errors due to direct and reflected solar and IR radiation, the temperature sensor should be specially protected. In addition, the temperature sensor should be operational in the presence of vibrations in UAV flights with stable characteristics to maintain calibration during measurements. For the meteosensors placed onboard the UAVs, one of the main requirements is the speed of response (the time constant) that should provide reliable measurements of the meteorological parameters during UAV ascent and descent with a given speed. Considering the foregoing, the air temperature sensor in radiation protection is better to arrange either outside of the UAV clamped on a long horizontal bar or on a special vertical holder above the UAV case. Such arrangement of the sensor provides its natural ventilation and influences insignificantly the aerodynamic stability of the complex. The temperature was measured with a 701-101BAA-B00 platinum sensor [14].

2.1.2 Humidity sensor. Successful functioning of the meteorological sensor of relative air humidity placed onboard the UAV depends on the rate of exchange by water molecules between the sensor and the atmosphere. When the temperature decreases, the sensor operation requires good external ventilation because the free exchange by water molecules between the sensor and the atmosphere decreases; otherwise, considerable measurement errors occur. Protection against atmospheric precipitations is also needed. The sensor should be well ventilated, and the requirements to its arrangement are the same as to the temperature sensor: it should be placed outside of the UAV and clamped on an external bar. A HIH-5031-001 sensor was used to measure the air humidity [15].

2.1.3 Atmospheric pressure sensor.

The air pressure profile is used in modern numerical weather forecast models. It is also used to calculate (from the barometric formula) the UAV flight altitude along with its determination from signals of global satellite positioning systems. The pressure sensor should not be influenced by external factors (wind, air temperature, and vibration); it should be calibrated or tested regularly. Digital membrane piezoresistive or capacitive pressure sensors with temperature compensation and miniature metal or semiconductor aneroid boxes used as sensitive elements one of the sides of which is connected to a piezoresistor or is a capacitor plate are well suited for atmospheric pressure sensors. The systematic error of these sensors is determined by the dependence of indications on the internal sensor temperature and the hysteresis and elasticity of the aneroid box. To measure the atmospheric pressure, an MPL3115A2 digital pressure sensor [16] was used.

2.2 Requirements to the OMC design

Based on the requirements to the meteosensors considered above, we now can formulate the main requirements to the design of the OMC placed onboard the UAV. It should provide:

- Reliable operation at air temperatures, pressures, and humidities in the required altitude range year round,
- Protection of sensors against solar and IR radiation,
High rate of heat exchange between the temperature sensor and the surrounding medium,
- Inadmissibility of ingress of hot air flows from UAV engines on meteosensors,
- Protection of sensors and electronics against precipitations and moisture,
- Writing of measurement data to non-volatile memory with periods from 1 till 10 s,
- Radio transmission of the measured meteorological parameters to a ground-based station in real time,
- Vibration resistance,
- High maintainability and ease of installation on and removal from the copter carrier,
- Simple replacement and charging of power supply units,
- Compactness and small weight.

2.3. Requirements to the copter carrier platform

The multicopter can flight in different ways: it can hang over the earth at a preset altitude, rotate round an axis, and move in any direction including strictly upwards. It comprises the frame with 4, 6, 8, or 12 brushless motors clamped on the frame, propellers, electronics, and lithium battery.

We consider the principle of multicopter flight on an example of a quadcopter (platform with 4 motors). Pairs of its motors rotate in opposite directions. When hanging, all propellers rotate with the same speeds, the forces acting between them are equalized thereby allowing the quadcopter to soar steadily in air without rotating about its axis. To rotate about the axis, one opposite pair of motors starts to rotate faster, and another pair rotates more slowly to keep the overall balance of the thrust and altitude. To rotate in another direction, the first pair of motors rotates more slowly, and the second pair rotates faster. A flight in a preset direction is provided by simple tilting of the copter in the corresponding direction and increase in the rotation speed of the motors on the opposite sides. From the viewpoint of aerodynamics, the multicopter is an unstable design and it flies accurately due to the controller that controls motors and sensors of position, acceleration, flight direction, air pressure, temperature, and satellite navigation. Nevertheless, the embodiment in the comparatively small complex of many of the latest technical achievements has allowed us to develop a sufficiently reliable complex for solving a wide class of problems. To measure the vertical profiles of the air temperature, humidity, and pressure, the multicopter platform with the following characteristics is required:

- Weight of the OMC placed onboard the copter platform no less than 500 g (this weight is sufficient to measure the vertical distributions of the main meteorological parameters using modern electronic units),
- The maximum flight altitude no less than 2 000 m (as a rule, this altitude allows the meteorological parameters to be measured in the ABL);
- Maximum vertical speed no less than 5 m/s (to obtain data on transient atmospheric processes, it is required to scan the ABL during a limited time and to use the data processing procedures well-developed for radiosondes ascending with speeds from 4 to 6 m/s),
- Maximum horizontal speed no less than 20 m/s (to operate under conditions of strong winds),
- Flight time no less than 20 min (sufficient for ascending to altitudes no less than 2 km),
- Simple control and operation,
- Automatic or semi-automatic flight regime,
- Compactness and small weight.

