Published by IOP Publishing for Sissa Medialab
Received: *January 20, 2022*
Revised: *March 19, 2022*
Accepted: *April 23, 2022*
Published: *May 30, 2022*

# Radioactive source strength effect on gamma radiation monitoring with a NaI (Tl) scintillation detector

**E. Yeboah,[a,*] G.A. Yakovlev,[b] S.V. Smirnov[c] and V.S. Yakovleva[a]**

[a] *National Research Tomsk Polytechnic University, 30, Lenina Avenue, 634050, Tomsk, Russia*
[b] *Tomsk State University, 36, Lenina Avenue, 634050, Tomsk, Russia*
[c] *Institute of Monitoring of Climatic and Ecological Systems of Siberian Branch of the Russian Academy of Sciences, 10/3 Academichesky Avenue, 634055, Tomsk, Russia*

*E-mail:* eugeniayeboah64@gmail.com

Abstract: The accurate monitoring of gamma radiation doses in the environment has become essential due to its effect on human health. In this study, the temperature dependence of NaI (Tl) scintillation detectors based on the daily/annually measured dose rate in the environment as well as the importance of selecting the appropriate radioactive source strength when calibrating NaI (Tl) detectors for gamma radiation monitoring were investigated. The temperature correction coefficients discovered during the calibration of the BDKG-03 detector by Atomtex were verified, and whether the time duration of the measurement interval has an effect on readings of gamma radiation was also investigated in the city of Tomsk. NaI (Tl) scintillation detectors were used to monitor the gamma background radiation in the environment. The detectors were calibrated with both high and low radioactive sources to obtain a temperature correction coefficient in order to stabilize the influence of temperature change on the detector at different time intervals. This was used to study the correlation between the daily and annual dose rates of low gamma background radiation. The results showed that there was a shift in the spectrum of the daily and annual dose rates calculated using the algorithm obtained when the detector was calibrated with a highly radioactive source to the position of the constant coefficient for low-level dose. However, the ones obtained when the detector was calibrated with a low radioactive source and that of the constant coefficient for a low-level dose overlapped each other. This demonstrated that the type of radioactive source used in detector calibration during manufacture has an effect on the temperature correction coefficient, which in turn has an effect on the accuracy of the ambient dose rate when used to monitor gamma radiation. The duration of the time interval for measurement was found to be very important since it has an effect on dose rate readings.

Keywords: Detector alignment and calibration methods (lasers, sources, particle-beams); Gamma detectors (scintillators, CZT, HPGe, HgI etc); Radiation monitoring

[*] Corresponding author.


https://doi.org/10.1088/1748-0221/17/05/P05041

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## Contents



## 1 Introduction

The scintillation detector is one of the world's oldest radiation detectors for ambient radiation monitoring [1]. Scintillation detectors such as Thallium-activated Sodium Iodide scintillation detectors [NaI (Tl)] are used to monitor radiation levels in an open environment [2].

Temperature has a significant impact on the properties of inorganic scintillators because they are vulnerable to weather conditions. The influence of temperature on radiation detectors has been extensively studied, indicating that they are affected by temperature and thus necessitate the use of a temperature correction coefficient [3]. The temperature effect is so significant that it necessitates a spectrum process to correct it [4]. When the ambient temperature is significantly higher than the room temperature, the temperature dependence of crystal performance is most noticeable. Temperature has a different effect on each scintillation crystal. Petroleum logging is one example of an industrial application that has a small temperature effect on the detector. Scintillation crystals such as NaI (Tl), BGO, and CSI (Na) are intended for use in high-temperature environments and are thus temperature-sensitive [5].

All radiation detectors must be calibrated properly in order to function properly. When using scintillation detectors for gamma radiation monitoring, the calibration technique is separated into three steps [6]: energy calibration, resolution calibration, and efficiency calibration. These calibrations allow for accurate identification and determination of the activity of the isotopes in question. One of the common procedures for assessing the external exposure of humans in the case of environmental contamination with technogenic gamma-ray emitting radionuclides is the direct measurement of the gamma dose rate in air using a gamma-ray dosimeter [7].

