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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Solar Radiation Measurements at the Fonovaya Observatory: Part I: Methodical Aspects and Specifications

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Abstract—We discuss the methodical aspects and approaches used to arrange solar radiation measurements at the Fonovaya Observatory at the V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, and the capabilities of the new radiation unit, integrated into the Observatory measurement system in 2020. It is equipped with a set of instruments allowing a continuous monitoring of the total (0.285–2.8 μm), total UV (0.280–0.400 μm), and UV-B radiation (0.280–0.315 μm), as well as the radiation balance. We describe the capabilities of software specially developed for the measurement data acquisition, transmission, and processing.

Keywords: atmosphere, radiation, monitoring, radiation balance, ultraviolet radiation, shortwave and longwave radiation

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INTRODUCTION

Global climate warming has been observed on the Earth in recent decades. Therefore, studies aimed at clarifying how climate warming occurs become especially important for mitigating negative environmental consequences. The Intergovernmental Panel on Climate Change (IPCC) experts attribute the temperature growth to the changes in the Earth's radiation budget (ERB), the main components of which are the total radiation and surface albedo. The variations in the solar radiative fluxes are determined by factors, each having a varying contribution, depending on the physical-geographical and climatic features of the region.

In the Second Assessment Report on climate changes and their consequences for the territory of the Russian Federation it is concluded that the current climate change in Russia, on the whole, should be characterized as a continued warming at a rate more than a factor of 2.5 larger than the global warming rate [1]. It is noteworthy that the global tendency for the warming slowdown cannot as yet be discerned for the territory of Russia. Climate change in Russia is not just restricted to the increase in air temperature near the Earth's surface, but is manifested in all components of the climate system and, in particular, in extreme characters of climate and changes in hydrological regime and in ice cover of Russian seas. The authors of the report consider that changes in greenhouse gas concentrations have mainly contributed to the temperature increase on the territory of Russia since the second half of the twentieth century. However, they also suggest that the natural external effects are significantly manifested in the interannual temperature oscillations. The incoming solar radiation and the level of longwave emission are among the most important factors of the climate change and, in particular, the temperature of surface air. How significant are the contributions from separate factors is estimated by numerical models; therefore, an active application of model calculations requires correct input parameters for model verification. Considering that the warming rate is still higher in Russia than elsewhere on the planet, significant attention should be devoted to developing a national network of stations for monitoring the radiation characteristics and the state of the surface air layer.

The staff of V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences (IAO SB RAS), has monitored the atmospheric parameters in the surface layer on the territory of Western Siberia: at the Tropospheric Ozone Research (TOR) station in Tomsk since 1995 [2]; at the network of stations arranged in collaboration with the National Institute for Environmental Studies (Tsukuba, Japan) since 2004 [3], and at the station for monitoring the atmospheric parameters on the territory of the Fonovaya Observatory. Periodic measurements of total solar radiation were initiated in 2009 at this station. Until 2016, the measurements were carried out episodically during complex scientific experiments and using a Yanishevsky–Savinov M-115M pyranometer.

The Fonovaya Observatory is located on the eastern bank of the Ob River 60 km west of Tomsk (56°25′ N, 84°04′ E) [4]. The territory is surrounded by mixed forest (birches, aspens, and Scotch pines). The large area separating the station and Tomsk is covered by coniferous trees. There are no big industrial plants near the Observatory.

The complex was gradually extended to include new instruments for measuring the gas and aerosol compositions and radiative parameters of the atmosphere. Full-scale monitoring of total solar radiation at the Fonovaya Observatory began in July 2016. For this, we used a Kipp&Zonen pyranometer CM3, measuring the solar radiative flux in the wavelength range 0.305–2.8 μm. A PQS1 sensor for measuring the photosynthetically active radiation was installed in April 2019. Our observation time series showed that the ongoing radiation processes can be studied more comprehensively if supplementing the Observatory complex with sensors for measuring the intensities of the total, ultraviolet (UV), and infrared (IR) radiation. It is noteworthy that, in complying with the World Meteorological Organization (WMO) requirements for measurements of meteorological parameters [5], sensors no worse than Good Quality (GQ) level (by WMO classification) should be used.

