INSTRUMENTS AND METHODS OF MEASUREMENT

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# Relation of gamma dose rate with the intensity of rain showers

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Experimental and theoretical studies of the influence of the intensity, amount and duration of liquid atmospheric precipitation on the formation of $\gamma$-background in the surface layer of the atmosphere are presented. It was observed that precipitation causes an increase in the $\gamma$-radiation dose rate in the form of bursts. In this case, the total amount of precipitation in an event determines the magnitude of the burst of the dose rate, and the intensity of precipitation determines the rate of increase in the dose rate of $\gamma$-radiation. A mathematical model, which establishes a quantitative relationship between the dose rate of $\gamma$-radiation and the intensity (amount) of liquid atmospheric precipitation has been developed and verified ($R^2$ = 0.93).

*Keywords: gamma-radiation, gamma-background, radon decay products, precipitation, atmosphere, mathematical model.*

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## Introduction

The monitoring of $\gamma$-radiation background of the surface layer of the atmosphere has been carried out for many decades. It has been shown that the $\gamma$-dose rate is not constant in time and space and depends on various factors such as the state of the atmosphere, time of day, season and geological and geographical characteristics of

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the investigated region [1, 2, 3, 4, 5]. It has also been repeatedly found that periods of precipitation are accompanied by anomalous increases (bursts) of $\gamma$-radiation background [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. This phenomenon is explained by the processes of washing out of short-lived $\beta$- and $\gamma$-emitting decay products of radon and thoron from the atmosphere onto various surfaces (soil, various coatings) and known as "radon washout"[3].

Attempts to find a quantitative relationship between the intensity of precipitation and the magnitude of bursts of $\gamma$-radiation dose rate were undertaken earlier [2, 7, 9, 17, 18], but no significant relationship was found. Perhaps this was due to the insufficient temporal resolution of the data [19]. Additionally, the washout capability of precipitation depends on rainfall duration and intensity [10, 20, 21]. In [5], the absence of a significant relationship between the intensity of precipitation and the magnitude of bursts of $\gamma$-radiation dose rate was explained that during precipitation the atmosphere is cleared and the amount of radon decay products decreases. Consequently, the next event with the same intensity will result in less precipitated radon decay products.

The "rainout-washout"model developed in [2], which divides the atmosphere into two parts of in-the-cloud and under-the-cloud, has not yet received experimental confirmation. Moreover, it significantly complicates theoretical calculations due to the many poorly known input parameters of the model.

A number of models, each with different levels of complexity and based on different assumptions, have been developed to analyse rainfall-related radon progeny peaks in the ambient gamma dose considering the various processes involved [2, 6, 16, 17]. Nevertheless, there is still no mathematical model describing the relationship between the excess in dose rate and the mean value of intensity or amount of precipitation in one event.

To establish a quantitative relationship between the intensity, the amount of liquid atmospheric precipitation and the magnitude of the burst of the radiation $\gamma$-background of the surface atmosphere, radiation monitoring must be synchronized with the measurement of the dynamics of precipitation intensity. Measurements must be made with a good temporal resolution, allowing for not only qualitative, but also quantitative analysis. In addition, the equipment for radiation and meteorological monitoring should not be far apart [15].

Considering the above, the goal of our work was to develop a mathematical model establishing a quantitative relationship between the dose rate of $\gamma$-radiation and the characteristics of precipitation.

## Experiment equipment

In 2017, starting from snow melt and until the beginning of the establishment of snow cover, the $\gamma$-radiation dose rate and the $\gamma$-radiation flux density were measured with a high data sampling rate of 1 minute, using the BDKG-03 scintillation detector (manufactured by ATOMTEX, Republic of Belarus). The BDKG-03 detector contains a NaI(Tl) scintillator with dimensions ⌀25x40 mm as a sensitive element. The range of registered $\gamma$-radiation energies is from 50 keV to 3 MeV. BDKG-03 detectors were installed at the experimental sites of geophysical observatory of Institute of Monitoring of Climatic and Ecological Systems of Siberian Branch of the Russian Academy of Science on a meteorological mast at heights of 1 m, 5 m and 10 m, and also on the roof of the building at a height of 21 m. In this work, we will consider only the data of a $\gamma$-radiation detector installed at a height of 1 m from the earth's surface. Precipitation intensity data with a high temporal resolution were recorded by the Davis Rain Collector II shuttle rain gauge (Davis Instruments, USA), the WXT520 meteorological station (Vaisala, Finland), and the OPTIOS optical (laser) rain gauge [22]. The volumetric activity of radon isotopes and daughter products of their decay in the atmosphere was monitored by an EQF 3200 radiometer (SARAD, Germany) installed at a distance of about 10 m from the meteorological mast at a height of 1 m from the earth's surface. Periodic measurements of the volumetric activity of radon isotopes and daughter products of their decay were carried out by the measuring complex "Alfarad plus - AR"(OOO NTM-Zashchita, Moscow, RF). To measure the radon flux density from the soil surface, an Alfarad plus-AR radiometer was used complete with an autonomous blower and an accumulation chamber.