NaI (Tl) detectors are inexpensive and have high performance, so they can be used for gamma spectrometry to identify radionuclides. Their main disadvantage, however, is gain instability at high temperatures, not their low resolution. This is why temperature correction coefficients are embedded in the detectors to eliminate this effect. They are used in environmental monitoring to detect low count rates from weak radioactive sources [8]. It is well understood that the light yield of NaI (Tl) scintillators changes as a function of temperature [9] and is thus temperature dependent [10]. This is because at low temperatures, the light yield increases and decreases at room temperatures [11]. In addition, when using NaI (Tl) detectors, the channel shift of low background peaks is affected by the ambient temperature and the acquisition time [12], which can be resolved by utilizing the stabilization procedure. Primarily, short peak shaping times and high temperatures cause thermal instability in NaI (Tl) scintillators [13].

Over the years, it has been discovered that the photomultiplier (PMT) scintillation detectors are temperature dependent [14]. Temperature changes cause gain shifts in detectors, but most detectors have built-in active system gain stabilization. This aids in maintaining energy resolution and energy calibration in the face of temperature changes in the environment. The effective stabilization of detectors suitable for outdoor use is vital because the temperature outside changes dramatically over time due to strong and sudden changes in the ambient temperature. A temperature stabilization test is performed because every detector should be able to withstand temperatures ranging from −30 to +55°C [15, 16]. This test is done by calibrating the detector with a radioactive source or background radiation. Usually, the test is conducted in an environmental climatic chamber [17]. A spectrum process is required to correct the significant effect of temperature on scintillators. The methods employed are needed to return shifted and recorded spectrums to their reference spectrums [18]. This helps to eliminate the effect of temperature variation when taking readings. The most essential factor to consider when carrying out this process is the overall system's linearity, which allows linear operations to be carried out [19].

Casanovas et al. (2012) used two methods to stabilize the energy spectrum measured. They used experimental data obtained in a laboratory under controlled conditions to correct the spectrum in the first method, whereas one known peak in the spectrum was used to correct the channel in the second method. After conducting their experiments, they validated the results obtained from using these methods. The results they obtained for both methods of stabilization of the detectors were acceptable. Padányi et al. (2020) investigated the temperature dependence of detector characteristics when using NaI (Tl) detectors and compared calculated results. The comparison revealed a small deviation, leading them to conclude that their method was adequate.

The BDKG-03 is a type of scintillation detector used by students at the National Research Tomsk Polytechnic University to monitor gamma radiation in the environment. The results obtained using this detector for monitoring of low gamma background radiation raised concerns about the accuracy of the count per minute (cpm) used in the factory algorithm; this led to the suggestion that the detectors may have been calibrated with high activity radioactive sources [22]. The accuracy of $\gamma$-radiation measurement depends greatly on temperature when using a scintillation detector by ATOMEX Inc. for measurement [23]. Monitoring of count rate and $\gamma$-background radiation levels is very poor when using BDKG-03 for radiation monitoring due to temperature changes [24].

In this work, a study was carried out to investigate the temperature dependence of NaI (Tl) scintillation detectors based on the daily/annually measured dose rate in the environment as well as the importance of selecting the appropriate radioactive source strength when calibrating NaI (Tl) detectors for gamma radiation monitoring. The temperature correction coefficients found during the calibration of the BDKG-03 detector by ATOMEX Inc. were verified, and whether the time duration of the measurement interval has an effect on readings of gamma radiation was investigated.