To ensure a reliable interpretation of data obtained from different solar radiation observation stations and networks, and transmitted to the world data centers, the WMO described the principles of measurements, developed recommendations to ensure high-quality measurements, and formulated requirements for measurements of radiation parameters [5–7]. In addition, the International Organization for Standardization (ISO), which is a developer and publisher of the international standards based on the terminology and methodology similar to those used by the WMO, developed ISO 9060:2018 standard (9060:1990) [8]: Solar energy: Specification and classification of instruments for measuring hemispherical (*total*) and direct solar radiation. The WMO and ISO standards differ insignificantly in how they specify the classification of sun radiometers; the ISO standard is primarily aimed at satisfying the specific requirements on the practical use of solar energy and instrumentation, without dwelling on details of scientific research. ISO 9060:2018 standard states a classification and specification of instruments for measuring total and direct solar radiation in the wavelength range 0.3–3 μm.

The Russian Federation is a WMO member and ISO observer. However, in the field of ensuring the integrity of measurements of spectral density of the energy brightness, spectral density of the radiation power, and the spectral density of energy irradiance of continuous optical radiation in the wavelength range from 0.2 to 25.0 μm, as well as the method for testing the instruments for measuring the energy irradiance of solar radiation, Russia adopted national standards (GOSTs R 8.861-2013 and R 8.807-2012) [9, 10]. They strongly differ from WMO and ISO standards. For instance, the methodic aspects of testing the measuring sensors and, in particular, pyranometers in the GOSTs primarily bear on the M-80m and M-115m sensors (produced as early as the former Soviet Union) or Peleng SF-06 (produced nowadays in the Republic of Belarus). The WMO and ISO standards bear on later models of thermoelectric pyranometers installed at network stations around the world; they differ in the construction of thermal battery and, in most cases, are now manufactured as double dome pyranometers (have two transparent hemispheres).

Measuring solar UV radiation is important because of its effect on the environment and human health [11–13]. UV radiation may increase on the Earth's surface because of the depletion of ozone layer [14, 15]. Total UV radiation strongly depends on clouds and, to a lesser degree, on atmospheric aerosols [16–18]. Also, the underlying surface appreciably contributes owing to multiple scattering effects. This is especially true for measurements in regions under snow cover.

The UV radiation measurements are difficult to standardize because the data obtained are used in different ways. In many countries, the UV radiation measurements are carried out not by meteorological services but in the interests of health and environmental protection. This complicates the standardization of instruments and observation methods. Therefore, the WMO also developed recommendations and standard procedures to classify and calibrate UV spectroradiometers and filter UV radiometers used to measure solar UV radiation [19–22]. The requirements for the spectral measurements of UV-B radiation were formulated in WMO report no. 32 [23].

MODERNIZATION OF THE RADIATION MEASUREMENT UNIT AT FONOVAYA OBSERVATORY

Not all manufacturers produce sensors capable of measuring in the UV, shortwave, and far-IR regions and operating year-round under the climate conditions of Western Siberia. Therefore, IAO SB RAS chose Kipp&Zonen sensors in complying with WMO requirements to instruments for atmospheric research at network stations.

In November 2020, the instrumental unit for radiation measurements at the Fonovaya Observatory was modernized to include a new group of instruments (SMP10, SUV-B, SUV5, and CNR4 manufactured by Kipp&Zonen).

To control the measurements and acquisition/transmission of information from the CM3 pyranometer and PQS1 sensor, we use the software developed earlier to support the operation of the meteorological, gas, and aerosol units of the Observatory's measurement complex [4]. The specifications and the method for controlling measurements and acquiring/transmitting data from sensors installed in 2020 are presented below.

