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METROLOGICAL SUPPORT OF MONITORING SYSTEMS BASED ON UNMANNED AERIAL VEHICLES

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The article discusses the fields and methods of application of unmanned aerial vehicles (UAV). Current legislation in Russia and in the world, significantly limit the use of UAV in monitoring. For the first time, we present a solution to the problem of a monitoring measurement system included in the state register of measuring instruments using the example of the basic UAV model. We conducted an analysis of promising approaches to the creation of UAV metrological and methodological support, as well as ways to adapt their target load to meet the challenges of operational monitoring of air pollution.

***Key words*:** unmanned aerial vehicle; metrological support; operational monitoring; legislative restrictions

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Introduction. Over the past decade, companies developing unmanned aerial vehicles (UAV) for civilian use have gone from prototypes to serial production of full-fledged aerial vehicles that meet all modern safety requirements. Modern onboard radio-electronic and aviation equipment of UAV allows operating flights in all climatic zones. In addition, the range of their safe use in most cases is wider than that of manned civil aircraft. In this regard, the attempts of developers and users to equip UAV with technical means are logical, because that allow not only to make observations but also to perform quite specific measurements.

There is an experience of domestic and foreign developers on the UAV use in environmental monitoring, biogeographic research, inventory, and cadastral tasks. A well-known attempt of UAV use for zoogeographical survey is a survey conducted on the territory of the Belogorye Nature Reserve (Belgorod region, Russia). The purpose of this field experiment was to assess the capabilities of the equipment in solving problems of counting wild animals. As a result of research, it was found that this approach is applicable only for an approximate assessment. According to such traits as trails, laying spots, and scratches, only a fraction of the animals was evaluated by species and abundance. In comparison with the well-known method of winter route tracking, the accuracy of the population size estimation was significantly lower [1].

The UAV applicability was also evaluated in the performance of the environmental monitoring tasks [2, 10-12]. In particular, there is published data on the UAV use for environmental monitoring of river mouths and beach areas. The data obtained from UAV allowed to reveal the places of unauthorized storage of solid municipal and industrial waste; to assess the extent of pollution by wastewater from the Black Sea and the effects of mudslides and rockfalls; to find out the facts of illegal construction and land seizure [9].

Problem statement. Currently, there is a significant amount of published data on the use of UAV for observation. Many developers and researchers offer craft equipped with measuring devices. The demand for UAV for private and commercial use is increasing. The leadership positions in the world market are occupied by manufacturers from Asia, Europe, and North America (Fig.1). According to analysts, the share of sales of Russia-produced UAV does not exceed 2 %.

World market leaders are SenseFly, DJI, and 3D Robotics. DJI Innovation (Shenzhen), the most famous Chinese company, mainly develops UAV used for commercial aerial photography, real estate videotaping and mapping. UAV, produced by 3D Robotics (Berkeley, USA), one of the industry leaders, are used in agriculture, infrastructure projects, topographic mapping, and cartography. The Swiss company SenseFly (Lausanne, Switzerland) produces fixed-wing UAV, suggesting its use in agriculture and mining industry, predominantly in topographic mapping for subsequent use of the obtained data in geological information systems and inspection. A popular model of this brand is SenseFly-eBee, which is already abundantly used for precision agriculture (eBee AG) and observational monitoring of quarries and mines (eBee RTK).