## 2 Materials and methods

### 2.1 Instrument and conditions of experiment

An inorganic gamma scintillation NaI (Tl) detector, BDKG-03 (manufactured by ATOMTEX in Belarus), was used for collecting data. The scintillator NaI (Tl) is ⌀25 mm × 40 mm in size and the overall dimensions of the detector are ⌀60 mm×299 mm. It is a portable detector that measures the ambient gamma equivalent dose rate and an equivalent dose ranging from 0.03–300 µSv/h and 0.03 µSv–10 mSv, respectively. Using a USB connector, the detector was linked to a laptop with "Atexch" software installed on it. The software provides data on the dose, dose rate, count rate, and their respective errors [25]. The detector has an operating temperature of −30 to +50°C with an energy of 662 keV for gamma dose rate monitoring. It has a relative uncertainty of ±20 % for $^{137}$Cs of energy of 662 keV. The detector was calibrated using a $^{137}$Cs gamma radioactive source during manufacture of the detector.

The experiment was performed in a climatic chamber TYR 3626 with a volume of about 1000 L, a temperature ranging from -60 to +60 and a relative humidity of up to 98 %. The climatic chamber has a humidity accuracy of ±1 % RH and ±0.5°C accuracy of temperature fluctuation. The experiment was performed using natural background radiation instead of artificial radioactive sources such as $^{137}$Cs and $^{60}$Co due to doubts in the results obtained when the detector calibrated with $^{137}$Cs was used for monitoring the gamma dose of low background radiation. The detector was calibrated at a temperature range of −40 to +40°C.

### 2.2 Methodology

The experiment was conducted in the Tomsk region, located in Russia, using a climatic chamber. The experiment was performed twice under the same conditions. For the first experiment, two scintillation detectors were placed inside the climatic chamber and the dose rate and count rate of natural gamma background radiation were measured for temperatures ranging from −40 to +40°C at an interval of 5°C. Measurements were taken after a time interval of 1 min. The second experiment was conducted using only one detector of the same type at the same temperature range of −40 to +40°C but at an interval of 10°C and a time interval of 5 min.

At the end of the experiment, the temperature correction coefficient and the experimental algorithm were obtained and were used to calculate the dose rate of low gamma background radiation. The algorithm obtained by calibrating the detector with a low radioactive source for calculating dose rate is referred to as the experimental algorithm, whereas that obtained by calibrating the detector with a high radioactive source is referred to as the factory's algorithm. The factory's algorithm was obtained by calibrating the detector with $^{137}$Cs. The experimental algorithm and the factory's algorithm were both used to calculate the readings and investigate the correlation with changes in the meteorological parameters of low dose rate gamma background radiation taken in Tomsk in



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2019. The data for temperature, $T$ for the year 2019 was taken from http://rp5.ru/8218/ru. The dose rate was calculated from the measured count rate by using the experimental algorithm and the factory's algorithm. A graph of the dose rate calculated from the algorithm obtained by calibrating the detector with a high gamma radioactive source (experimental algorithm) and a low activity calibration source (factory algorithm) was plotted and compared to the dose rate calculated from the constant coefficient of low gamma background radiation for both the annual and daily measured dose rates. A correlation between temperature and the daily measured dose rate was also investigated.

### 2.3 Calculations for the dose rate

The dose rate measured by the detector is generally calculated using the formula:

$$H = N \times k(T) \tag{2.1}$$

Where $H$ denotes the dose rate, $N$ denotes the count rate, and $k(T)$ denotes the temperature correction coefficient. The temperature correction coefficient is temperature dependent due to the detector's temperature instabilities.

The experimental algorithm (obtained by calibrating the detector with a low gamma background) for calculating of the dose rate was calculated using the formula:

$$H_{\exp(1)} = N \times (1.12 \times 10^{-3} T + 1.562) \text{ (nSv/h)} \tag{2.2}$$

$$H_{\exp(2)} = N \times (3.34 \times 10^{-4} T + 1.622) \text{ (nSv/h)} \tag{2.3}$$

$$H_{\exp(3)} = N \times (8.43 \times 10^{-4} T + 2.126) \text{ (nSv/h)} \tag{2.4}$$

Where $H_{\exp(1)}$ and $H_{\exp(2)}$ denotes the experimental algorithm for low dose for the first experiment, $H_{\exp(3)}$ denotes the experimental algorithm for low dose for the second experiment, and $T$ denotes temperature.