In complying with manufacturer's requirements, all radiation sensors are installed 1.5 m above ground level (Fig. 1).

The specifications of the sensors currently used for the radiation measurements are presented in Table 1.

In contrast to the other sensors from Table 1, the CNR4 radiometer consists of a pair of pyranometers (one looking upward, and the other downward), a pair of pyrgeometers (configured likewise), and a built-in temperature sensor. The pair of pyranometers measures the shortwave fluxes of solar radiation and the radiation reflected from the Earth's surface (λ = 0.3–2.8 μm); the pair of pyrgeometers measures the longwave radiative flux, i.e., emission from the Earth and sky (λ = 4.5–42 μm). All four sensors are integrated directly into the instrument casing. The radiation balance between the incoming and outgoing radiation fluxes is determined by Eqs. (1)–(4):

$$B = Q - R_{\mathrm{sw}} - (E_{\mathrm{s}} - E_{\mathrm{a}}), \quad (1)$$

$$Q = \frac{U_Q}{S}, \quad R_{\mathrm{sw}} = \frac{U_{R_{\mathrm{sw}}}}{S} \quad (2)$$

are the total solar and reflected shortwave radiation, W/m^2; U_Q and $U_{R_{\mathrm{sw}}}$ are the output voltages, μV; S is the sensitivity of the sensors to shortwave radiation, μV/(W/m^2);

$$E_{\mathrm{s}} = \frac{U_{E_{\mathrm{s}}}}{S} + 5.67\times10^{-8}T^4, \quad E_{\mathrm{a}} = \frac{U_{E_{\mathrm{a}}}}{S} + 5.67\times10^{-8}T^4 \quad (3)$$

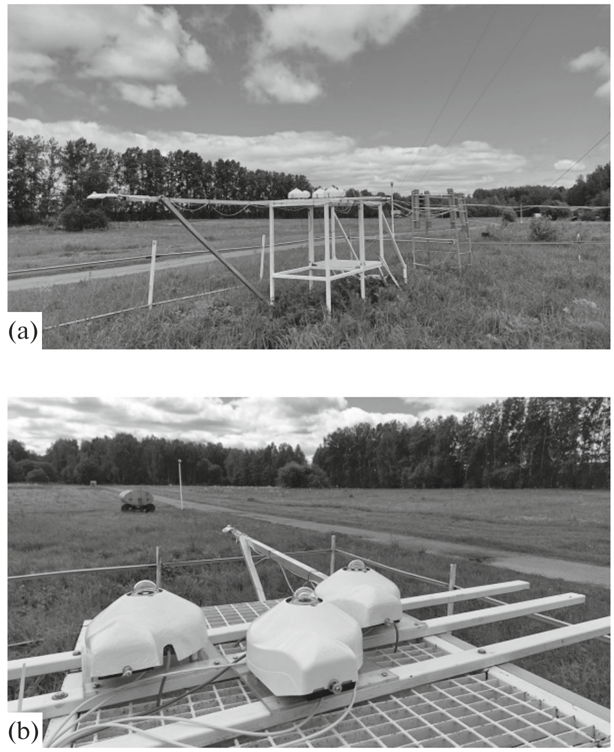

Fig. 1. Arrangement of additionally installed sensors for measuring the radiation parameters on the territory of the Fonovaya Observatory: (a) general view; and (b) sensors equipped by ventilation installation CVF4 or its analog.

are the intrinsic emission of the Earth's surface and the longwave counterradiation of the atmosphere, W/m^2; $U_{E_{\mathrm{s}}}$ and $U_{E_{\mathrm{a}}}$ are the output voltages, μV;

$$T = \frac{-\alpha + \sqrt{\alpha^2 - 4\beta\left(\frac{-R}{100} + 1\right)}}{2\beta} + 273.15 \quad (4)$$

is the temperature of the sensors, K; R is the resistance of the temperature sensor, Ω; $\alpha = 3.9080 \times 10^{-3}$; $\beta = -5.8019 \times 10^{-7}$.

