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ANALYSIS OF MODERN ATMOSPHERIC ELECTROSTATIC FIELD MEASURING INSTRUMENTS AND METHODS

The object of research is the process of measuring the strength of the atmospheric electrostatic field. This paper is devoted to an analytical review and comparative analysis of modern methods and instruments for measuring atmospheric electrostatic field strength. The results of scientific research and modern practical technologies, which are used to develop technical means and increase the accuracy of measuring the strength of electrostatic fields, are considered.

In the work, the general functional requirements for the hardware of systems for measuring the atmospheric electrostatic field strength are formed and the main directions of research and practical tasks for its creation are defined. The design features and characteristics of existing measuring instruments are considered in detail. The advantages and disadvantages of electrometers, electrostatic field mills, microelectromechanical electrostatic field mills, and electric field imaging systems are determined given their portability, sensitivity, measuring frequency, accuracy, measurement range, linearity, and cost. The analysis of the state of modern methods and measuring instruments for the strength of the electrostatic field showed that one of the best solutions for measuring the electrostatic field strength of the atmosphere today is the use of an improved electrostatic field mill.

It was determined that one of the important problems for ensuring the development of methods and means of atmospheric electrostatic field strength measuring is the need to generalize the structure of the measuring instruments and calculate its metrological characteristics. It has been established that solving the problem of increasing the accuracy of atmospheric electrostatic field strength measurement requires a comprehensive approach based on improving the design of the sensor structure of the meter, increasing the accuracy of navigation and positioning, increasing the autonomy of work, improving communication and data transmission systems, as well as ensuring high stability and reliability of work under the influence of external factors. Improving the structure and improving the characteristics of electrostatic field mills in the future will ensure the necessary accuracy, compactness, and availability for measurement and its inclusion in the automated system of atmospheric electrostatic field monitoring and forecasting.

Keywords: *electrostatic measurements, atmospheric electric field, electrostatic field, measuring instruments, electrostatic field mill.*

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1. Introduction

Atmospheric electricity is a set of electrical phenomena and processes in the atmosphere [1]. In the lower layers of the atmosphere, all clouds, precipitation, fog, and dust are usually electrically charged, even in a clean atmosphere there is always an electric field [2, 3]. The main informative parameter of the electric field measurement is Electric field strength, denoted by the E, which standard unit is the volt per meter (V/m or V m^{-1}).

Studies that were conducted in the areas of «good» weather, starting in the 19th century, showed that the earth's surface has a stationary electric field, with an average electrostatic field strength (EFS) of about 130 V/m. At the same time, the Earth has a negative charge equal to about $3{\cdot}10^5$ C, and the atmosphere is generally positively charged. However, during precipitation, and especially thunderstorms, blizzards, dust storms, etc., the EFS can sharply change direction and magnitude, sometimes reaching 1 KV/m [4, 5]. The largest values of the EFS are present in the middle latitudes, and it decreases towards the poles and the equator. In areas of «good» weather, parameter E generally decreases with height, for example, over the oceans. Near the earth's surface, in the so-called mixing layer with a thickness of 300–3000 m, where aerosols accumulate, the strength of the electric field can increase with height. Above the mixing layer, parameter E decreases with height, according to an exponential law, and at an altitude of 10 km does not exceed a few V/m. This decrease in EFS is because the atmosphere contains positive volume charges, the density of which also decreases rapidly with height [6].

Measuring the EFS of the surface layers of the atmosphere is used for many scientific and practical tasks, one of the widespread tasks is the determination of the dynamic charge distribution in thunderclouds and for a better understanding of atmospheric electrification [7–11]. Also important is the task of preventing lightning hazards to protect material assets and ensure safety at airports, golf courses, radio transmission facilities, etc. [12–14].

Today, the world leaders in the development and production of measuring instruments of the atmospheric EFS are the United States of America, Germany, Japan, and the Netherlands [15, 16]. Abroad, commercial firms and scientific institutions, such as the National Aeronautics and Space Administration (NASA) [17], have been involved in developing atmospheric electrostatic field strength measurements, indicating that research in this area is promising in the commercial and scientific spheres.

The wide variety of modern constructive solutions of EFS measuring instruments allows measuring the electrostatic field of the atmosphere both on the surface of the earth and at a distance from it, by installing measuring devices on airplanes [18], balloons [19], and rockets [20].

In general, when solving the tasks of measuring atmospheric EFS, the equipment should be able to be placed stationary at a certain point, and also be portable, since it is necessary to provide for its use by the operator or installation on an aircraft. Thus, developers face the following hardware requirements:

1. In case of stationary use:
   - the equipment is installed at a distance from people and buildings on special platforms with a flat surface;
   - measurements are not carried out continuously, but at certain time intervals during the day.
2. For portable use:
   - the device should be compact in size;
   - have autonomous power supply and low energy consumption;
   - record data on the coordinates of measurement points;
   - receive data in real-time with subsequent storage or transmission;
   - have a small mass;
   - when the device is used by the operator, its influence on the measurement process should be minimized. For this purpose, during movement, keep the instrument at a short distance from the operator and from the ground (at least 0.5 m) on a special rod.

Today, along with the already known, new promising methods and instruments for EFS measurement are being actively developed and researched, which can be applied to ensure the necessary conditions for conducting measurements and increase the accuracy of atmospheric EFS measurement. Because of this, it is an important task of conducting an analytical review of the latest publications on this topic and provide a comparative analysis of existing solutions for measuring atmospheric EFS.

Thus, *the aim of the research* is the determination of the general trends in the development of EFS measuring instruments and substantiate the optimal approach to the development of hardware, software, and methodological providing, which will meet the specified requirements and increases the accuracy of atmospheric EFS measurement.

2. Materials and Methods

The object of research is the process of measuring the strength of the atmospheric electrostatic field.

2.1. Electrometers. Measuring instruments used to measure EFS can be conventionally divided into several main categories according to the types of sensors used in them, these are Electrometers, Electrostatic field mills, Microelectromechanical electrostatic field mills, and Electric Field Imaging systems. This section is about Electrometers.