2.4. UAV models intended for measuring the meteorological parameters

At the first stage, we searched for optimal location of meteosensors and optimal OMC design and measurement procedure with allowance for perturbations of the surrounding medium caused by air flows from the working motors. Two design variants had been developed and tested. In the first variant (figure 1a), the sensors were arranged at the edges of the horizontal bars at a distance of 70 cm from the motors. In most cases, this provided minimal influence of air jets from the motors on the sensors, but increased the overall dimensions and windage of the entire system and worsened the flight
conditions. It was experimentally established that thermal flows from the running UAV motors propagated at distances of several tens of meters. This prevents placing of sensors under the carrier and also decreases the accuracy of temperature and humidity measurements during descents when the sensors are in air heated by running engines. In the second variant (figure 1b and c), the sensors were arranged on the vertical rod above the UAV at a distance of 40–50 cm. This arrangement of the meteorological sensors was more acceptable.

In the developed models, the temperature and humidity sensors are enclosed in a radiation shield (Figure 1c, d, and e). On the printed-circuit board of the measuring unit, a pressure sensor and a radio modem with an antenna were located. The ground-based part of the meteorological complex included an external directed antenna, a telecommunication unit, and a computer. The telecommunication unit matches the USB interface with the radio modem module. As a result, several operating OMC models had been developed and realized at the IMCES SB RAS (figure 1) in the following sequence: onboard an MK Quadro XL quadcopter, DJI (model S900) hexacopter [8], and Walkera Voyager 3 quadcopter.

The meteorological parameters measured by OMCs and their main characteristics are given in tables 1 and 2.

| Table 1. Measurable meteorological parameters. |
|-----------------------------------------------|
| Measurable parameter | Measurement range | Error |
|----------------------|--------------------|-------|
| Air temperature, °C  | -70 … +55          | ±0.2 at $T \leq 30^\circ$C |
|                      |                    | ±0.3 at $T > 30^\circ$C |
| Relative air humidity, % | 0 … 100           | ±2.5 at $T > 0^\circ$C |
|                      |                    | ±5 at $T < 0^\circ$C |
| Atmospheric pressure, GPa | 500 … 1100    | ±0.5 Resolution of 0.0025 |

| Table 2. Main OMC characteristics. |
|------------------------------------|
| Characteristic                     | Parameters |
|------------------------------------|-------------|
| Range of working temperatures of the controller, °C | -50 … +50 |
| Time constant of temperature measurement, s | 2.5 |
| Time constant of pressure measurement, s | 1 |
| Time constant of humidity measurement, s | 3 |
| Weight, g                          | 450         |
| Supply voltage, V                  | 3.6 … 10    |
| Period of continuous operation, h  | 4           |
| Software, remote server for data storage, user attachment for controller configuration, data read-out from the controller and the server, visualization, export of data in the csv text format | Available |
| Adjustable measurement period, s   | 1 … 3000    |
| Volume of non-volatile memory      | 9 000       |
| Data transmission interface        | USB, SDcard, WIFI, GSM |
| Degree of protection against external actions | IP 66 |

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Figure 1. OMC placed onboard the MK Quadro XL quadcopter and clamped on the bars 0.7 m long (a) and OMC placed onboard the DJI (model S900) hexacopter and clamped on the rod 0.5 m long (b); the rod with the measuring unit and power supply elements extracted from it (c); OMC placed vertically above the Walkera Voyager 3 quadcopter and clamped on the rod 40 cm long (d); and the rod with clamping element (e).
3. Outdoor tests of the meteorological complex

The developed OMC with UAVs of the above-indicated types were tested outdoors. The time of their flight was limited by the capacity of the storage battery; it was 20…40 min for the complexes of the above-indicated types; this was sufficient to ascent the UAVs at altitudes up to 2…3 km and to descent them. Several storage batteries can be used to perform long-term measurements. Our tests showed that for example, unlike the weather balloon the trajectory of which depends on the wind, strictly vertical profiles of the meteorological parameters can be measured, and horizontal flight along a preset trajectory over a given territory can be performed. The vertical resolution depended on the ascend speed and the time constant of the employed sensor. During experimental flights, the vertical resolution was 10–15 m. The data obtained allowed us to estimate the achievable measurement altitude. The time of ascend to an altitude of 3 km was up to 15 min, and the descent time was up to 8 min. The multicopter could be launched several times along a preset trajectory, which allowed us to study the dynamics of the profiles of the measurable meteorological parameters. To reduce the time of recording transient processes in the atmosphere, we propose to use simultaneously several multicopters arranged as an aerial shelf.