Equation (2.1) compared with equation (2.2), (2.3) and (2.4), implies that:

$$k_1(T) = (1.12 \times 10^{-3} T + 1.562) \text{ (nSv/h)/(imp/s)} \tag{2.5}$$

$$k_2(T) = (3.34 \times 10^{-4} T + 1.622) \text{ (nSv/h)/(imp/s)} \tag{2.6}$$

$$k_3(T) = (8.43 \times 10^{-4} T + 2.126) \text{ (nSv/h)/(imp/s)} \tag{2.7}$$

$k_1(T)$ and $k_2(T)$ denotes the temperature correction coefficient for low dose for the first experiment, $k_3(T)$ denotes the temperature correction coefficient for low dose for the second experiment and (imp/s) — impulse per second is the unit for count rate.

The constant coefficient for calculating the low gamma dose rate for daily variation was calculated using the formula:

$$H_{\text{daily}} = N \times K2 \tag{2.8}$$

Where $H_{\text{daily}}$ is the constant coefficient for calculating the low gamma dose rate for daily variation, and $K2$ is the temperature correction coefficient for daily variation.

K2 was calculated using the formula:

$$K2 = \frac{\text{Average daily dose rate}}{\text{Average daily count rate}} = 1.87 \text{ (nSv/h)/(imp/s)} \tag{2.9}$$



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Where average daily dose and count rate is the average of the total gamma dose and count rate measured on daily basis.

The constant coefficient for calculating the low gamma dose rate for annual variation was calculated using the formula:

$$H_{\text{annual}} = N \times K1 \tag{2.10}$$

Where $H_{\text{annual}}$ denotes the constant coefficient for calculating the low gamma dose rate for annual variation, and $K1$ is the temperature correction coefficient for annual variation.

K1 was calculated using the formula:

$$K1 = \frac{\text{Average annual dose rate}}{\text{Average annual count rate}} = 1.69\,(\text{nSv/h})/(\text{imp/s}) \tag{2.11}$$

Where average annual dose and count rate is the average of the total gamma dose and count rate measured yearly.

## 3 Results and Discussions

### 3.1 Finding the experimental algorithm of the three detectors

The measurements of count rate and dose rate are shown in figure 1. A nonlinear dependence was observed for the three detectors according to the measurement of the dose rate. The results of the dose rate obtained showed a weak dependence on temperature for areas of low doses. The uncertainty for measurements taken for a time interval of 1 minute for count rate and dose rate ranges from ±4.00 to 6.00 % and ±11.00 to ±12.00 % respectively, whereas that of 5 minutes ranges from ±2.20 to 2.27 % and ±4.93 to ±5.37 % respectively. The error for both count rate and dose rate for measurements taken at 1 minute time interval was larger than that of 5 minutes. In addition, the measurement of dose rate and count rate for 1 minute was more distorted than that of 5 minutes. As shown in figure 2, the built-in algorithm of the temperature correction coefficient during the manufacture of the three detectors showed an unreliable result. The graphs were divided into two ranges of −40 to −20°C and −15 to +40°C to obtain two equations for the temperature correction coefficient for each detector during the environmental readings, which is not supposed to be the case since each detector is described by one formula. Hence the need for a new expression for the temperature correction coefficient.

The dependence of the dose rate calculated without using the built-in temperature correction factor is shown in figure 3. The dose rate was calculated using that of the ambient temperature. There was a weak dependence for the measurement taken for 1 minute, but the measurement taken for 5 minutes showed a strong dependence. This shows that the duration of the measurement of dose rate is very important for the accuracy of the results obtained. An equation for the graph of the three detectors was found and this was used to derive equation (2.2)–(2.4).