Further in this work, we will consider only the process of washing out of the radon decay products (DPs) by precipitation (under-the-cloud).

## Reaction of $\gamma$-background on liquid precipitation

During the period of studies of the dynamics of the dose rate of $\gamma$-radiation, the flux density of $\gamma$-radiation in the near-ground atmosphere, the intensity and amount of liquid atmospheric precipitation, bursts in the $\gamma$-background were detected. These bursts occurred synchronously with the periods of precipitation. The general picture of synchronously appearing bursts in the atmospheric $\gamma$-background at an altitude of 1 m and rainfall precipitation in summer 2017 is illustrated in Fig. 1.

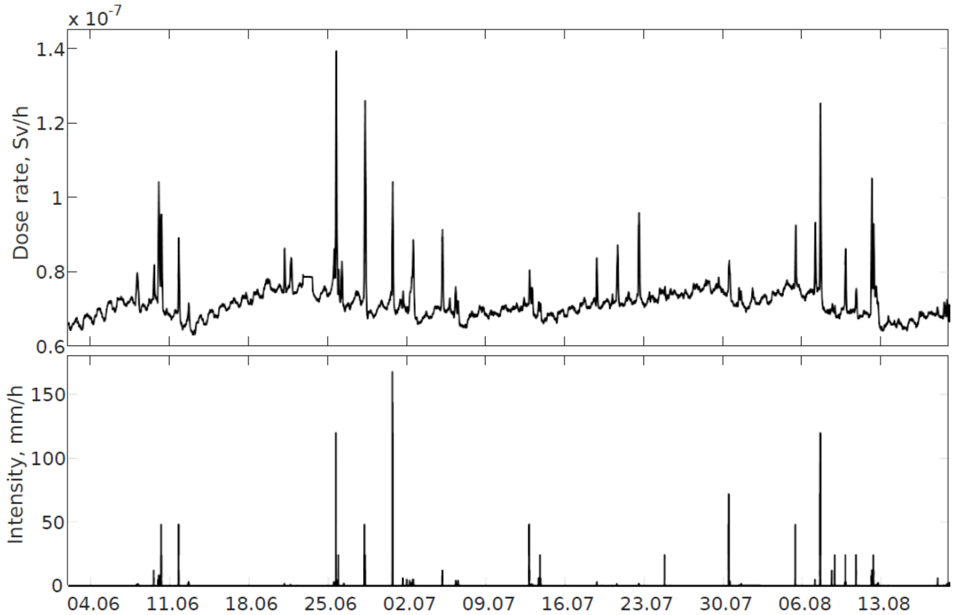


Fig. 1. An example of different shapes of the bursts of the $\gamma$-radiation background. First is $\gamma$-background in Sv/h; Second is the intensity of precipitation in mm/h

A detailed analysis of long-term experimental data on the $\gamma$-background showed that all the detected bursts that do not have a certain periodicity are caused by precipitation (excluding bursts caused by errors in the operation of the $\gamma$-radiation detectors). Analysis of the experimental data (Fig. 1) showed that the magnitude of the burst in the $\gamma$-background does not always correlate with the intensity of precipitation $I(t)$, as well as the amount of precipitation $Q(t)$, which is in good agreement with the experimental data on the $\gamma$-background [7, 9, 17].