Table 1. Specifications of the radiation unit at Fonovaya Observatory

Instrument/ sensor Kipp&Zonen	λ, μm	Measured parameter	Range	Error, %	Start year of measurements
CM3	0.305–2.8	Q, W/m^2	0–2000	<±2	2016
PQS1	0.4–0.7	PAR, μmol m^{-2} s^{-1}		<±2	2019
SMP10*	0.285–2.8	Q, W/m^2	0–4000	<±2	2020
SUV5*	0.280–0.400	UV, W/m^2	0–400	<±1.5	2020
SUV-B*	0.280–0.315	UV-B, W/m^2	0–9	<±2	2020
CNR4	0.3–2.8; 4.5–42	B, W/m^2	−200 to +800	<±2	2020

* Sensor is equipped by a CVF4 ventilation unit or its analog.

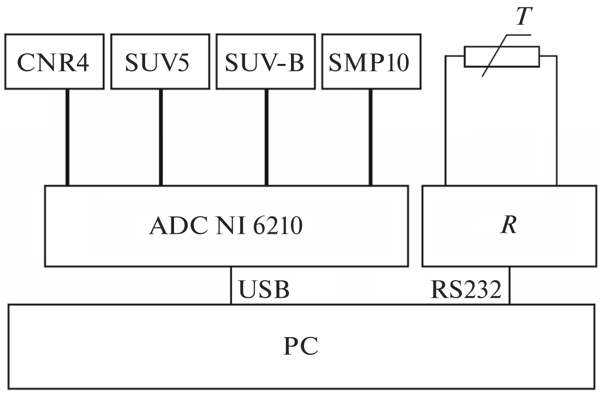

Fig. 2. Signal connection diagram of radiation and temperature sensors with the computer.

Readings from a standard temperature sensor Pt100 were used to derive data on the temperature of the CNR4 radiometer. The primary transducer of the temperature sensor is a platinum conductor, with a resistance of 100 Ω under normal temperature conditions (0°C). As the temperature of the conductor decreases (increases) in the working range, its resistance decreases (increases) according to the linear law. The measured resistance was used to calculate the temperature of the sensor.

A converter (integrated circuit MAX31865) was used for resistance digitization. Four converters (one per sensor) and a controller (ATMEGA328P) are assembled into a single casing and mounted in a heated room in the immediate vicinity of the computer used for the primary storage of the data measured by the sensors in the radiation unit at the Fonovaya Observatory. At present, only one converter (receiving data on the temperature of the CNR4 radiometer) out of four is operational; but the temperatures of other sensors will subsequently be measured via these free channels. The converters are connected to the temperature sensors via four-wire circuit, whereby the parasitic resistance of the wire can be compensated for and electromagnetic interference reduced. Linear voltage stabilizers are included in the power circuits of each MAX31865 converter.

The converters are connected to the controller via the common SPI interface, which interrogates each converter one by one. The data obtained are collected into packets and transferred to the personal computer (PC) via a USB bus once a second. A packet contains both digitized initial data (resistance) and those recalculated into temperatures, which are used as additional information in testing the instrument performance. No inquiry for data receipt from the PC is required.

The board with the converters and controller has sockets to connect four temperature sensors according to a four-wire circuit and a microUSB socket to connect to the PC. A power supply unit with an output voltage of 5 V is used.

Values of UV radiation in the wavelength range 0.280–0.400 μm and UV-B radiation in the wavelength range 0.280–0.315 μm measured by the SUV5 and SUV-B sensors are calculated as

$$\mathrm{UV} = \frac{U_{\mathrm{UV}}}{S}, \quad \mathrm{UV\text{-}B} = \frac{U_{\mathrm{UV\text{-}B}}}{S}, \tag{5}$$

where U_Q, U_{UV}, $U_{\mathrm{UV\text{-}B}}$ are the output voltages, μV.