### 3.2 Dose rate calculated from the factory's algorithm

Figure 4 presents the daily dose rate dependence on atmospheric temperature. This shows that the factory's algorithm is unsuitable for calculating low gamma background radiation because the scintillation detector is usually affected by temperature. This raised concerns about the accuracy of



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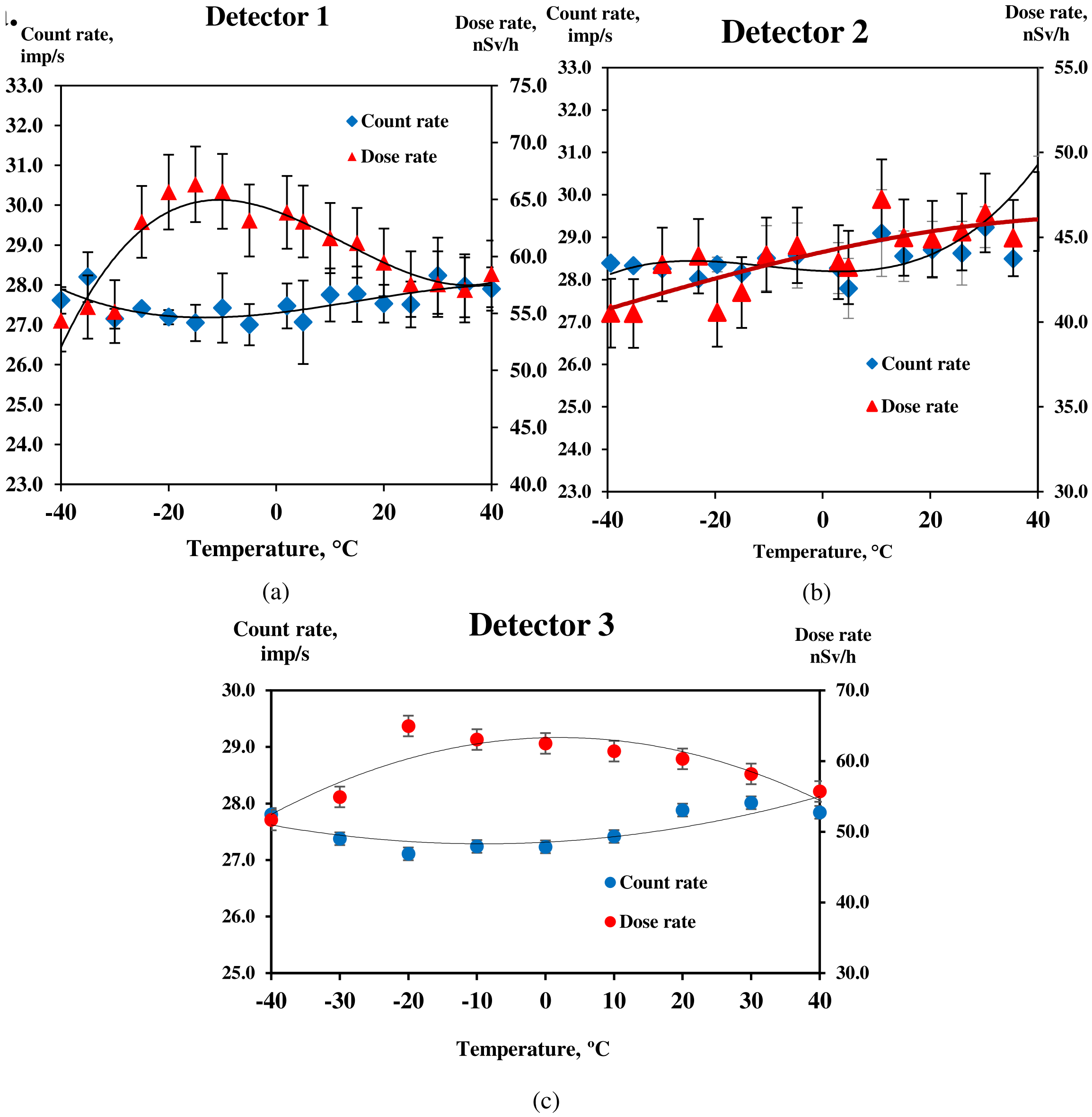