Electrometer was one of the first designed instruments for measuring the EFS. Its first variations, developed in the 18th century, were graduated electroscopes. A modern electrometer is a highly sensitive electronic voltmeter whose input resistance is so high that for most practical purposes the current flowing through it can be assumed to be zero. The actual value of the input resistance for modern electronic electrometers is approximately 10^{14} Ω. Because of the extremely high input impedance, electrometers require special design solutions, such as electrical shields and special insulating materials.

The work [21] presents several solutions for valve electrometers, which use a special vacuum tube with a very high amplification factor and input resistance. The input current flows into the grid with high resistance, and the voltage thus created is greatly amplified in the anode circuit. Valves designed for use in electrometers have leakage currents of only a few femtoampers, which allows for the measurement of fairly small currents. In a specialized circuit called an inverted triode, the roles of anode and grid are reversed. This design allows the control electrode to be located at the maximum distance from the space charge region surrounding the filament, minimizing the number of electrons collected by the control electrode and thus minimizing the input current.

Most modern electrometers consist of a solid-state amplifier that uses one or more field-effect transistors connected to an external diode or ionization chamber. Electrometers designed for use with ionization chambers may contain a high-voltage power supply used to bias the ionization chamber. Solid-state electrometers are often multi-functional devices that can measure voltage, charge, resistance, and current. They measure voltage using «voltage balancing» in which the input voltage is compared to an internal reference voltage source using electronic circuitry with a very high input resistance (on the order of 10^{14} Ω). A similar circuit, modified to work as a current-to-voltage converter, allows the device to measure currents of several femtoamperes. In combination with an internal voltage source, the current measurement mode can be adapted to measure very high resistances, on the order of 10^{17} Ω. Finally, by calculating from the known capacitance of the input terminal of the electrometer, the instrument can measure very small electrical charges, down to fractions of a picocoulomb.

A linear electrometer capable of measuring current in a wide range is presented in the work [22]. The schematic analysis of the electrometer and the automatic gain-switching system are described. The electrometer can measure current from 100 pA to 15 mA. Unlike typical logarithmic electrometers that use a diode as a non-linear element in the feedback circuit of the operational amplifier, which allows converting the current without switching. The output is compressed and therefore limited. However, a complex circuit is inevitable to minimize the temperature drift of the circuit's accuracy. The author suggests using automatic gain switching (AGS). This system provides a large dynamic range, but to some extent retains the accuracy of a linear amplifier. It is less susceptible to temperature fluctuations, but the system uses switches that can degrade performance at low currents due to leakage currents. The output signal of such an amplifier fluctuates between the maximum threshold and the minimum threshold depending on the amplitude of the input signal. The proposed circuit is capable of measuring current from 100 pA to 15 mA. The current accuracy of the current measurement is within 0.4 % for the entire specified range.

The study [23] describes an electrometric system with a dynamic range of ±300 V/m, which uses passive horizontal antennas to measure the electric potential of the atmosphere at a height of 1 m and 2 m above the earth's surface. The input currents drawn by the electrometer circuit are in the order of femtoampers, and the protective drive output is provided to minimize leakage. The linearity of the portable electrometer in the input range has been demonstrated to be comparable to that of a commercial laboratory electrometer, and the antenna potential can be determined to be within a few volts in a fair-weather electric field. Several such portable systems can be combined using a common high-voltage source to measure the electrical potential profile of the atmosphere above the surface at a remote location.

In [24] describes a new hybrid system that combines linear and logarithmic electrometers to provide an extended dynamic range (50 pA), using the small (4 %) overall temperature drift of the linear device to allow in-situ calibration of the logarithmic device.

So, one of the main disadvantages of electrometers is that at low currents (<1 pA) the response time of electrometers becomes significant (>10 s), which makes it suitable only for stationary use. Another disadvantage of electrometers is sensitivity to environmental changes, so measurements of values less than 1 pA take place in laboratories with fixed climatic conditions. Electrometers are often used in nuclear physics experiments because they can measure the tiny charges left in matter by the passage of ionizing radiation. The most common use of modern electrometers is to measure radiation using ionization chambers in instruments such as Geiger counters.

2.2. Electrostatic field mill. An electrostatic field mill (EFM) works by moving a grounded shield plate over the electrode sensor plates, alternately exposing the sensor plates to an electric field, and then shielding them. Electrostatic field mills have good sensitivity and protection against interference due to their design features, which makes them an ideal solution for the tasks of measuring atmospheric electricity with dynamic changes in environmental parameters. They are widely used to observe the movement and evolution of storms, to monitor the electric field in fair weather at remote locations, and to measure the vertical electric field inside clouds with EFM deployments on balloons.

The study [25] describes a new ground-based EFM design that focuses on reducing the manufacturing and operational costs of researching while maintaining the scientific capabilities offered by previous designs and commercially available devices. The theory of operation, data processing, and calibration of the device are also described. Examples of first-generation digital EFM data applied within the Relampago campaign in Argentina are presented.

The design of the presented device is typical, it consists of a grounded rotor driven by an engine and sensor plates connected in two sets of three plates. The rotation speed of the shield plates is actively controlled by software using a proportional-integral-derivative controller (PID controller or three-term controller), which is tuned to 33.3 Hz as an optimal balance between time resolution, power consumption, and mechanical durability. Reducing the data sampling frequency from the nominal 100 Hz will increase the resolution of the electric field measurement. This can be used in applications that do not require fast electric field measurements, such as global electric circuit (GEC) studies, where 1 Hz is typically used for measurements. A unique feature of this EFM is that the signal from the optical encoder is directly sampled and recorded by another Analog-to-digital converter (ADC), unlike other field mills that perform phase demodulation using analog electronics. The EFM data sampling period in good weather shows an effective resolution of about 2 V/m. To demonstrate the ability of EFM to investigate electric fields in fair weather, further testing of EFM sensitivity, particularly the temperature dependence of instrument sensitivity and DC bias drift, is required.