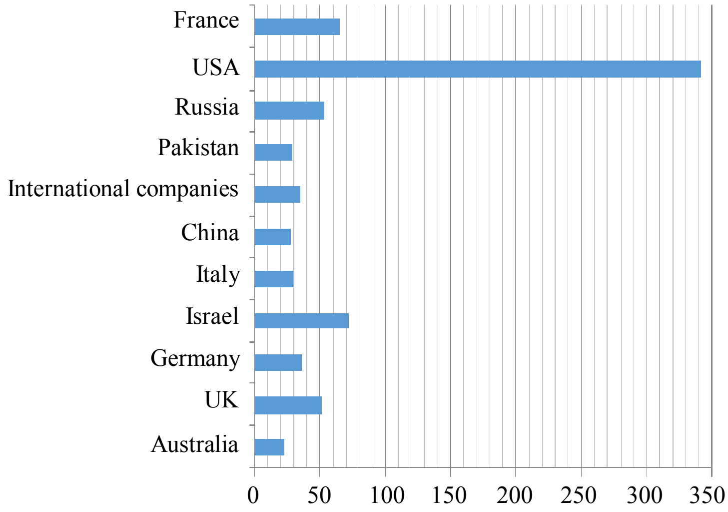

Fig.1. Number of UAV manufacturers around the globe

The key Russian UAV producer is ZALA AERO GROUP Unmanned Systems (Izhevsk, Russia). The company produces a variety of UAV in the form of helicopters, airplanes, airships, and multicopters. These UAV are used in monitoring to detect oil spills; during rescue operations; in cartography and aerial photography to create topographic maps; for scientific purposes; for testing various additional special equipment.

In the Russian UAV market, the NPP Radar MMS R&D JSC (St. Petersburg) has recently emerged. This company is known in the world market for developments in the sphere of radio-electronic systems and special and civil complexes. Currently, the company is engaged in the production of an unmanned helicopter, designed for operational aerial monitoring of large areas and extended earth, water, and ice surfaces located in remote areas. The developers have included sets of plug-in modules of the target load equipment in the UAV construction. The block module includes not only observation tools, but also equipment listed in the state register of measuring instruments: multicomponent gas analyzer, dust analyzer and gamma radiation dosimeter.

It should be noted that despite attempts to include registered measuring instruments in the UAV design, currently no measuring system based on the UAV is not included in the state register of measuring instruments. In addition, there are no certified methodologies for the use of registered measuring instruments under operating conditions of UAV. It is obvious that, in accordance with the current legislation, obtaining legitimate measurement results requires solving a number of issues related to methodological and metrological support of measuring systems and UAV-based systems. These include a need to create new specialized measuring instruments, adapt the designs of known measuring instruments for use within UAV system, develop measurement techniques and conduct their attestation, etc.

This study is devoted to the systematization of information on the current Russian and worldwide legislation in the field of UAV use; analysis of promising approaches to the development of metrological and methodological UAV support, allowing expanding the scope of practical application in monitoring issues.

Methodology. To achieve our goals, we carried out a systematic analysis of legislation, as well as metrological and methodological support of measurements based on the UAV use.

We performed an assessment of the environmental monitoring systems improvement with the introduction of UAV instrument control.

Results. It is concluded that Russian legislative norms for the UAV with and without payload are not yet fully developed.

Currently, the legalization of the UAV use requires its registration by industry self-regulatory organizations. UAV with a maximum take-off weight of 0.25 to 30 kg, imported into the territory of the Russian Federation or produced in our country, should be accounted in accordance with the procedure established by Government of the Russian Federation. A Unified UAV Accounting System is currently available on the website https://uavreg.ru. It functions to identify vehicles, take into account their number and accumulate statistical information on their application. This system is not a state one. It is possible to distinguish a registered device by the presence of a special radio tag that carries information about the UAV owner and technical characteristics. The registration in the Federal Air Transport Agency system is provided for the vehicles with a maximum take-off weight of more than 30 kg, as their accounting is regulated by Federal Law of December 30, 2015, N 462 «On Amendments to the Air Code of the Russian Federation regarding the use of unmanned aerial vehicles». Characteristics of some Russian and foreign UAVs are presented in Table 1. Analysis of the global and domestic market for such products suggests its embryonic state. Issues of typification and unification were not resolved or were resolved within the framework of private production, which explains the high cost of systems and certain limitations in the use of unified measuring equipment.

The legal UAVs use in solving national economic problems (depending on the area of application and the range of tasks to be solved) requires permits from the Air Force of the Russian Federation; Federal Security Service; committees for road management, landscaping, transport and communications (local authorities); zonal center and civil sector of the main center of the Joint Air Traffic Management System of the Russian Federation. Despite the fact that the described precautionary measures were introduced to increase the level of airspace safety and prevent aviation violations, in some cases they become serious constraints when it comes to UAV operational use in monitoring systems.