Next, we will consider in more detail the structure of an individual burst and a series of bursts in the $\gamma$-background and analyze the effect of rain shower, taking into account the change in the meteorological state of the surface atmosphere on the dose rate of $\gamma$-radiation. The analysis of the results of the experiment to study the effect of heavy rain showers on the radiation background of the surface atmosphere allowed us to determine that the rate of increase in the dose rate of $\gamma$-radiation, which is characterized by the derivative $d\bar{y}/dt$, is determined by the current intensity of precipitation $I(t)$. Also we founded that the total amount of precipitation $Q(t)$ determines the magnitude of the burst in the dose rate of $\gamma$-radiation. I was obtained that the time of the end of precipitation corresponds to the maximum in the burst of the dose rate of $\gamma$-radiation, and after the end of precipitation, the dose rate quasi-exponentially decreases to the background value due to the radioactive decay of $^{214}$Pb and $^{214}$Bi.

The obtained experimental results formed the basis for a model for quantitative assessment of the characteristics of rain showers based on data on the change in the dose rate of $\gamma$-radiation radiation.

## The Model for determining the intensity of rain shower from the $\gamma$-background of the surface atmosphere

The burst in the dose rate is caused by the $\gamma$-radiation of the short-lived daughter decay products of radon $^{214}$Pb and $^{214}$Bi deposited by precipitation on the earth's surface, as the main contributors to the total dose rate, in comparison with other decay products of radon and thoron.

Analysis of both experimental data and theoretical material from the field of nuclear physics and the interaction of ionizing radiation with matter allows us to assert that the magnitude of the burst in the dose rate of $\gamma$-radiation $\Delta\dot{H}$ (dose rate excess), $\mu Sv/h$, is proportional to the activity $A^{s}_{DPs}$, Bq/m$^2$, of radionuclides washed out onto the earth's surface, each of which makes a constant contribution to the total dose rate $\dot{H}$ of $\gamma$-radiation of the surface atmosphere at a certain height R, m, from the earth's surface, depending on the nuclear-physical characteristics of the radionuclide.

$$\Delta\dot{H}(R) \sim A^{s}_{DPs}. \tag{1}$$

The value of $\Delta\dot{H}$ can be determined from experimental data (at R=1 m) as

$$\Delta\dot{H} = \dot{H}_{end} - \dot{H}_{b}, \tag{2}$$

where $\dot{H}_b$ is the value of the dose rate of $\gamma$-radiation at the moment of the beginning of the fallout of liquid atmospheric precipitation, which is defined in the data time series as a point after which a continuous increase in the dose rate is observed during the time tend to the maximum value of $\dot{H}_{end}, \mu Sv/h; \dot{H}_{end}$ is the maximum value of the $\gamma$-radiation dose rate in the "burst", $\mu Sv/h$.

The dose rate of $\gamma$-radiation created at a distance R from the earth's surface (as a radionuclide source) by a certain j-th radionuclide of unit activity $\dot{H}^{1\ Bq}_{j}$ is a constant value, i.e. constant for the j-th radionuclide [23].

So, knowing the activity of deposited on the earth's surface radionuclides and dose coefficients per unit activity $\dot{H}_j^{1Bq}$ or these radionuclides at R=1 m, it is possible to establish an exact equality between the measured burst value (excess) of the dose rate of $\gamma$-radiation and the activity of radionuclides washed out onto the earth's surface:

$$\Delta\dot{H} = \sum_{j=1}^{n} \dot{H}_j^{1Bq} \cdot A_j^s, \quad \mu Sv/h, \tag{3}$$

where $j$ is a radionuclide and $n$ is the amount of deposited radionuclides.

The quantity $\dot{H}_j^{1Bq}$, called the dose-equivalent rate per unit of activity for $j$-radionuclide at a specified distance $R$ from a radiating object of arbitrary geometric shape, can be calculated using the specific gamma-ray dose constant (SGRDC) [23] from equations described in [24, 25, 26], as well as with the help of GEANT4.