In the paper [26], a numerical model of the field mill sensor was developed based on the Finite element analysis (FEA) method for optimal parameters. Compared to the traditional analytical model used for the field mill sensor, the numerical model provides a better fit for the measurement results. The optimal number of plates and the gap between the rotor and the sensitive electrode were obtained based on the design parameters of the prototype. The field mill sensor has been designed, calibrated, and successfully tested at the national High-Voltage Test Facility (China).

Several simulations were carried out to establish the optimal geometric parameters of the sensor plate. Several simulations were carried out with different numbers of sectors of the sensor and shielding plates, in the results of which it was found that with an increase in the number of sectors, the intensity of the electric field on the sensitive electrode decreases, and the influence of the edge effect increases. It was established that with six sectors the induced current on the sensor plates was maximum. A simulation was also carried out in which the height between the sensor and shielding plates was changed, in which it was established that when the distance between the plates increased, the induced electric charge decreased, and when the plates were brought closer together, the parasitic capacitance between them increased. Thus, the optimal distance between the plates of 4.2 mm was established.

Based on the analysis, the system prototype is designed to have eight sectors, with inner and outer blade diameters of 10 and 30 mm, respectively. The gap between the plates was set at 3 mm, and the radius of the sensor body was 40 mm. The height of the sensor is 90 mm, and the housing is made of aluminum with a nickel-plated coating to avoid the accumulation of ion flux under power lines. The measurement results are obtained from the output signal of a field mill sensor prototype with a motor running at 3000 rpm (or 50 Hz). It was established that the results of the numerical method are in good agreement with the experimental results. Calibration of the device was carried out by the IEEE 1227TM-1990(R2010) standard. The calibration results established that the linearity of the electric field strength of the sensors is better than 1 % in the electric field limits of ±60 KV/m. The accuracy of the prototype electric field sensor is 2.4 %, which is better than that of a commercial field mill sensor. Measurement error is mainly caused by changes in the mechanical structure introduced during the manufacturing and assembly processes.

The study [18] describes a new generation of electric field mills with rotating blades, developed and manufactured at the NASA Marshall Space Flight Center (USA, Huntsville). The mills have separate microprocessors that digitize the electrical field signal on the mill and respond to commands from the data system computer. The mills are very sensitive (1 V/m per 1 bit), have a wide dynamic range of 115 dB, and have a very low noise level of 1 least significant bit (LSB). These aircraft-mounted mills can measure fields from 1 V/m to 500 KV/m. Sending commands once per second from the data acquisition computer to each mill ensures accurate timing and synchronization. The EFMs can also be commanded to perform an in-flight self-calibration, which is performed periodically to monitor the health and health of each mill.

The body and plates are made of polished 316 stainless steel. The rev sensor, motor shaft, and protective housing are spaced from the plates to minimize shorting caused by precipitation. The polarity is determined by a synchronizing signal received from a slit optical sensor that indicates the specific angular position of the motor shaft. A brushless DC motor was used because this type of motor produces less electrical noise than a conventional brushed motor and lasts longer. A 16-bit bipolar A/D converter was used in the device. The full measurement range of the device is ±1.15 MV/m, and when using an additional gain of 18.2 times, the maximum measurement range is reduced to ±63.6 KV/m, but the device has better sensitivity. Calibration of the flat plate showed the resolution of the field mill to be 1.94 V/m per 1 bit in sensitive channel mode. When EFMs were installed on the plane, the electric field increased by about 2 times. This means that the field detected during flight ranges from about 1 V/m to about 575 KV/m, which is much higher than the fields we normally find inside electrified clouds (about 50 KV/m outside the active zone), balloons and rockets regularly measure fields of 100–150 KV/m, and on rare occasions they can reach values of 300–400 KV/m.

The Atmospheric Measurement of Potential and ElectRic field on Aircraft (AMPERA) system presented in [27] was integrated into the Falcon 20 SAFIRE (F20) within the framework of the project of using new data on atmospheric electricity for research and the environment EXAEDRE (EXploiting new Atmospheric Electricity Data for Research and the Environment) project. Since September 2018, a flight campaign has been conducted over Corsica (France) to study electrical activity during thunderstorms. During this campaign, eight science flights were flown during or near thunderstorms. During flights inside electrified clouds, the value of the atmospheric electrostatic field was recorded, which was about 79 KV/m at an altitude of 8400 m. The highest measured value of the reduced atmospheric electrostatic field is 194 KV/m during lightning strike F20. Combining these results with data from previous campaigns suggests that there is a threshold (depending on the size of the aircraft) for striking an aircraft.

During the measurements, an electrostatic field mill was used, the characteristics and performance of which were determined as a result of laboratory tests:

- the dynamic range of the device is from ±5 V/m to ±1 MV/m;
- the resolution of the device for field strengths below 5 KV/m is 5 V/m, and for higher values – 20 V/m;
- data update frequency – 10 Hz;
- the device is powered by 28 V (DC) and has a maximum power consumption of 25 W;
- the dimensions of the device are 120 mm in diameter and 115 mm in height.

Analyzing the presented solutions of electrostatic field mills, it is possible to note a rather high sensitivity of the devices (up to the level of 1–2 V/m) and a wide measurement range (from units of V/m to hundreds of KV/m). The proposed designs of EFMs have good interference resistance to the action of external influences, which reduces the drift of the device parameters many times, thus making its measurement results more reliable. It is because of this that EFM has become so popular in the tasks of measuring atmospheric electricity.

But with all its advantages, the use of EFM for atmospheric electrostatic field strength measurements has space for development and improvement. The obtained results can be improved due to the use of modern modeling tools, new schematic and technical solutions, and advanced electrical components. As the simulation in the study [26] shows, the sensitivity of the sensor can be improved due to the configuration and structure of the sensor, and in the work [18] an improved low-noise circuit of the device is demonstrated, which increases its measurement accuracy. In the future, EFMs can become accurate, compact, and cheap measuring tools that will find their application as convenient non-contact measuring devices.