Our tests allowed us to consider such measuring complex as an effective tool for real-time measurements of vertical profiles of the atmospheric meteorological parameters, their verification, and application of remote methods of atmospheric sounding.

4. Verification of measurements of the vertical temperature profile in the atmosphere

The meteorological UAVs perform contact measurements of vertical profiles of the meteorological parameters with high spatial resolution using calibrated meteosensors. Therefore, it is an ideal means for verification of systems of remote measurements of the atmospheric parameters. Only high meteorological masts or radiosonde measurements are alternative to them, but all of them have lower spatial resolution. The meteorological complexes placed onboard the UAVs allow one to measure and to study a thin structure of the ABL.

All systems of remote sensing of the atmosphere require testing of procedures of indirect measurements of the atmospheric parameters and periodic verification – testing of the correspondence between their measurements and actual values of the meteorological parameters. Recently the UAVs are increasingly employed for this purpose.

![Figure 2. Walker Voyager 3 quadcopter in flight.](image)

In the last few years, in particular, the MTP-5 temperature profiler is widely used to solve this problem [17]. It is based on the passive method of recording thermal radio emission of the atmosphere
at the frequency of oxygen absorption oncoming from different elevation directions. The vertical profile of the air temperature is determined at altitudes up to 1 km by processing the measured signals using a special program. The MTP-5 profiler is approved as a measuring device with a limiting error of temperature measurement of 1.2 °C and sampling temperature discrete no more than 25 m at altitudes from 0 to 100 m for temperatures within ± 50 °C and no more than 50 m at altitudes from 100 to 1000 m. The profiler data have already been compared with radiosonde and sodar data and measurements on high meteorological masts and showed fairly good results.

We also measured the vertical profiles of the temperature and air humidity with the meteorological complex placed onboard the Walkera Voyager 3 quadcopter (figure 2) in the lower atmosphere and compared them with data of the MTP-5 temperature profiler for different atmospheric stratifications. The most interesting results of comparison were obtained for the stable atmospheric stratification in the presence of elevated temperature inversions. They are presented below.

Figure 3. Vertical profiles of the temperature (T, °C) and absolute humidity (E, g/m³) obtained during the UAV ascent and descent and data of temperature measurements with the MTP-5 temperature profiler.
Figure 3 shows some results of such measurements in the presence of temperature inversions in the lower layer of the atmosphere. From figure 3 it can be seen that the curves of the MTP-5 temperature profiler are smoother, which is caused by lower spatial and temporal resolutions of the profiler. Each temperature profile was recorded with the profiler with a discrete period of 5 min. In figure 3a, the UAV profiles have the weak surface temperature inversion to altitude of ~40 m and the elevated inversion with the lower boundary at 200 m. The profiler also shows the elevated inversion, but its data diverge with increasing altitude. In figure 3b, the UAV shows the presence of a thin layer of elevated temperature inversion at altitudes of 300–350 m, whereas the profiler did not detect it. The same can be seen in figure 3c: the UAV shows the elevated temperature inversion at altitudes of 250–330 m, which is not seen in the temperature profile recorded with the profiler. For other atmospheric stratifications, the curves behave synchronously with high values of the correlation coefficient.

Results of our comparison demonstrate the divergence of the data obtained with the OMC and MTP-5 for the stable atmospheric stratification and indicate the necessity of obtaining additional experimental data for higher altitude range.

5. Conclusions
Our investigations and outdoor tests have shown that the meteorological complexes placed onboard multicopters are effective tools for measuring the vertical profiles of the main meteorological parameters (the air temperature, humidity, and pressure) in the atmospheric boundary layer. The vertical resolution of these measuring systems depends on the speed of ascent and the time constant of the employed meteosensors (~1 s). During our experiments, the vertical resolution was 10–15 m. The flight altitude or the altitude range depends on the type of the employed multicopter. Usually it took us 17 min to ascent to an altitude of about 3 km, and it took us up to 8 min to descent. The multicopter can be launched several times along a preset trajectory in real time, which allows one to trace the dynamics of the measurable vertical profiles of the meteorological parameters. To reduce the recording time of transient processes in the atmosphere, simultaneously several multicopters can be used arranged as an aerial shelf. To measure the wind speed and direction, algorithms of their measurements should be developed and tested outdoors. Results of comparison of the measured vertical temperature profiles with the data of the MTP-5 temperature profiler allow us to consider the meteorological complex placed onboard the UAV as an effective tool for verification of the methods of remote sounding of the atmosphere.