For this work, the dose coefficients for $^{214}$Pb and $^{214}$Bi were calculated using GEANT4 [27] at an altitude of $R = 1$ m from the earth's surface for a disk source with a radius of 500 m, taking into account the lower threshold for registration of $\gamma$-radiation by the BDKG-03 detectors equal to 50 keV. The standard set of physical processes QGSP_BIC_HP built into GEANT4 was used with some modification for our task, similar to the example "extended/radioactivedecay/rdecay02" from the GEANT4 library. The statistics were 20 billion events for each individual calculation (radionuclide). Dose coefficients were:

$$\dot{H}_{Pb-214}^{1\ Bq} = 8.48 \cdot 10^{-7}, \frac{\mu Sv/h}{Bq/m^2}; \tag{4}$$

$$\dot{H}_{Bi-214}^{1\ Bq} = 4.86 \cdot 10^{-6}, \frac{\mu Sv/h}{Bq/m^2}. \tag{5}$$

The activity $A_{DPs}^s$ of deposited by precipitation on the earth's surface radionuclides will be determined by making the assumption that in the clouds the activity of the decay products of radon $^{214}$Pb and $^{214}$Bi is negligible, or they almost decayed during the cloud movement, and it can be neglected. In this case, the activity $A_{DPs}^s$ of deposited radionuclides depends on their total activity in the atmosphere, the intensity and duration of precipitation, or the amount of precipitation. If we consider an air column with a base of 1 m$^2$ and a height of h, m, then the activity of radionuclides deposited on the earth's surface over the entire period of precipitation will be determined from the expressions:

$$A_{Pb-214}^s = \int_0^h (A_{Pb-214}^a(z) \cdot Q \cdot k_1 \cdot k_2) dz = A_{Pb-214}^{ah} \cdot I \cdot t_{end} \cdot k_1 \cdot k_2, \quad Bq/m^2; \tag{6}$$

$$A_{Bi-214}^s = \int_0^h (A_{Bi-214}^a(z) \cdot Q \cdot k_1 \cdot k_2) dz = A_{Bi-214}^{ah} \cdot I \cdot t_{end} \cdot k_1 \cdot k_2, \quad Bq/m^2; \tag{7}$$

where $k_1$ is the coefficient of the absolute washout capability of precipitation, equal to 36 $m^{-1}$ ($10^{-5}$ $h/(mm \cdot s)$) [28], $m^{-1}$; $k_2$ is the coefficient of the relative washout capability of precipitation, equal to 2.8 for a rain shower, 1 – for rain, 4.5 – for drizzle [28], rel. units; $Q$ is the amount of precipitation in one event, m; $I$ is the average intensity of precipitation, m/s; $t_{end}$ is the duration of precipitation, s; $A_{Pb-214}^a(z)$ and $A_{Bi-214}^a(z)$ are the functions of the volumetric activity distribution of $^{214}$Pb and $^{214}$Bi with height $z$ in the atmosphere, $Bq/m^3$; $A_{Pb-214}^{ah}$ and $A_{Bi-214}^{ah}$ are the integral values of the volumetric activities of $^{214}$Pb and $^{214}$Bi in the atmospheric column with a base of 1 $m^2$ and a height of $h$, $Bq/m^2$.

When a radioactive equilibrium is reached in the atmosphere between radon and its short-lived decay products, and at $h \to \infty$, $A^{ah}_{Pb-214}$ and $A^{ah}_{Bi-214}$ can be determined by the value of the radon flux density from the soil surface $q_{Rn}, Bq \cdot m^{-2} \cdot s^{-1}$, from a simple relation

$$A^{ah}_{Pb-214} = A^{ah}_{Bi-214} = q_{Rn}/\lambda_{Rn} \tag{8}$$

where $\lambda_{Rn}$ is the radioactive decay constant of radon $^{222}$Rn, $s^{-1}$.

The values of $A^{ah}_{Pb-214}$ and $A^{ah}_{Bi-214}$ can also be calculated knowing the distribution functions of $^{214}$Pb and $^{214}$Bi with height, for example, from the equations for the transfer of radon isotopes and their decay daughter products in the surface atmosphere.

Let us open the left and right sides of equality (3), using expressions (6), (8), and take into account that $^{214}$Pb and $^{214}$Bi are the main dose-forming radionuclides of the short-lived decay products of radon isotopes. We obtain the final formulas for assessing the average values of the amount and intensity of liquid atmospheric precipitation for one event:

$$Q = \frac{\lambda_{Rn} \cdot \Delta\dot{H}}{q_{Rn} \cdot k_1 \cdot k_2 \cdot (\dot{H}^{1Bq}_{Pb-214} + \dot{H}^{1Bq}_{Bi-214})}, \quad m; \tag{9}$$

$$I = \frac{\lambda_{Rn} \cdot \Delta\dot{H}}{q_{Rn} \cdot k_1 \cdot k_2 \cdot t_{end} \cdot (\dot{H}^{1Bq}_{Pb-214} + \dot{H}^{1Bq}_{Bi-214})}, \quad m/s; \tag{10}$$

The proposed model makes it possible to determine both the intensity of liquid atmospheric precipitation in m/s (mm/h) and their amount in m (mm), it is suitable for both single measurements and for long-term automated monitoring of the intensity of the liquid phase of precipitation, if dosimeters or $\gamma$-radiation detectors operating in monitoring mode.