2.3. Microelectromechanical electrostatic field mill. The principle of operation of most EFM implemented in the form of microelectromechanical systems (MEMS) is based on the induction of charge on the covers of the sensor plates. Unlike the sensors discussed above, in 2.3. Microelectromechanical electrostatic field mill (MEMEFM), the shielding of the sensor plates occurs due to resonance modes.

Since the first presentation of MEMEFM in 1991 [28], the structure of these sensors has gone through several iterations and improvements in their manufacturing technology, which made it possible to improve their characteristics. During this period, researchers developed and documented various MEMS EFM [29–40], but their sensitivity to electrostatic field action remained quite low for practical use.

Recent studies of MEMEFM are aimed at improving their structure and increasing the accuracy of EFS measurements. Thus, in [41], the first iteration of MEMS with a double vertical electrometer and an EFM is presented. The device uses vertically located electrodes that resonate transversely relative to each other and act as a variable capacitor that converts the existing electric field into an electric signal.

As a result of the simulation, the developed device should theoretically induce a current signal at the second harmonic with an amplitude of 0.87 pA, at a resonance frequency of the device of 12.62 KHz with a Q factor of 22.54. This current was then amplified $5 \cdot 10^5$ times using a Transimpedance amplifier (TIA). According to the researchers, if the simulation is accurate, the useful signal is 31 mVrms and the system noise level is 10.7 mVrms. The obtained estimated sensitivity of the sensor is 2.19 fA/(V/m). But, when conducting a physical experiment, this sensor did not detect a useful signal. As determined, the input resistance of the electrometer was about 800 KΩ, while the required input resistance should be greater than 1 GΩ. In this case, the input resistance acted as a pull-up resistor that forced the input node to be at zero potential.

Despite the good theoretical foundation and reliable model of the sensor demonstrated in the study [41], mistakes were made during the design of the real device, which prevented practical confirmation of the results.

In the study [42], a single-crystal three-dimensional MEMEFM is presented, in which a rotary mechanism in the plane is used to simultaneously detect the components of the electrostatic field of the *X*, *Y*, and *Z* axes. This design of the device made it possible to investigate the MEMS response to a three-dimensional electrostatic field of different directions. The parameters of the strip electrodes were optimized by the FEA method and their resonance frequencies of the first six orders in the vibration mode were determined, which were 838.68, 1076.0, 1076.0, 1150.7, 1454.4, and 1934.7 Hz, and in rotation mode (which is the operating mode of the microsensor), the resonant frequency was 1454.4 Hz.

The presented type of sensor structure is implemented as follows: the signal from the sensor plates enters the TP with a high-precision resistor with a nominal value of 1 GΩ, after which a differential amplifier is located, which amplifies the differential output of two opposite sensitive elements by 50 times, and also reduces common-mode noise and increases the signal ratio/noise. The value obtained during the experiment of the actual resonant frequency of rotation was 1291 Hz.

The results of determining the characteristics of the device showed that the measured linearity errors in the field strength range from 0 to 50 KV/m were within 5.5 %. The measured linearity parameters showed that the alternating current of each measurement axis can be at the level of fA with an electric field of 1 KV/m. Measurement errors in all planes ranged from 9.96 % to 14.04 %. These errors can be attributed to systematic errors of asymmetry of the sensor structure caused by the manufacturing process. In conclusion, it can be noted that the demonstrated 3D MEMEFM has great prospects for its integration into unmanned aerial vehicles due to its compact size (approximately 11x11 mm), but the obtained measurement accuracy is inferior to already existing sensors.

In the publication [43], a highly sensitive MEMEFM based on torsional resonance is presented. The proposed MEMS uses a torsion gate, which consists of shielding electrodes and torsion beams. Movable shielding electrodes and fixed sensitive electrodes are made on the same plane. The two-stroke electrostatic drive method is used to excite the torsional valve. As a result of the experiment, the resonance frequency of the MEMEFM was determined, which was 5190 Hz, and the tested resonance frequency of the simulation was 5358 Hz. The discrepancy between the frequency values is explained by the variation in the sensor manufacturing process and the accuracy of the simulation. In the electrostatic field range of 0–50 KV/m, a linearity of 0.15 % was obtained, and the error was below 0.38 % in three consecutive measurements. Also, the MEMS showed a high sensitivity of 48.2 fA/(V/m), which was achieved by using TP.

The advantages of this study, compared to the one presented in [42], include a high frequency of shielding of sensor plates and the use of a differential scheme for switching on sensor plates. Along with this, the study [43] has a number of remarks, which can be attributed to the fact that the calculated sensitivity of the sensor takes into account the amplification factor of the TP, which is not part of the MEMS. Also, the scheme and noise characteristics of this tract are not presented. The determination of the presented measurement error is based on a small sample of data, and the method of conducting the experiment is only partially described.

Summarizing the material presented, it is possible to single out a unique solution for the construction of MEMS with improved mechanical characteristics that increase the sensitivity of the EFM, but the presented results of the conducted experiment cannot be considered exhaustive. The insufficient experimental data and the large sampling step do not give a clear idea of the measurement error.

In general, evaluating the current state of development of MEMEFM, the following advantages of this atmospheric electrostatic field measuring instrument can be highlighted: research has a good theoretical basis, methods of EFS measurement and modeling tools have also been developed, proven manufacturing technology and small size of the sensor, low power consumption and small cost. These devices can be used in charge accumulation monitoring systems in electronic components and the atmosphere. Their small dimensions are the key to their use in unmanned aerial vehicles. But in the current state, these devices, which are still at the stage of development and testing, have a large measurement error (in the range of 10–15 %), which makes them unsuitable for accurate measurements. In the future, research in this direction can improve the characteristics of MEMEFM, which will make it possible to compete with other field strength meters. Photolithographic MEMS manufacturing technology will allow the production of these sensors in large batches, which will make it possible to use microsensors as low-cost sensors of electrostatic charge and field with high resolution.