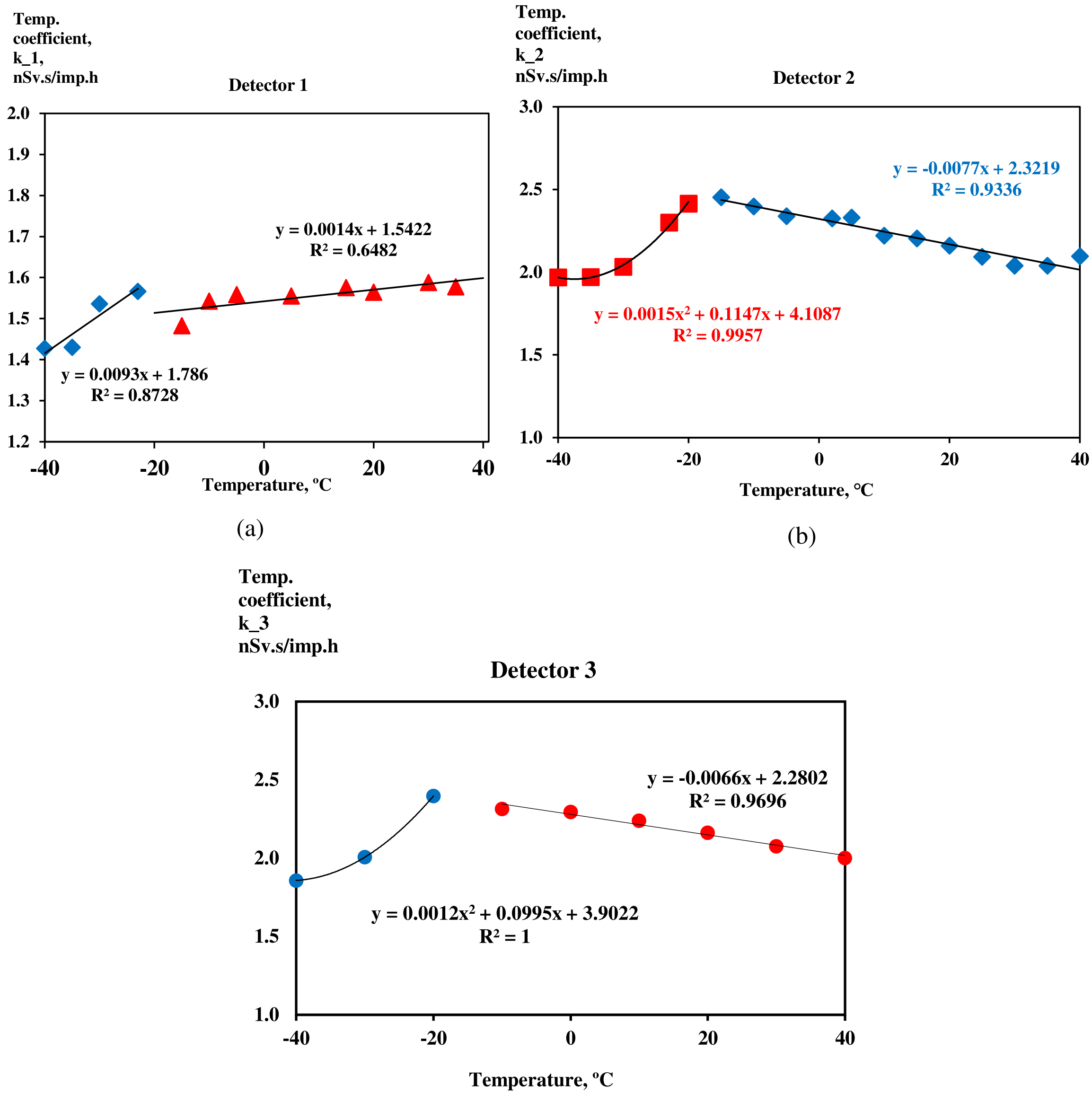



**Figure 1.** Count rate and dose rate of the three detectors taken at a time interval of a) 1 minute for detector 1, b) 1 minute for detector 2, c) 5 minutes for detector 3.

the algorithm for converting pulses to dose when a detector calibrated with a high activity radioactive source is used to monitor low gamma background radiation.