Since $\Delta\dot{H}$ in equation (9) end (10), it is determined by a simple difference (see equation (2), due to this, (9) does not take into account the radioactive decay occurring with Pb-214 and Bi-214. In order to obtain corrections for the radioactive decay occurring in rainwater, it is necessary to create groups of differential equations. One of which will not take into account radioactive decays:

$$\begin{cases} \dfrac{dA^s_{Pb-214}(t)}{dt} = L(t) \cdot A^h_{Pb-214}(t), \\ \dfrac{dA^s_{Bi-214}(t)}{dt} = L(t) \cdot A^h_{Bi-214}(t) \end{cases} \tag{11}$$

where $L(t) = I(t) \cdot k_1 \cdot k_2$ is a function of the washout coefficient versus time. And the second one takes into account radioactive decays:

$$\begin{cases} \dfrac{dA^s_{Pb-214}(t)}{dt} = L(t) \cdot A^h_{Pb-214}(t) + \lambda_{Pb-214} \cdot A^s_{Po}(t) - \lambda_{Pb-214} \cdot A^s_{Pb-214}(t), \\ \dfrac{dA^s_{Bi-214}(t)}{dt} = L(t) \cdot A^h_{Bi-214}(t) + \lambda_{Bi-214} \cdot A^s_{Pb-214}(t) - \lambda_{Bi-214} \cdot A^s_{Bi-214}(t). \end{cases} \tag{12}$$

To find the correction coefficients, we divide the right parts of group equation (12) to the corresponding right-hand parts of the system (11). That is:

$$\begin{cases} k_{Pb-214}(t) = \frac{L(t)\cdot A^h_{Pb-214}(t)+\lambda_{Pb-214}\cdot A^s_{Po}(t)-\lambda_{Pb-214}\cdot A^s_{Pb-214}(t)}{L(t)\cdot A^h_{Pb-214}(t)}, \\ k_{Bi-214}(t) = \frac{L(t)\cdot A^h_{Bi-214}(t)+\lambda_{Bi-214}\cdot A^s_{Pb-214}(t)-\lambda_{Bi-214}\cdot A^s_{Bi-214}(t)}{L(t)\cdot A^h_{Bi-214}(t)}. \end{cases} \tag{13}$$

where $k_{Pb-214}(t)$ is a coefficient that takes into account the processes of changing the activity of Pb-214 in rainwater; $k_{Bi-214}(t)$ is a coefficient that takes into account the processes of changing the activity of Bi-214 in rainwater. Now rewrite the equation (11) and the subsequent one taking into account the obtained coefficients:

$$Q = \frac{\lambda_{Rn}\cdot \Delta\dot{H}}{q_{Rn}\cdot k_1\cdot k_2\cdot(\dot{H}^{1Bq}_{Pb-214}\cdot k_{Pb-214}(t)+k_{Bi-214}(t)\cdot\dot{H}^{1Bq}_{Bi-214})}, \quad m; \tag{14}$$

$$I = \frac{\lambda_{Rn}\cdot \Delta\dot{H}}{q_{Rn}\cdot k_1\cdot k_2\cdot t_{end}\cdot(\dot{H}^{1Bq}_{Pb-214}\cdot k_{Pb-214}(t)+k_{Bi-214}(t)\cdot\dot{H}^{1Bq}_{Bi-214})}, \quad m/s; \tag{15}$$

For convenience, in Table 1, we present the coefficients found depending on the duration and intensity of precipitation.