2.4. Electric Field Imaging. One of the non-trivial modern tools for measuring EFS is Electric Field Imaging (EFI). For the first time, EFI was mentioned in [44] as an electric field imaging system (EFIS) for creating a new physical channel for machine perception of human actions. The paper presents relatively simple, inexpensive hardware and signal processing methods for obtaining geometric information about the configuration and movement of the human body through electrostatic field measurements. The study of EFI for the implementation of robotic grasping technology is presented in [45]. Research and development of this type of EFS measuring instrument was also carried out at the NASA research center [46]. They developed a non-contact system based on EFI capable of quantitatively measuring the magnitude and direction of electrostatic fields in the near and far fields [46].

The study [47] presented EFIS, which consists of a sensor array, data processing equipment, and an output device. Registering the voltage difference at several points of the sensor array, EFIS calculates the electric potential at points far from the sensor. It is known that different objects interact with electric fields in different ways, depending on their shape and dielectric properties (for example, impedance, resistance). The presented system for constructing a three-dimensional image uses the dielectric properties of the studied object, which are determined by measuring very weak electric fields. The obtained electric potential data are collected into a three-dimensional map of the magnitude and direction of electric fields using methods similar to computer tomography. The research presented in the work is based on the use of patents [48–50].

The fields of application of this EFS measuring instrument cover a very wide spectrum. The latest developments of EFIS relate to non-destructive testing tools for composite flaw detection, assessment of electrical properties of insulators, and assessment of electrical shielding of cables [51–53].

The use of electric fields that are safe for the human body makes it possible to use them in the field of medicine. EFIS can conduct remote non-contact monitoring of the vascular and respiratory systems, visualize the brain, detect cancer cells, and is also used in polarization wave imaging of the heart [54]. In [55], EFI is used for the telemetry of cochlear implants. Also, this method is widely used in the field of security to check and detect dangerous items in luggage [56, 57], in forensic medical examination, to reproduce the history of events, to determine where people walked and what they touched, both with and without gloves at crime scenes [56].

In addition, an alternative EFIS optimized for potential use in estimating electric fields at large distances (greater than 1 mile) is being developed. Such a system could be used in meteorology to forecast the weather and develop protection against dangerous atmospheric phenomena, such as lightning [58]. One promising application of EFIS is geophysical exploration for oil or mineral exploration.

Based on the considered publications and patents, the following advantages of using EFI can be distinguished:

- developed on available and relatively inexpensive components;
- portable;
- measurements can be made at close and far distances from the sensor;
- safe;
- has a wide range of applications.

Although EFIS has great potential for high-resolution and near-real-time imaging, at this stage it is impossible to obtain the required resolution without the use of special software. In general, EFIS cannot fully be a measuring device, because in existing EFIS only the gradient of electrostatic field change is determined, and not its quantitative value. By combining the use of EFIS as a sensor array and a reference EFS measurement instrument, it is potentially possible to bring the gradient of electrostatic field change to realistic values. At this stage of development, EFIS will have to go through many more studies and improvements, but in the future, such systems have great potential for their use in the fields of production, medicine, meteorology, geophysical exploration, etc.

3. Results and Discussion

In order to determine the optimal, from the point of view of the hardware requirements, approach to atmospheric electrostatic field strength measurement, a comparative analysis of potentially suitable EFS measurement tools was carried out according to the following criteria: Portability, Sensitivity, Measuring frequency, Accuracy, Measurement range, Linearity, Cost. The obtained characteristics are given in Table 1.

Among the considered tools for measuring EFS, electrostatic field mills remain relevant as the best instrument for solving the problem of measuring atmospheric electrostatic strength. Designs such as electrometers are morally outdated and do not meet the specified requirements for equipment, and EFS measuring instruments developed on the basis of MEMS technology have not yet achieved the necessary measurement accuracy. The use of EFIS is promising for the tasks of research and measurement of atmospheric EFS, but at this stage, they cannot be considered as measuring devices. Electrostatic field imaging systems at this stage of development do not allow obtaining a quantitative indicator of EFS and are still in the development process.

Table 1

Comparative characteristics of EFS measurement instruments

Criteria	Electrometer	EFM	MEMEFM	EFIS
Portability	+	+	+	–
Sensitivity	–	1.9 V/m	100 V/m	–
Measuring frequency	1–10 Hz	50–150 Hz	150–250 Hz	~10 Hz
Accuracy	~4 %	2.5 %	10–15 %	–
Measurement range	±300 V/m	±1 MV/m	±50 KV/m	±1 kV/m
Linearity	–	~1 %	~5.5 %	–
Cost	Medium	Medium	Low	Medium

Despite the fact that the electrostatic field mills are widely used in the community of atmospheric electricity, for the study of phenomena related to the atmospheric electric field, the task of increasing the accuracy of the device and its improvement remain relevant. The rapid pace of the development of electronics and the emergence of new modeling tools create prerequisites for the development and improvement of schematic and technical solutions that can be implemented in the EFM design. It should be noted that although various constructions of EFM have been developed and documented, this topic is not popularized, and methods of construction of EF and features of calculations are not documented. Therefore, along with the improvement of the EFM itself, there was a need to generalize the structure of the meter and calculate its metrological characteristics. Thus, in order to increase the accuracy of EFM measurement, a number of scientific and practical tasks need to be solved, which can be grouped according to the following directions:

1. Development of a universal mathematical model of the EF sensor in order to reduce its methodical error.
2. Conducting an analysis of the components of the mathematical model, on the basis of which to determine the optimal parameters of the EF sensor structure.
3. Improvement of the EFM functional scheme.
4. Development of a methodology for calculating the instrumental error for determining critical parameters during the selection of components for the construction of the device.
5. Modeling the geometric and physical characteristics of the EFM sensor plate to achieve the maximum sensitivity of the device.
6. Construction of a prototype EFM with improved metrological characteristics.
7. Development of a methodology for conducting physical experiments.
8. Conducting physical tests and experiments in order to determine the error values of the improved EF.