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References

[1] Khan A C, Alvi B A, Safi E A and Khan I U 2018 Drones for Good in Smart Cities: A Review Proc. Int. Conf. on Electrical, Electronics, Computers, Communications, Mechanical and Computing (EECCMC) (India) 28th & 29th January 2018 7 pp
[2] Floreano D and Wood R J 2015 Science, technology and the future of small autonomous drones Nature 521 p 460
[3] Watts A C, Ambrosia V G and Hinkley E A 2012 Unmanned aircraft systems in remote sensing and scientific research: Classification and considerations of use Remote Sensing 4 pp 1671-92
[4] Rastorguev I P 2014 Unmanned technologies of monitoring of weather conditions Geliogeofizicheskie Issledovaniya 8 pp 51-54
[5] Brosy C, Krampf K, Zeeman M, Schafer K, Emeis S and Kunstmann H 2017 Simultaneous multicopter-based air sampling and sensing of meteorological variables Atmospheric Measurement Technique 10 pp 2773-84
[6] Sitnikov N M , Akmulin D V, Borisov Yu A et al. 2013 The Use of Unmanned Aerial Vehicles for the Atmospheric Monitoring Meteorology and Hydrology 1 pp 90-99
[7] Chin-Chung Chang, Chin-Yuan Chang, Jia-Lin Wang et al. 2020 An optimized multicopter UAV sounding technique (MUST) for probing comprehensive atmospheric variables Chemosphere 254 126867

[8] Kurakov S A., Zuev V V 2016 Unmanned aerial vehicle for measuring vertical profiles of the meteorological parameters in the atmospheric boundary layer Atmospheric and Oceanic Optics 29 11 pp 994-999 (In Russian)

[9] Bell T., Greene B., Klein P., Carney M., & Chilson P. (2019). Confronting the Boundary Layer Data Gap: Evaluating New and Existing Methodologies of Probing the Lower Atmosphere. Atmospheric Measurement Techniques Discussions, (December), 1–23

[10] Kral S., Reuder J., Vihma T., Suomi I., O’Connor E., Kouznetsov R., Wrenger B., Rautenberg A., Urbancic G., Jonassen M., Båserud L., Maronga B., MAYER S., Lorenz T., Holtslag A., Steeneveld G.-J., Seidl A., Müller M., Lindenberg C., Langohr C., Voss H., BANGE J., Hundhausen M., Hilsheimer P., & Schygulla M. (2018). Innovative Strategies for Observations in the Arctic Atmospheric Boundary Layer (ISOBAR)—The Hailuoto 2017 Campaign. Atmosphere, 9(7), 268

[11] Segales A. R., Greene B. R., Bell T. M., Doyle W., Martin J. J., Pillar-Little E. A., & Chilson P. B. (2020). The CopterSonde: an insight into the development of a smart unmanned aircraft system for atmospheric boundary layer research. Atmospheric Measurement Techniques, 13(5), 2833–2848

[12] Varentsov M. I., Yu Artamonov A., Pashkin A. D., & Repina I. A. (2019). Experience in the quadcopter-based meteorological observations in the atmospheric boundary layer. IOP Conference Series: Earth and Environmental Science, 231, 012053

[13] Varentsov M., Stepanenko V., Repina I., Artamonov A., Bogomolov V., Kuksova N., Marchuk E., Pashkin A., & Varentsov A. (2021). Balloons and Quadcopters: Intercomparison of Two Low-Cost Wind Profiling Methods. Atmosphere, 12(3), 380

[14] Honeywell 2020 Sensing and Internet of Things 701-101BAA https://sensing.honeywell.com/701-101BAA-B00-rtd-sensors

[15] Honeywell 2020 Sensing and Internet of Things. HIH-5031-001 http://sensing.honeywell.com/HIH-5031-001-Humidity-Sensors

[16] NXP Semiconductor. MPL3115A2: 20 to 110 kPa, Absolute Digital Pressure Sensor http://www.nxp.com/products/automotive-products/sensors/pressure-sensors-for-automotive/barometric-pressure-15-to-115-kpa/20-to-110kpa-absolute-digital-pressure-sensor:MPL3115A2?fsrch=1&sr=1&pageNum=1.

[17] Kadygrov E N and Kuznetsova I N 2015 Methodical recommendations for application of remote measurements of temperature profiles in the atmospheric boundary layer with microwave profilers: Theory and practice (Dolgoprudnyi: Fizmatkniga) 171 pp.