*Table 1*

**The coefficients $k_{Pb-214}; k_{Bi-214}$ depending on the duration (D) and intensity of precipitation**

| D, min. | Precipitation intensity, mm/h | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.5 | 1 | 3 | 5 | 7 | 10 | 20 | 30 | 40 | 50 | 100 |
| 10 | .97;.99 | .93;.95 | .95;.97 | .96;.98 | .95;.97 | .92;.93 | .90;.92 | .89;.91 | .87;.89 | .85;.86 | .72;.74 |
| 20 | .94;.99 | .89;.94 | .89;.94 | .88;.93 | .88;.93 | .83;.88 | .81;.85 | .78;.82 | .73;.77 | .70;.73 | .52;.54 |
| 30 | .89;.98 | .82;.90 | .83;.90 | .81;.89 | .80;.87 | .77;.84 | .71;.77 | .66;.72 | .63;.68 | .57;.62 | .41;.44 |
| 40 | .77;.88 | .77;.87 | .76;.86 | .73;.83 | .72;.82 | .69;.78 | .63;.70 | .58;.64 | .52;.58 | .48;.53 | .33;.35 |
| 50 | .74;.86 | .74;.85 | .73;.84 | .70;.81 | .69;.79 | .65;.75 | .59;.67 | .54;.61 | .48;.54 | .44;.50 | .29;.32 |
| 60 | .66;.78 | .64;.76 | .63;.75 | .61;.72 | .59;.7 | .57;.67 | .51;.6 | .43;.5 | .39;.45 | .35;.40 | .23;.25 |
| 70 | .48;.58 | .48;.58 | .47;.57 | .45;.54 | .44;.53 | .40;.49 | .37;.44 | .33;.39 | .29;.34 | .27;.31 | .17;.19 |
| 80 | .35;.44 | .34;.42 | .34;.42 | .33;.42 | .32;.40 | .31;.38 | .27;.33 | .25;.30 | .22;.26 | .20;.23 | .13;.14 |
| 90 | .26;.33 | .25;.33 | .25;.32 | .24;.31 | .24;.30 | .22;.28 | .21;.26 | .18;.22 | .16;.20 | .15;.18 | .09;.11 |
| 100 | .19;.25 | .19;.25 | .18;.24 | .18;.23 | .17;.22 | .16;.21 | .15;.19 | .13;.17 | .12;.15 | .11;.13 | .07;.09 |
| 110 | .14;.19 | .13;.18 | .13;.18 | .13;.17 | .13;.17 | .12;.16 | .11;.14 | .09;.12 | .08;.11 | .08;.10 | .05;.06 |
| 120 | .1;.14 | .1;.14 | .1;.13 | .09;.13 | .09;.13 | .08;.12 | .08;.11 | .07;.09 | .06;.08 | .06;.07 | .04;.05 |

## The model verification

The model for determining the intensity and amount of liquid precipitation from the values of the $\gamma$-radiation dose rate measured at a height of 1 m from the earth's surface was verified using the data of radiation and geophysical monitoring carried out in 2017. For the analysis, 44 precipitation events were selected.

To verify the model, the following precipitation events were not taken into account: a) precipitation leading to complex responses in the $\gamma$-background with 2 or more maxima; b) precipitation that does not give a clearly defined "peak"in comparison with the detector noise. After filtering out these events, only 44 cases remained, associated with rain shower and an increase in the dose rate (pulse counting rate) of $\gamma$-radiation, for which the average values of the intensity and amount of precipitation were calculated.

The average value of the radon flux density from the soil surface measured during the period under consideration varied in the range from $18.2\pm5.5$ to $27.6\pm8.3$ $mBq\cdot m^{-2}\cdot s^{-1}$. The comparison of the mean values of the rain shower intensity calculated by the model and measured by the shuttle precipitation gauge precipitation events is shown in Figure 2.