The practical significance of the results obtained in the study is:

1. Determination of trends in the development of EFS measuring instruments;
2. Determination of functional requirements for the development of EFS measuring tools in order to increase the accuracy of atmospheric EFS measurement;
3. Determination of scientific and practical tasks for improvement of existing and development of new atmospheric EFS measuring instruments.

The limitations of this study. Electrostatic field strength measuring instruments, today, are very specific devices that are mostly used in meteorology, some narrowly specialized areas of production and research projects. This makes it difficult to find documentation and research materials on this topic. The analysis presented in the study is based on research materials and documented experiments, the results and numerical values of which are rather difficult to verify and reproduce, due to this, the numerical values presented in the work may differ from the real ones.

The influence of martial law conditions. The large-scale military aggression of the russian federation against Ukraine launched on February 24, 2022, caused a number of acute problems in the field of science and innovation. Partially destroyed or damaged research infrastructure, reduction of state and local budget expenditures on education and forced displacement of scientific and scientific-pedagogical workers from their own homes and places of employment contributed to the loss of scientific potential in the field of scientific research. Along with this, logistical connections became more complicated, and production capacity decreased, which directly affected the possibility of mock-up and small-scale production of research models and own devices. It became necessary to create scientific developments oriented to military tasks and aimed at combating the consequences of military actions on the territory of Ukraine.

Prospects for further research of atmospheric EFS measuring instruments, along with the tasks of improving the designs and measurement accuracy of atmospheric EFS measuring devices, also include the research and implementation of the intellectualization of the meters. To do this, it is necessary to improve methodical, algorithmic, and software for visualization of the received data on the parameters of the electrostatic field of the atmosphere and their further analysis. The use of modern technologies of machine learning and artificial intelligence will provide intellectual support for atmospheric monitoring systems, and the creation of a visualization system and research of the received data on atmospheric EFS will allow determining the prerequisites for the occurrence of a natural disaster and timely warning of the population.

4. Conclusions

The analysis of the state of modern methods and measuring instruments for the atmospheric electrostatic fields' strength carried out in the study showed that the developers face the following topical urgent tasks:

1. Increasing the accuracy of measuring the strength of the electrostatic field of the atmosphere.
2. Improving the sensitivity of existing sensors or developing new ones.
3. Improvement of the existing constructive solutions of atmospheric EFS measuring instruments.
4. Improvement of the EFS calculation methodology (compensation of measurement errors caused by: edge effects, directivity diagram; tolerances of geometric dimensions of sensors, etc.).
5. Development of a methodology for calibration of devices.
6. Development of software for processing and visualization of received data.

Trends in the development of atmospheric electrostatic field strength measuring instruments are aimed at improving existing and developing new measuring devices and sensors for their inclusion in automated systems for monitoring and forecasting dangerous meteorological phenomena, such as thunderstorms. The use of modern technologies of machine learning and artificial intelligence will provide intellectual support for atmospheric monitoring systems, and the design of a visualization system and research of the received data on atmospheric EFS will allow determining the prerequisites for the occurrence of a natural disaster and timely warning of the population. In the future, this technology can be used for demining fields and geophysical exploration in the search for minerals.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

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Data availability

The manuscript has no associated data.

References

1. Whipple, F. J. W. (2007). Modern views on atmospheric electricity. *Quarterly Journal of the Royal Meteorological Society, 64 (275),* 199–222. doi: https://doi.org/10.1002/qj.49706427502
2. Roble, R., Tzur, I. (1986). *The global atmospheric electrical circuit. The Earth's electrical environment.* Washington: National Academies Press, 206–231.
3. Markson, R. (2007). The Global Circuit Intensity: Its Measurement and Variation over the Last 50 Years. *Bulletin of the American Meteorological Society, 88 (2),* 223–242. doi: https://doi.org/10.1175/bams-88-2-223
4. Liu, C., Williams, E. R., Zipser, E. J., Burns, G. (2010). Diurnal Variations of Global Thunderstorms and Electrified Shower Clouds and Their Contribution to the Global Electrical Circuit. *Journal of the Atmospheric Sciences, 67 (2),* 309–323. doi: https://doi.org/10.1175/2009jas3248.1
5. Blakeslee, R. J., Mach, D. M., Bateman, M. G., Bailey, J. C. (2014). Seasonal variations in the lightning diurnal cycle and implications for the global electric circuit. *Atmospheric Research, 135-136,* 228–243. doi: https://doi.org/10.1016/j.atmosres.2012.09.023
6. Anisimov, S. V., Galichenko, S. V., Aphinogenov, K. V., Prokhorchuk, A. A. (2017). Evaluation of the Atmospheric Boundary-Layer Electrical Variability. *Boundary-Layer Meteorology, 327–348.* doi: https://doi.org/10.1007/s10546-017-0328-0
7. Jacobson, E. A., Krider, E. P. (1976). Electrostatic Field Changes Produced by Florida Lightning. *Journal of the Atmospheric Sciences, 33 (1),* 103–117. doi: https://doi.org/10.1175/1520-0469(1976)033<0103:efcpbf>2.0.co;2