Equipping a UAV with optical equipment and/or a detection device, as well as a measuring instrument, imposes additional legal restrictions on its use. For example, a production or user installation of a video recording device (FPV camera, video camera, or camera) on UAV for covert visual surveillance (and virtually any recording from UAV falls under such surveillance) is legally restricted (Criminal Code of the Russian Federation, article 138.1). The licensing requirements for producers, suppliers, and users of equipment are determined by the following list of documents: Federal Law N 99 «On licensing special activities», Resolution of the Government of the Russian Federation N 526 «On approval of the regulations on the licensing of development, production, sale, and acquisition for the purpose of selling special technical means for the secret acquisition of information by individual entrepreneurs and legal entities carrying out entrepreneurial activities», Decree of the Government of the Russian Federation N 214 «On approval of the regulations on import to the Russian Federation and export from the Russian Federation special technical means intended for secret information and a list of types of special hardware designed for secret information, import and export are subject to licensing».

When performing instrumental measurements to obtain legitimate results, appropriate methodological and metrological support of measuring systems based on unmanned aircraft is required. Installed measuring devices must be included in the state register of measuring instruments and be accompanied by the following documentation: certificate of approval of the measurement type; type description (annex to the certificate), which indicates all the metrological characteristics that are assigned to the measuring instrument of this type; method of calibration means of measurement of this type; measurement method, certified according to GOST R 8.563-2009 «GSI. Methods of measurement»; certificate of verification of measuring instruments.

Table 1

Characteristics of some UAV available on the market

Characteristics	Model, vehicle type, company					
	Phantom 3 Quadcopter DJI Innovation	eBee RTK Airplane SenseFly	ZALA 421-02X Helicopter ZALA AERO GROUP Unmanned Systems	MBPV-37 Helicopter The NPP Radar MMS R&D JSC	Rubesh-20 Airplane JSC Aerocon	Orlan-10 Airplane The Special Technology Center LLC
Weight, kg	1.2	0.7	90	35	20	14, (20)
Flight time, min.	25	40	90-120	60	480	600
Horizontal flight speed, km/h	57	36-60	65	0-80	70-140	70-150
Radio range, km	0.5	3	25/50	18	100	500-1000
Operation method	Manual	Automatic, semi-automatic	Automatic	Manual, automatic, semi-automatic	Automatic	Automatic
Working temperature of the ambient °C	From 0 to +40	–	From –30 to +40	from –20 to +35	–	From –30 to +40
Application	Aerial photography: inspection of the fire location, real estate video taping , and mapping	In agriculture, exploration, and monitoring of windbreaks, nature reserves, for orthophoto mapping, for 3D terrain and urban development modeling	Environmental monitoring, monitoring of emergency zones, monitoring of trunk oil and gas pipelines	Operational aerial monitoring of large areas and extended earth, water, and ice surfaces located in remote areas.	Military sector: search and observational work, coordination of military units, damage assessment in combat sites	Targeting, panoramic and planned photo and video shooting, suppression of radio signals, detection of VHF-UHF radio emission sources
Wind speed, m/s	–	–	–	Not more than 10	–	Not more than 10

As an example, consider the configuration of one of the monitoring complexes based on the UAV, which characteristics are closest to identifying it as an unmanned measuring system used for instrumental measurements in monitoring studies. This system was produced by Radar MMS Research and Production Enterprise according to the technical task of the Mining University. The monitoring complex is based on the UAV of helicopter type (BVS-VT) with the following characteristics: maximum take-off weight – 35 kg; payload mass (measuring instruments, auxiliary equipment) – 12 kg; flight time – 60 minutes (with an additional tank – 90 minutes); working height 50-1000 m above the surface; maximum airspeed - 80 km/h; radio range (between UAV and base or radio repeater) – 18 km. The stated characteristics are achieved at ambient temperatures from –20 to +35 °C and wind speed of no more than 10 m/s [8].

Modular design with unified connectors was used for the board analog-to-digital converter. This allows, if necessary, to quickly change the composition of the payload equipment and transport the monitoring complex unassembled [4].