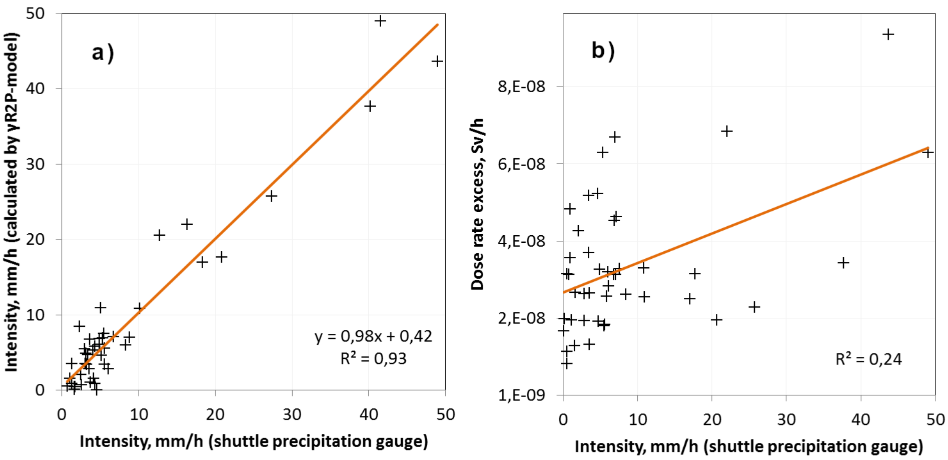


Fig. 2. Comparison of the average precipitation intensity for the event, measured by the shuttle precipitation gauge and: a) intensity estimated by the model; b) dose rate excess $\Delta\dot{H}$, with the linear regression (solid line)

Regression analysis (linear regression in Fig. 2a) showed goodness of fit between theoretical and experimental data on the average precipitation intensity for the event. Despite the fact that not all clouds were of the same origin (frontal cloudiness, air-mass cloudiness or mesoscale systems), the proposed the model showed good efficiency for its application in practice, proved by the linear regression coefficient ($R^2$ = 0.93) between the measured and estimated values of the mean per event intensity.

In order to reliably verify that there is no correlation between bursts in the gamma background and the intensity of precipitation, which, as it was believed earlier, should exist, Fig. 2b shows a comparison of the excess of the gamma dose rate over the background $\Delta\dot{H}$ measured at the burst maximum and measured by the shuttle precipitation gauge of average values of the intensity of showers for the same events. R-squared value found to be 0.24 reliably confirms this.

Reducing the sampling rate of the data leads to an increase in the error. In order to obtain a higher temporal resolution while maintaining the error at the same level or less, it is necessary to use more sensitive detector (for example, NaI(Tl) scintillator with a larger sensitive volume). This will make it possible to more accurately identify areas in the dynamics of the $\gamma$-background with different growth rates (slope of the derivative).

## Conclusion

Analysis of the results of a 7-month experiment to study the characteristics of the reaction of the atmospheric $\gamma$-background to liquid atmospheric precipitation made it possible to establish a quantitative relationship between the dose rate of $\gamma$-radiation and the characteristics of precipitation, and draw the following conclusions: i) the rate of increase in the dose rate of $\gamma$-radiation during a period of heavy rainfall, or the dose rate time derivative, is determined by the current intensity of precipitation $I(t)$; ii) the total amount of precipitation $Q(t)$ that fell during one event determines the magnitude of the burst (excess over the $\gamma$-background level) of the $\gamma$-radiation dose rate; iii) the timing of the end of precipitation, followed by the radioactive decay of the radionuclides $^{214}$Pb and $^{214}$Bi deposited on the earth's surface, is determined by the time of the onset of the maximum in the burst of the dose rate of $\gamma$-radiation.

To establish a quantitative relationship between the dose rate of $\gamma$-radiation and the intensity (amount) of rain shower, a mathematical model was developed. Verification of this model for 44 rain shower events selected for the period under study showed good efficiency proved by the linear regression coefficient ($R^2$ = 0.93) between the measured and estimated values of the average rainfall intensity for the event.

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**Contribution and Responsibility.** All authors contributed to this article. Authors are solely responsible for providing the final version of the article in print. The final version of the manuscript was approved by all authors.

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ПРИБОРЫ И МЕТОДЫ ИЗМЕРЕНИЙ

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# Связь мощности дозы гамма-излучения с интенсивностью ливневых осадков

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Представлены экспериментальные и теоретические исследования влияния интенсивности, количества и продолжительности жидких атмосферных осадков на формирование $\gamma$-фона в приземном слое атмосферы. Было замечено, что осадки вызывают увеличение мощности дозы $\gamma$-излучения в виде всплесков. В этом случае общее количество осадков в событии определяет величину всплеска мощности дозы, а интенсивность осадков определяет скорость увеличения мощности дозы $\gamma$-излучения. Разработана и проверена математическая модель, устанавливающая количественную связь между мощностью дозы $\gamma$-излучения и интенсивностью (количеством) жидких атмосферных осадков ($R^2$ = 0,93).

*Ключевые слова: гамма-излучение, гамма-фон, продукты распада радона, осадки, атмосфера, математическая модель.*

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