8. Koshak, W. J., Krider, E. P. (1989). Analysis of lightning field changes during active Florida thunderstorms. *Journal of Geophysical Research, 94 (D1),* 1165. doi: https://doi.org/10.1029/jd094id01p01165
9. Koshak, W. J., Krider, E. P. (1994). A Linear Method for Analyzing Lightning Field Changes. *Journal of the Atmospheric Sciences, 51 (4),* 473–488. doi: https://doi.org/10.1175/1520-0469(1994)051<0473:almfal>2.0.co;2
10. Maier, L. M., Krider, E. P. (1986). The charges that are deposited by cloud-to-ground lightning in Florida. *Journal of Geophysical Research, 91 (D12),* 13275. doi: https://doi.org/10.1029/jd091id12p13275
11. Murphy, M. J., Krider, E. P., Maier, M. W. (1996). Lightning charge analyses in small Convection and Precipitation Electrification (CaPE) experiment storms. *Journal of Geophysical Research: Atmospheres, 101 (D23),* 29615–29626. Portico. doi: https://doi.org/10.1029/96jd01538
12. Chubb, J., Harbour, J. (2000). A system for the advance warning of risk of lightning. *Paper presented at the Electrostatics Society of America 'ESA 2000' meeting Niagara Falls.* Niagara Falls.
13. Montanya, J., Bergas, J., Hermoso, B. (2004). Electric field measurements at ground level as a basis for lightning hazard warning. *Journal of Electrostatics, 60 (2-4),* 241–246. doi: https://doi.org/10.1016/j.elstat.2004.01.009
14. Murphy, M. J., Holle, R. L., Demetriades, N. W. S. (2008). Cloud-to-ground lightning warnings using electric field mill and lightning observations. *20th International Lightning Detection Conference (ILDC).* Tucson.
15. *7 Electrostatic Instrument Manufacturers in 2023.* Metoree. Available at: https://us.metoree.com/categories/static-electricity-meter/
16. *Electrostatic field measuring instrument max. ±30 kV | AD-1684A.* DirectIndustry. Available at: https://www.directindustry.com/prod/d-company-limited/product-54946-1443153.html
17. *GHRC: Lightning field campaigns, detection instruments, and research proposals.* Wayback Machine. Aviailable at: https://web.archive.org/web/20160307112621/http://thunder.msfc.nasa.gov/validation/validation.html#Interp
18. Bateman, M. G., Stewart, M. F., Podgorny, S. J., Christian, H. J., Mach, D. M., Blakeslee, R. J. et al. (2007). A Low-Noise, Microprocessor-Controlled, Internally Digitizing Rotating-Vane Electric Field Mill for Airborne Platforms. *Journal of Atmospheric and Oceanic Technology, 24 (7),* 1245–1255. doi: https://doi.org/10.1175/jtech2039.1
19. Chauzy, S., Médale, J.-C., Prieur, S., Soula, S. (1991). Multilevel measurement of the electric field underneath a thundercloud: 1. A new system and the associated data processing. *Journal of Geophysical Research, 96 (D12),* 22319. doi: https://doi.org/10.1029/91jd02031
20. Winn, W. P., Moore, C. B. (1971). Electric field measurements in thunderclouds using instrumented rockets. *Journal of Geophysical Research, 76 (21),* 5003–5017. doi: https://doi.org/10.1029/jc076i021p05003
21. Ackermann, L., Bouwers, A., Carlsson, C., Dümmlin, K., Goering, U., Haxel, O. et al. (1968). *Encyclopedia of Medical Radiology.* Verlag Berlin Heidelberg.
22. Acharya, Y. B. (2000). A wide range linear electrometer. *Review of Scientific Instruments, 71 (6),* 2585–2588. doi: https://doi.org/10.1063/1.1150653
23. Harrison, R. G. (1997). An antenna electrometer system for atmospheric electrical measurements. *Review of Scientific Instruments, 68 (3),* 1599–1603. doi: https://doi.org/10.1063/1.1147932
24. Harrison, R. G., Marlton, G. J., Nicoll, K. A., Airey, M. W., Williams, P. D. (2017). A self-calibrating wide range electrometer for in-cloud measurements. *Review of Scientific Instruments, 88 (12).* doi: https://doi.org/10.1063/1.5011177
25. Antunes de Sá, A., Marshall, R., Sousa, A., Viets, A., Deierling, W. (2020). An Array of Low-Cost, High-Speed, Autonomous Electric Field Mills for Thunderstorm Research. *Earth and Space Science, 7 (11).* doi: https://doi.org/10.1029/2020ea001309
26. Cui, Y., Yuan, H., Song, X., Zhao, L., Liu, Y., Lin, L. (2018). Model, Design, and Testing of Field Mill Sensors for Measuring Electric Fields Under High-Voltage Direct-Current Power Lines. *IEEE Transactions on Industrial Electronics, 65 (1),* 608–615. doi: https://doi.org/10.1109/tie.2017.2719618
27. Buguet, M., Lalande, P., Laroche, P., Blanchet, P., Bouchard, A., Chazottes, A. (2021). Thundercloud Electrostatic Field Measurements during the Inflight EXAEDRE Campaign and during Lightning Strike to the Aircraft. *Atmosphere, 12 (12),* 1645. doi: https://doi.org/10.3390/atmos12121645
28. Hsu, C. H., Muller, R. S. (1991). *Micromechanical electrostatic voltmeter. TRANSDUCERS '91: 1991 International Conference on Solid-State Sensors and Actuators.* Digest of Technical Papers. San Francisco. doi: https://doi.org/10.1109/sensor.1991.148966
29. Yong Zhu, Lee, J. E.-Y., Seshia, A. A. (2008). A Resonant Micromachined Electrostatic Charge Sensor. *IEEE Sensors Journal, 8 (9),* 1499–1505. doi: https://doi.org/10.1109/jsen.2008.923597
30. Peng, C., Chen, X., Bai, Q., Luo, L., Xia, S. (2006). A novel high performance micromechanical resonant electrostatic field sensor used in atmospheric electric field detection. *Proceedings of the IEEE International Conference on MICRO Electro Mechanical Systems.* Las Vegas. doi: https://doi.org/10.1109/memsys.2006.1627895
31. Chen, X., Peng, C., Xia, S. (2008). Design of a thermally driven resonant miniature electric field sensor with feedback control. *Proceedings of the IEEE International Conference on Nano/micro Engineered and Molecular Systems.* Sanya. doi: https://doi.org/10.1109/nems.2008.4484329
32. Riehl, P. S., Scott, K. L., Muller, R. S., Howe, R. T., Yasaitis, J. A. (2003). Electrostatic charge and field sensors based on micromechanical resonators. *Journal of Microelectromechanical Systems, 12 (5),* 577–589. doi: https://doi.org/10.1109/jmems.2003.818066
33. Gong, C., Tao, H., Peng, C., Bai, Q., Chen, S., Xia, S. (2005). A novel miniature interlacing vibrating electric field sensor. *Proceedings of the IEEE Sensors.* Irvine. doi: https://doi.org/10.1109/icsens.2005.1597722
34. Yang, P., Peng, C., Zhang, H., Liu, S., Fang, D., Xia, S. (2011). A high sensitivity SOI electric-field sensor with novel comb-shaped microelectrodes. *Proceedings of the 16th International Solid-State Sensors, Actuators and Microsystems Conference.* Beijing. doi: https://doi.org/10.1109/transducers.2011.5969165
35. Horenstein, M. N., Stone, P. R. (2001). A micro-aperture electrostatic field mill based on MEMS technology. *Journal of Electrostatics, 51-52,* 515–521. doi: https://doi.org/10.1016/s0304-3886(01)00048-1
36. Bahreyni, B., Wijeweera, G., Shafai, C., Rajapakse, A. (2007). Design and testing of a field-chopping electric field sensor using thermal actuators with mechanically amplified response. *Proceedings of the Solid-State Sensors, Actuators and Microsystems Conference.* Lyon. doi: https://doi.org/10.1109/sensor.2007.4300404
37. Bahreyni, B., Wijeweera, G., Shafai, C., Rajapakse, A. (2008). Analysis and Design of a Micromachined Electric-Field Sensor. *Journal of Microelectromechanical Systems, 17 (1),* 31–36. doi: https://doi.org/10.1109/jmems.2007.911870
38. Huang, J., Wu, X., Wang, X., Yan, X., Lin, L. (2015). A novel high-sensitivity electrostatic biased electric field sensor. *Journal of Micromechanics and Microengineering, 25 (9),* 095008. doi: https://doi.org/10.1088/0960-1317/25/9/095008
39. Wang, Y., Fang, D., Feng, K., Ren, R., Chen, B., Peng, C., Xia, S. (2015). A novel micro electric field sensor with X–Y dual axis sensitive differential structure. *Sensors and Actuators A: Physical, 229,* 1–7. doi: https://doi.org/10.1016/j.sna.2015.03.013
40. Ma, Q., Huang, K., Yu, Z., Wang, Z. (2017). An electric field sensor with double-layer floating structure for measurement of dc synthetic field coupled with ion flow. *Proceedings of the International Conference on Solid-State Sensors, Actuators and Microsystems.* Kaohsiung. doi: https://doi.org/10.1109/transducers.2017.7994192
41. Underwood, G. C. (2019). *A MEMS Dual Vertical Electrometer and Electric Field-Mill.* Aviailable at: https://scholar.afit.edu/etd/2288
42. Ling, B., Wang, Y., Peng, C., Li, B., Chu, Z., Li, B., Xia, S. (2017). Single-chip 3D electric field microsensor. *Frontiers of Mechanical Engineering, 12 (4),* 581–590. doi: https://doi.org/10.1007/s11465-017-0454-x
43. Chu, Z., Peng, C., Ren, R., Ling, B., Zhang, Z., Lei, H., Xia, S. (2018). A High Sensitivity Electric Field Microsensor Based on Torsional Resonance. *Sensors, 18 (1),* 286. doi: https://doi.org/10.3390/s18010286