The composition of the block modules of the system includes the following measuring instruments: multicomponent air pollution sensor «Polar-2», designed to measure the content of oxygen, carbon monoxide, carbon dioxide, nitrogen oxide, nitrogen dioxide, sulfur dioxide, hydrogen sulfide, ammonia, methane, and propane (or hexane) in the air of the working area; aerosol monitor

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DUSTTRAK 8533, designed to measure the mass concentration of aerosol particles of different origin in the atmospheric air and the air of the working area; DGD-S11D gamma radiation dosimeter or UDMG-100 detection device designed for continuous measurement of gamma radiation ambient equivalent dose rate . The metrological characteristics of the UAV target load equipment are presented in Table 2. As part of the payload, it is also possible to use handheld detector for the detection of methane gas at a safe distance LaserMethaneMini (produced by TokyoGas Engineering Co., Ltd) and a thermal imaging camera.

Table 2

Characteristics of measuring instruments from the target load equipment BLA-VT of the Mining University (produced by Radar MMS Research and Production Enterprise JSC)

Monitored Parameters	Component content range	Component content measurement range	Limits of permissible error		Target load hardware module
			Absolute	Relative, %	
Oxygen O_2	From 0 to 25 %	From 0 to 25 %	±0.2% vol. share	–	ATSN-GA-VT Basic measurement instrument – air pollution sensor «Polar-2»
Carbon monoxide CO	From 0 to 200 mg/m^3	From 0 to 20 mg/m^3 inc. 0 to 200 mg/m^3	±1 mg/m^3	±5	
Nitrogen oxide NO	From 0 to 50 mg/m^3	From 0 to 20 mg/m^3 inc. 5 to 50 mg/m^3	±0.5 mg/m^3	±10	
Nitrogen dioxide NO_2	From 0 to 200 mg/m^3	From 0 to 20 mg/m^3 inc. 2 to 20 mg/m^3	±0.2 mg/m^3	±10	
Sulfur dioxide SO_2	From 0 to 100 mg/m^3	From 0 to 10 mg/m^3 inc. 10 to 100 mg/m^3	±1 mg/m^3	±10	
Hydrogen sulfide H_2S	From 0 to 100 mg/m^3	From 0 to 10 mg/m^3 inc. 10 to 100 mg/m^3	±1 mg/m^3	±10	
Ammonia NH_3	From 0 to 100 mg/m^3	From 0 to 20 mg/m^3 inc. 20 to 100 mg/m^3	±2 mg/m^3	±10	
	From 0 to 1000 mg/m^3	From 0 to 200 mg/m^3 inc. 200 to 1000 mg/m^3	±20 mg/m^3	±10	
Carbon dioxide CO_2	From 0 to 5 %	From 0 to 0.5 % inc. 0.5 to 5 %	±0.05% vol. share	±10	
Hydrocarbons by CH_4	From 0 to 5 %	From 0 to 0.5 % inc. 0.5 to 5 %	±0.05% vol. share	±10	
	From 0 to 100%	From 0 to 10% inc. 10 to 100 %	±1% vol. share	±10	
Hydrocarbons to C_3H_8	From 0 to 1 %	From 0 to 0.2 % inc. 0.2 to 1 %	±0.2% vol. share	±10	
Hydrocarbons by C_6H_{14}	From 0 to 0.5 %	From 0 to 0.1 % inc. 0.1 to 0.5 %	±0.01% vol. share	±10	
ADER of gamma radiation	From 0.1 to 1 $\mu Sv \cdot h^{-1}$	From 0.1 $mSv \cdot h^{-1}$ to 10 $mSv \cdot h^{-1}$	–	±(15 + 1/H), where H is a dimensionless unit numerically equal to the measured ADER value, $\mu Sv \cdot h^{-1}$	ATSN-GD-VT Basic measurement instrument - dosimeter DGB-S11D
	From 1 $mSv \cdot h^{-1}$ to 10 $mSv \cdot h^{-1}$	From 0.1 $mSv \cdot h^{-1}$ to 10 $mSv \cdot h^{-1}$	–	±15	
	From 10 to 100 $Sv \cdot h^{-1}$	From 0.1 $mSv \cdot h^{-1}$ to 10 $mSv \cdot h^{-1}$	–	±20	