All radiation sensors (SMP10, SUV-B, SUV5, and CNR4) are connected to a multifunctional input–output device (MIOD) in a differential mode. As was indicated above, the temperature sensor(s) is connected to the resistance converter board. Analog-to-digital converter (ADC) NI USB-6210 is used as the MIOD; it has eight analog inputs (16 bits, 250 kbit/s), four digital inputs, four digital outputs, and two 32-bit counters. The device comprises a built-in amplifier designed for rapid signal stabilization at a high scanning frequency. In all, seven out of eight analog inputs are operational in the MIOD, because CNR4 radiometer has four separate outputs for each sensor. The signal diagram of the radiation unit is presented in Fig. 2.

SOFTWARE FOR RADIATION UNIT

Original software was developed in the LabView 8.5 environment for controlling measurements, as well as for sensor-based data acquisition and transfer. This software enables the instrumental complex to operate in both automatic and manual modes. The automatic mode is implemented by specifying an algorithm for the measurements. Each step of the algorithm contains an action command and the time in which the sequence of actions should be carried out. At the end of each measurement cycle, all data obtained including service data are recorded in the primary database (DB). Then, a connection is established to the central IAO SB RAS server via a GSM channel of the cellular network, after which all data acquired during the previous stages are transmitted to a remote server, where they are recorded in the main and backup DBs.

Once a second, software interrogates the MIOD and resistance converter board and calculates the averages of all measured parameters and their standard deviations (SDs). The time over which the average is calculated is specified in software settings to be 1–60 min. After this time has elapsed (every 5 min in our case), these averages and SDs are saved into the local DB and assigned a date and end time of the five-minute measurement cycle. The general view of the local DB with the names of parameters saved is presented in Table 2.

At the end of each hour, all data collected are transmitted to the main IAO SB RAS server in Tomsk. On the server, they are placed in a common DB, then processed, and plotted on the Laboratory of Atmosphere Composition Climatology (LACC) website (https://lop.iao.ru/RU/fon/SR/). Subsequently, via the WEB interface of the LACC website, the data can be selected from the main database in a pre-

Table 2. General view of local database with names of parameters stored

Record no.	Field for parameter name	Data type	Note
1	Datetime	Timestamp	Date, time
2	CNR4_Upper_pyr	Float	Average value of primary data, voltage at pyranometer
3	CNR4_Upper_pyr_sko	Float	SD
4	CNR4_Low_pyr	Float	Average value of primary data, voltage at pyranometer
5	CNR4_Low_pyr_sko	Float	SD
6	CNR4_Upper_pyg	Float	Average value of primary data, voltage at pyranometer
7	CNR4_Upper_pyg_sko	Float	SD
8	CNR4_low_pyg	Float	Primary data, voltage at pyranometer
9	CNR4_low_pyg_sko	Float	SD
10	SMP10	Float	Average value of primary data, voltage at pyranometer
11	SMP10_sko	Float	SD
12	SUVB	Float	Average value of primary data, voltage at UV–B radiometer
13	SUVB_sko	Float	SD
14	SUV5	Float	Average value of primary data, voltage at UV radiometer
15	SUV5_sko	Float	SD
16	R_CNR4	Float	Resistance of thermistor
17	R_CNR4_sko	Float	SD
18	T_CNR4	Float	Calculated temperature
19	T_CNR4_sko	Float	SD
20–31	–	Float	Resistance of thermistor and SD, calculated temperature and SD for SMP10, SUVB, and SUV5 sensors*
32	CNR4_upper_pyr_W	Float	Calculated power of total radiation
33	CNR4_upper_pyr_W_sko	Float	SD
34	CNR4_low_pyr_W	Float	Calculated power of reflected shortwave radiation
35	CNR4_low_pyr_W_sko	Float	SD
36	CNR4_upper_pyg_W	Float	Calculated power of longwave counterradiation of the atmosphere
37	CNR4_upper_pyg_W_sko	Float	SD
38	CNR4_low_pyg_W	Float	Calculated power of intrinsic Earth's emissions
39	CNR4_low_pyg_W_sko	Float	SD
40	SMP10_W	Float	Calculated power of total radiation
41	SMP10_W_sko	Float	SD
42	SUVB_W	Float	Calculated power of UV–B radiation
43	SUVB_W_sko	Float	SD
44	SUV5_W	Float	Calculated power of UV radiation
45	SUV5_W_sko	Float	SD
46	CNR4_B	Float	Calculated Earth's radiation balance
47	CNR4_B_sko	Float	SD
48	mode0	Char(50)	Notes