44. Smith, J. R. (1999). *Electric field imaging.* Massachusetts Institute of Technology.
45. Smith, J. R., Garcia, E., Wistort, R., Krishnamoorthy, G. (2007). Electric field imaging pretouch for robotic graspers. *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems,* 676–683. doi: https://doi.org/10.1109/iros.2007.4399609
46. *Electric Field Imaging System. T2 Portal.* NASA Technology Transfer Portal Home. Available at: https://technology.nasa.gov/patent/LAR-TOPS-116 last accessed: 15.07.2023
47. Generazio, E. R. (2017). Electric potential and electric field imaging. *AIP Conference Proceedings. AIP Publishing, 1806 (1).* doi: https://doi.org/10.1063/1.4974566
48. Generazio, E. R. (2016). Pat. No. 9,279,719 USA. *Electric field quantitative measurement system and method.* 08.05.2016.
49. Generazio, E. R. (2017). Pat. No. 9,804,199 USA. *Ephemeral electric potential and electric field sensor.* 31.10.2017.
50. Generazio, E. R. (2017). Pat. No. 9,559,616 USA. *Quasi-static electric field generator.* 31.01.2017.
51. Generazio, E. R. (2020). Pat. No. 10,712,378 USA. *Dynamic multidimensional electric potential and electric field quantitative measurement system and method.* 14.07.2020.
52. Generazio, E. R. (2021). Pat. No. 10,900,930 USA. *Method for phonon assisted creation and annihilation of subsurface electric dipoles.* 26.01.2021.
53. Generazio, E. R. (2022). Pat. No. 11,293,964 USA. *Dynamic multidimensional electric potential and electric field quantitative measurement system and method.* 05.04.2022.
54. Generazio, E. R. (2022). Pat. No. 11,360,048 USA. *Method for phonon assisted creation and annihilation of subsurface electric dipoles.* 14.07.2022.
55. Mens, L. H. M. (2007). Advances in Cochlear Implant Telemetry: Evoked Neural Responses, Electrical Field Imaging, and Technical Integrity. *Trends in Amplification, 11 (3),* 143–159. doi: https://doi.org/10.1177/1084713807304362
56. *NASA Technical Reports Server (NTRS).* Available at: https://ntrs.nasa.gov/api/citations/20160008937/downloads/20160008937.pdf
57. Generazio, E. R. (2019). Pat. No. 10,281,430 USA. *Identification and characterization of remote objects by electric charge tunneling, injection, and induction, and an erasable organic molecular memory.* 07.05.2019.
58. Generazio, E. R. (2020). Pat. No. 10,620,252 USA. *Electric field imaging system.* 14.04.2020.

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