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End of Table 2

Monitored Parameters	Component content range	Component content measurement range	Limits of permissible error		Target load hardware module
			Absolute	Relative, %	
ADER of gamma radiation	From $1{\cdot}10^{-7}$ to 10 $Sv{\cdot}h^{-1}$	From $1{\cdot}10^{-7}$ to 10 $Sv{\cdot}h^{-1}$	–	±[20+3/P], where P is a dimensionless unit numerically equal to the measured ADER value, $\mu Sv{\cdot}h^{-1}$	ATSN-GD-VT Basic measurement instrument – detection device UDMG-100

The system was created to solve educational, research, and applied tasks: conducting remote aerial monitoring, video recording and aerial photography from heights of 50-600 m; thermal imaging; measurement of atmospheric radiation pollution; detection of methane leaks; quantitative determination of oxygen, carbon monoxide, carbon dioxide, nitrous oxide, nitrogen dioxide, sulfur dioxide, and hydrogen sulfide concentrations; measurement of temperature and pressure (vacuum) in the sampling zone.

Despite the use of instruments included in the state register of measuring instruments (Table 2) as part of the target load equipment, the main problem in studies and data processing is the lack of methodological support for performing measurements (certified measurement techniques) that take into account new operating conditions for measuring instruments. There are certain features in the use of measuring instruments designed to perform measurements in static conditions within the UAV system. When using a small-sized helicopter as a base UAV in the measurement process, it is technically not possible to obtain readings at the same point in space, which is explained by the movement of air masses (movement of the air flow in the vertical direction), accuracy of the positioning system, delay of autopilot signals and execution of control signals, etc. In particular, during gas-analytical measurements, 5-10 readings are averaged. Thus, the measurement procedure should take into account the factors of constant UAV movement, as well as the movement of air masses and ensure that the measurement result is obtained for a defined area.

St. Petersburg Mining University is the only patent holder for methodological support of measurements using unmanned air systems and complexes [5-7].

Discussion. The experience of operating the UAV-based measuring system was gathered during production tests and in solving research problems at production facilities of such companies as SUE «Vodokanal of St. Petersburg», Prionezhskiy Gabbro-Diabaz JSC, Apatit JSC, Chelyabinskaya Ugolnaya Kompaniya JSC, Russian Copper Company JSC. The basic UAV showed good handling, the ability to work from limited sites and operate the monitoring complex in a wide range of environmental parameters. An example of presenting the results of carbon monoxide content measurements within the Korkino coal mine using BVS-VT during monitoring studies performed in the course of pilot tests of a system with an instrument block of the ATSN-GA-VT target load is shown in Fig.2.

The tests of the complex showed that significant differences in the measurement conditions for measuring instruments included in the block modules of the target load equipment require processing of measurement techniques. To a greater extent, the sections «Measurement conditions» and «Data processing» need to be revised. In addition, the metrological characteristics stated in the descriptions of the measuring instruments of block modules of the target load equipment must be comprehensively checked in the new conditions of their operation as part of the UAV-based monitoring complex.

With the almost complete absence of measuring instruments, the use of which is possible as part of small-sized unmanned measurement systems, it is advisable to carry out an approval procedure for the type of measuring instrument for each measuring complex individually. With the

