Autonomous weather stations for unmanned aerial vehicles. Preliminary results of measurements of meteorological profiles

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Abstract. Results of measuring vertical profiles of major meteorological quantities in the atmospheric boundary layer up to an altitude of 1000 m by an ultrasonic weather station AMK-03 placed on copter-type UAVs and a suspension of a tethered balloon during its ascent and descent are presented. Recommendations on a procedure for performing measurements by using an ultrasonic weather station based on a tethered balloon are given.

1. Introduction
The operational remote methods of optical and acoustic sounding of the atmosphere for measuring the vertical profiles of the main meteorological values: temperature, pressure, relative humidity, velocity, and wind direction in the atmospheric boundary layer have one significant drawback: ambiguous solution of the sounding equation [1]. Contact methods for measuring these values using automated weather stations (AWSs) installed on unmanned aerial vehicles (UAVs) [2, 3, 4, 5], although they are not operative, provide representative data that can be used to calibrate the results of lidar and sodar measurements [6]. This paper provides a brief description of automatic weather stations developed at IMCES SB RAS and intended for placement on an UAV of the drone-copter type and a tethered balloon. Preliminary results of measurements of the vertical profiles of the main meteorological values in the ABL to heights of 1 km are also presented using automatic weather stations installed on the UAV.

Until now the main standard means of contact measurement of high-altitude meteorological profiles are radiosondes, which are launched only 2 times a day [7]. Placing AWSs on UAVs provides a fairly rapid measurement of meteorological values in mesoscale territory (by area), as well as at different altitude levels for several tens of minutes.

The copter-type UAVs provide free motion of AWSs in vertical and horizontal directions in a controlled area of several square kilometers, which makes it possible to measure the vertical profiles of meteorological quantities and to determine possible local horizontal inhomogeneities of the fields of these quantities. A tethered balloon placed on an AWS provides measurement of high-altitude profiles of meteorological quantities, and also makes it possible to measure meteorological values at a given altitude level for several days.

When installing an AWS on a UAV, it is necessary to take into account its influence on the results of measurements of meteorological quantities. Thus, when placing an AWS on a UAV of the type of a
copter (quadro- or hexacopter), it is necessary to remove the meteorological sensors as much as possible from the air currents created by the copter screws. When using a tethered balloon as a carrier, the AWS should be placed on a suspension, which ensures the minimum effect of the balloon shell on the real airflows during the ascent and descent of the balloon.

2. Analysis and discussion of measurement data

For a UAV of the hexacopter DJI S900 type, we developed a portable electronic weather station called PEWS/UAV (Figure 1) [8]. It consists of electronic humidity and air temperature sensors, which are placed in the upper part of the measuring unit (1) in radiation protection. A pressure sensor is installed in the cylindrical bottom part (2) of the PEWS/UAV. To reduce the effect of the air currents created by UAV screws on measuring the temperature and humidity, the measuring unit (1) is placed at a height of 40 cm above the plane of the screws (4). The effect of reducing the influence of air flow on the measured parameters is also described in [4]. Higher placement of this block displaces the center of mass of the UAV. For the coordinate and time reference of the measurement results, the GPS navigation unit (3) is used. The received measuring information is recorded on a flash memory or immediately transmitted to the ground via a radio channel organized with the help of XBee-PRO radio modules (operating frequency: 2.4 GHz, data transfer rate: up to 250 Kbps). Accumulators hexakoptera DJI S900 provide a flight duration of not more than 35 minutes. A hexacopter can carry a payload of 3.2 kg. The accuracy of the device hanging in the GPS mode: vertical: \( \pm 0.5 \) m, horizontal: \( \pm 2.5 \) m.

![Figure 1. AMC PEWS/UAV: 1- measuring block in radiation protection with temperature and relative humidity sensors; 2- main part of the AMC; 3- GPS navigation unit; 4- hexakopter DJI S900.](image)

The technical characteristics of the PEWS/UAV are presented in Table 1.

| Parameter                                      | Value                      |
|------------------------------------------------|----------------------------|
| Measurement range of air temperature, \( T \), °C | -50 \ldots +50             |
| Error in measuring temperature, °C             | \( \pm 0.2 \) if \( T \leq +30 \) °C; \( \pm 0.3 \) if \( T > +30 \) °C |
| Relative humidity measurement range, %        | 15 \ldots 100              |
| Accuracy of measurement of relative humidity, %| \( \pm 2 \) if \( T > 0 \) °C; \( \pm 5 \) if \( T < 0 \) °C |
| Measurement range of atmospheric pressure, mm Hg| 520 \ldots 800             |
| Error of pressure measurement, mm Hg           | \( \pm 0.5 \)               |
The second type of UAV suitable for mounting on it of an ultrasonic AWS AMK-03 [9] is a K-25M-A tethered hybrid balloon manufactured by the OSKBES MAI [10], in which helium is used as the lift gas (maximum lift: 1 km).