* Temperature of these sensors is not measured at present.

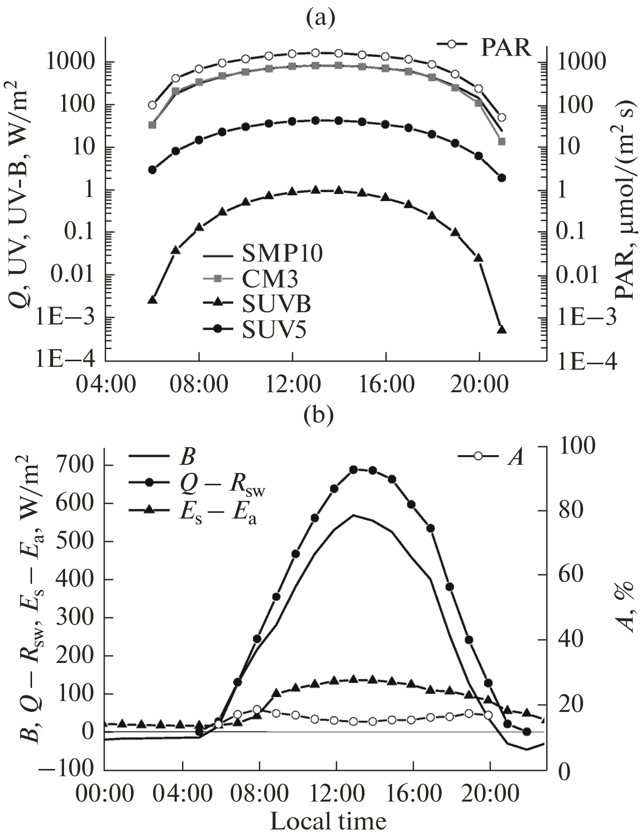

Fig. 3. Results obtained using the radiation complex on July 22, 2021: (a) total solar radiation (SMP10 and CM3), UV radiation (SUV5), UV-B radiation (SUVB), photosynthetically active radiation (PAR); (b) radiation balance (*B*), shortwave balance ($Q - R_{sw}$), longwave balance ($E_s - E_a$), and surface albedo (*A*).

scribed time interval. If necessary, hourly, diurnal, and monthly averaging options are allowed for in a chosen time interval.

As an example, Fig. 3 presents the results obtained at the radiation complex on July 22, 2021. Yearly measurements from the radiation complex will be presented in the second part of this paper.

CONCLUSIONS

The radiation complex at the Fonovaya Observatory has been modernized. At present, the measurement complex provides measurements of total solar, UV, and UV-B radiation, as well as radiation, shortwave, and longwave balances, surface albedo, and photosynthetically active radiation.

Specially for the new set of sensors, we created unique software which allow one to control the measurement process, acquire, record, and process the measured parameters, and transmit them to the common database.

The instruments showed good quality of measurements and reliable operation in autonomous mode under different weather conditions throughout the year. Sensors equipped with a CVF4 ventilation unit or its analogs were not subjected to the deposition of solid precipitation on the dome of receiving part during wintertime operation.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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