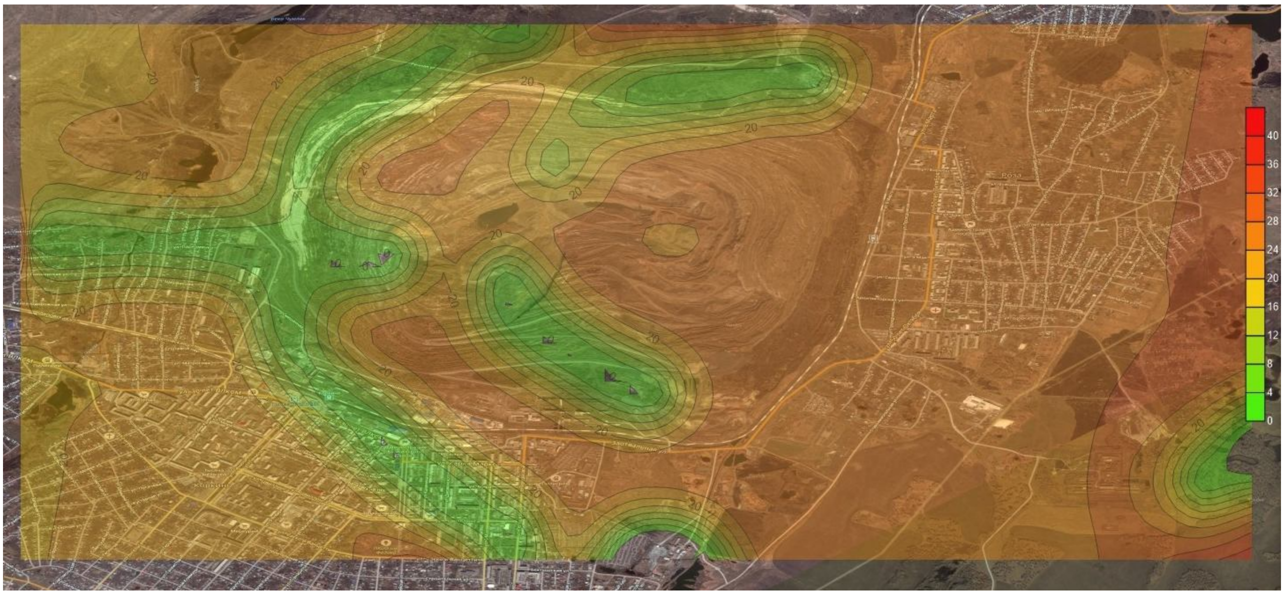

Fig.2. Index map of TLV_{daily} exceedances recorded using the BVS-VT-based measuring system

development of the instrumentation base of standardized measuring instruments intended for use on small-sized UAV, the free layout of such measuring systems and systems will become possible.

The already mentioned BVS-VT produced by Radar MMS Research and Production Enterprise JSC undergoes the approval procedure as a measuring system for UAV-based monitoring studies. Based on the Radar MMS Research and Production Enterprise JSC application, D.I. Mendeleyev Institute for Metrology (VNIIM) carried out tests for the approval of the BVS-VT complex completed with ATSN-GD-VT and ATSN-GA-VT target load modules. During the tests, the metrological characteristics of the complex were confirmed, which is reflected in the test reports.

The metrological control of the measuring system is based on the verification of the block module with air pollution sensor «Polar-2» serving as the basic measuring instrument. Methods of checking for other measuring instruments used in the measuring complex are independent, and it is not possible to check these measuring instruments as part of the complex. Thus, the measuring system BVS-VT produced by Radar MMS Research and Production Enterprise JSC with confirmed metrological characteristics can only be used in atmospheric air monitoring (Table 2).

When measuring the concentration of the pollutant in the air, the relative error should not exceed ± 25 % (GOST 17.2.4.02-81). The measurement technique is recognized as suitable if it allows measurements with a relative extended uncertainty (the boundaries of the relative total error) not exceeding 25 % [3]. In the conditions of BVS-VT application, it is difficult to confirm compliance with this requirement, since the measurement conditions differ significantly from the conditions for determining the basic error, as one of the normalized metrological characteristics specified in the calibration procedure. That is why it is necessary to estimate the uncertainty of measurements based on the normalized metrological characteristics of a measuring instrument, taking into account the conditions of measurement when it is used as part of a UAV-based measuring complex.

Let us reveal the sources of uncertainty for the air pollution sensor «Polar-2» being a part of the ATSN-GA-VT target load within the BVS-VT complex (with the indication of their standard uncertainties): uncertainty associated with dispersion in the readings – statistical data processing (u_{ai}); the uncertainty associated with the main error of the air pollution sensor (u_{ni}); possible instability of the air pollution sensor readings in the period between corrections (u_{ki}); variation of the output signal over the measuring channels (u_{ci}); the effect of changes in ambient temperature under operating conditions ($u_{\tau i}$); the impact of changes in atmospheric pressure in operating conditions (u_{pi}); the effect of changes in the relative humidity in operating conditions (u_{hi}); the effect of a change in the content of the non-measurable components of the analyzed gas mixture (u_{gi}); the effect of changes in the flow rate of the air passing through the air pollution sensor (u_{ai}).

The readings are normally distributed and estimated as an A-type uncertainty:

$$u_{ai} = \sqrt{\frac{\Sigma_{i=1}^{n}(Q_i - \overline{Q}_i)^2}{n(n-1)}},$$

where n is the number of values in the field of measurement; Q_i is the parameter value recorded by the air pollution sensor associated with the i count; $\overline{Q}_i$ – the value of the average value among the n measurements.