An aerostat can carry a payload weight of 12.5 kg. The lifting and lowering of the balloon is controlled by a winch placed on a trailer. Its power supply is from the network of 220 V, 50 Hz. The AWS AMK-03, together with a battery and a radio transmitter, are placed on the suspension, which is removed by ~2.5 m from the balloon shell (Figure 2).

![Figure 2. K-25M / A tethered balloon with ultrasonic AMC AMK-03 on suspension (a) and winch on a car trailer (b).](image)

Some results of measurements of the vertical profiles P, T and r obtained with the help of the PEMS / UAV laboratory model were presented in [8]. Figure 3 shows the results of measurements of the profiles T and r when the hexacopter is raised to a maximum height of 2000 m.

The measurements were carried out once every 5 seconds; curves 1 correspond to the profiles obtained during a UAV lift in 30 minutes with an average velocity $V_{sp}$ of 3 m/s, and the curves to the 2 profiles when the UAV was descended in 15 minutes at an average velocity $V_{sp}$ of 4 m/s. The discrepancy between the measurement results for the temperature within 1°C and relative humidity up to 5% for lifting and descent is explained by the inertness of the electronic sensors. The new pilot PEWS/UAV model uses less inertial sensors.

![Figure 3. Results of measurements of vertical profiles of temperature (a) and relative humidity (b) with the help of PEWS/UAV in September 2016 when lifting (1) and descending (2).](image)
Figure 4 presents meteorological profiles measured at two launches of the AWS AMK-03 on a tethered balloon on 06/09/2016 at a height of up to ~1 km. The experiments were carried out at the "Fonoviy" test site of the IAO SB RAS located near the village of Kireevsk (Shegarsky district, Tomsk region). Launch no. 1 was performed from 4:30 pm to 5:32 pm with an average speed of ascent of 30 m / min to an altitude of 960 m; then the balloon was lowered to a height of 200 m at the same speed. Launch no. 2 was carried out from 17:34 to 19:33, while the aerostat lifted from 200 to ~ 990 meters with stops of 10 minutes at altitudes of ~200, 400, 600, 800, and 990 meters and a subsequent descent from the level of 960 meters to the underlying surface.

The obtained profiles of T, v, and r generally agree well with the theoretical concepts of the altitude variation of these quantities. An exception is the velocity profile w, in which there are high (more than 1 m / s) negative values, not typical for the atmospheric conditions at the time of measurement. Moreover, at the stages of the balloon lifting the velocities significantly exceed the analogous values at the stages of descent. The fact noted, as well as the observed direct relationship between the values of w and v, allow us to conclude that the measured anomalous values of the velocity w are supposedly associated with the effect of compensatory descending motions of the ambient air during the balloon lifting and / or by the wind ball flowing down on the shell of the balloon. Thus, the distance between the shell balloon and the AMK-03 equal to 2.5 m is insufficient for reliable measurement of w and should be increased to at least 5 m.

The results of the measurement of T carried out at the stages of ascent and descent at the same altitude levels are characterized by a minimal difference (<1 °C). Comparison of the measured values of r at the rise and descent of the balloon (Figure 4a) performed without stopping and at the same speed, on the contrary, shows a large discrepancy (> 15%) between the values at one altitude, due to considerable inertia of the humidity sensor.

An analysis of the rate of approximation of the measured values of p to the true values of atmospheric humidity at fixed altitude levels during a time lag of 10 (Figure 2b), 5, and 3 min allowed us to conclude that for the measurement of reliable values of r at fixed levels, not less than 5 min.

The results of preliminary full-scale tests of AWS on UAV show that it is necessary to further develop the meteorological measurement technique with hangup of both types of UAVs at given altitudes.

Figure 4. Measured profiles of meteorological values at launches nos. 1 (a) and 2 (b).
3. Conclusions
The above analysis of the results shows that it is efficient to use multicopter-type devices with a portable electronic weather station and a tethered balloon with AWS AMK-03 for measuring vertical profiles of meteorological quantities in the ABL and monitoring their changes. It has been shown that to minimize the influence of the balloon shell on the measured values of w, the distance from it to the AMK-03 must be at least 5 meters. It has been found that the effect of changes in the atmospheric conditions on the profiles of meteorological variables in the APS measured with the help of ballistic UAS is, as a rule, insignificant for a period of ~ 30 min and can be neglected. It is determined that in order to obtain reliable values of the relative humidity profile, time lags of at least 5-minute duration are necessary.

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