The limits of the basic acceptable relative error of the air pollution sensor for each measured component are given in Table 2. The expressions for calculating the components of uncertainty for one monitored component are given in Table 3.

Table 3

Relative uncertainties of input values for ATSN-GA-VT in BVS-VT complex

Calculated expression	Decryption
$u_{ni} = \tau\frac{\delta_0}{\sqrt{3}}$	δ_0 is the limit of the basic acceptable relative error of the air pollution sensor, % The coefficient $\sqrt{3}$ is chosen from the assumption of a uniform distribution law of the error in the interval ($-\delta_0$; $+\delta_0$) between the readings adjustments
$u_{\kappa i} = \tau\frac{0{,}3\delta_0}{2\sqrt{3}}$	$0{,}3\delta_0$ is the limit of acceptable changes in readings between adjustments. Relative standard uncertainty is calculated for the middle of the interval (0; $+0.3\delta_0$)
$u_{ci} = \tau\frac{0{,}5\delta_0}{\sqrt{3}}$	$0{,}5\delta_0$ is the limit of permissible variation of the output signal through the measuring channels
$u_{\tau i} = \tau\frac{0{,}5\delta_0}{\sqrt{3}}\frac{(t_m-20)}{10}$	t_m — the highest ambient temperature at which measurements can be taken 0.5 δ'_0 – the limit of permissible additional error due to changes in the ambient temperature under operating conditions (20 – main error determination temperature, °C 10 – temperature change step, °C
$u_{дi} = \tau\frac{0{,}2\delta_0}{\sqrt{3}}$	$0{,}2\delta_0$ – the limit of acceptable additional error due to the changes in atmospheric pressure under operating conditions
$u_{вi} = \tau\frac{\delta_0}{\sqrt{3}}$	δ_0 – the limit of acceptable additional error due to the changes in the relative humidity of the environment under operating conditions
$u_{нi} = \tau\frac{\delta_0}{\sqrt{3}}$	δ_0 – the limit of the permissible total additional error due to changes in the content of the non-measurable components of the analyzed gas mixture
$u_{рi} = \tau\frac{0{,}5\delta_0}{\sqrt{3}}$	$0{,}5\delta_0$ – the limit of permissible additional error of the flow of the analyzed air passing through the air pollution sensor [3]

The distribution in all cases is assumed to be uniform, τ is the coefficient of the influence of environmental conditions on the result, determined on the basis of obtained statistical data.

The total standard uncertainty is defined as

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$$U_{\Sigma} = \sqrt{(u_{ai})^2 + (u_{ni})^2 + (u_{ki})^2 + (u_{ci})^2 + (u_{\tau i})^2 + (u_{\text{д}i})^2 + (u_{\text{в}i})^2 + (u_{\text{н}i})^2 + (u_{\text{р}i})^2} \ .$$

Extended uncertainty is obtained by multiplying the total standard uncertainty by the coverage ratio

$$U = U_{\Sigma}k,$$

where for the P = 0.95 confidence level, the coverage ratio is k = 2, since the distribution is assumed to be normal.

When calculating uncertainties for other modules of the target load equipment, calculations should be performed using a similar approach, taking into account the limits of permissible errors and statistical data.

Conclusion. The analysis of the current state of the metrological support of UAV-based measuring systems and a review of the legal framework it possible to draw the following conclusions:

1. To make a qualitative analysis of environmental components using UAV-based measuring systems, it is necessary to perform an extensive set of works on their metrological and methodological support. Currently, there is a wide range of measuring instruments, which, assuming their methodological and constructive adaptation according to metrological and mass-dimensional characteristics, are suitable for installation on the UAV. Many additional factors (to a greater extent, the measurement conditions) that affect the measuring capabilities of the complex, form the increased requirements for the stability of their metrological characteristics. At the present level of technological development, UAV-based measuring systems cannot be used for precision measurements.

2. The lack of a unified register of UAV registration and the uncertainty of the regulatory framework in the use of UAV-based complexes with payloads are an obstacle to such systems development, unification, and typification.

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