Figures 5 and 6 compare the dose rate calculated from the factory algorithm (shown in blue) versus the constant coefficient (shown in red) for both annual and daily variation, respectively. The data showed that there was a shift in the spectrum of the annual and daily variations of dose rate calculated using the factory algorithm to the position of that of the constant coefficient. This is because the constant coefficient is used to calculate the dose rate for low gamma background radiation, whereas the factory's algorithm was derived by calibrating the detector with a radioactive source of high activity. This shows that the detector was still affected by temperature change when



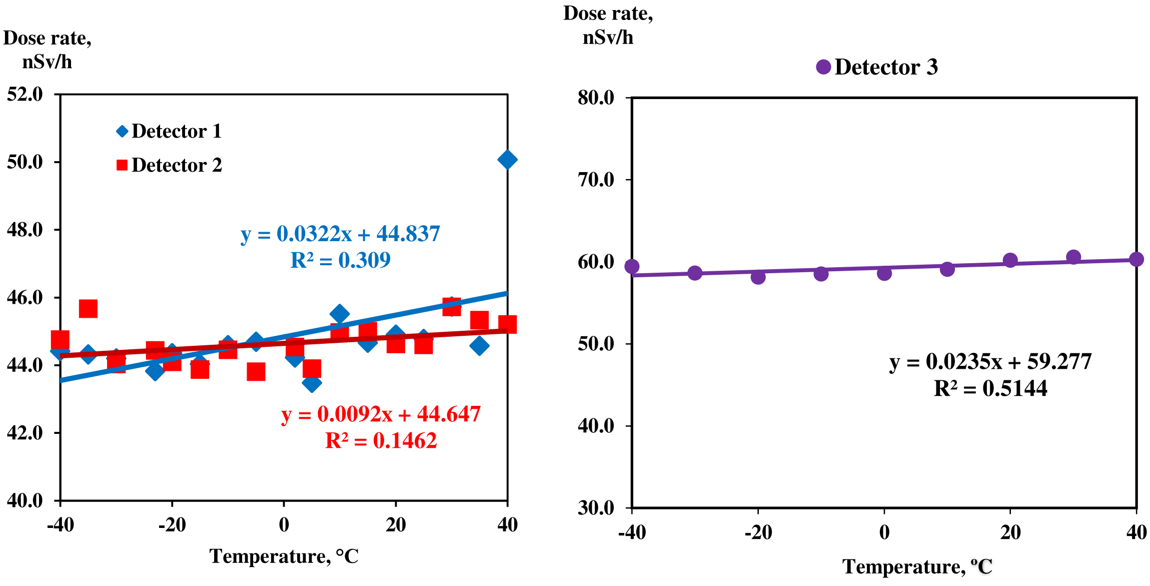

(c)

**Figure 2.** Temperature correction coefficient used when the three detectors were manufactured.

the factory's algorithm was used. In addition, there was a burst in the reactions of gamma dose to rain and snow for the annual variation, whereas that of the daily variation shows a different trend. This, once again, raised concerns about the algorithm's accuracy in converting pulses to doses when the detector calibrated with high gamma activity is used to measure gamma radiation of low dose.

### 3.3 Dose rate calculated from experimental algorithm

Figure 7 compares the dose rate calculated when using the factory's algorithm and the experimental algorithm to calculate the dose rate for low background radiation. When the detector calibrated with a high gamma radioactive source was used to measure low gamma background radiation under the




(a) (b)

**Figure 3.** Dose rate calculated from ambient conditions.

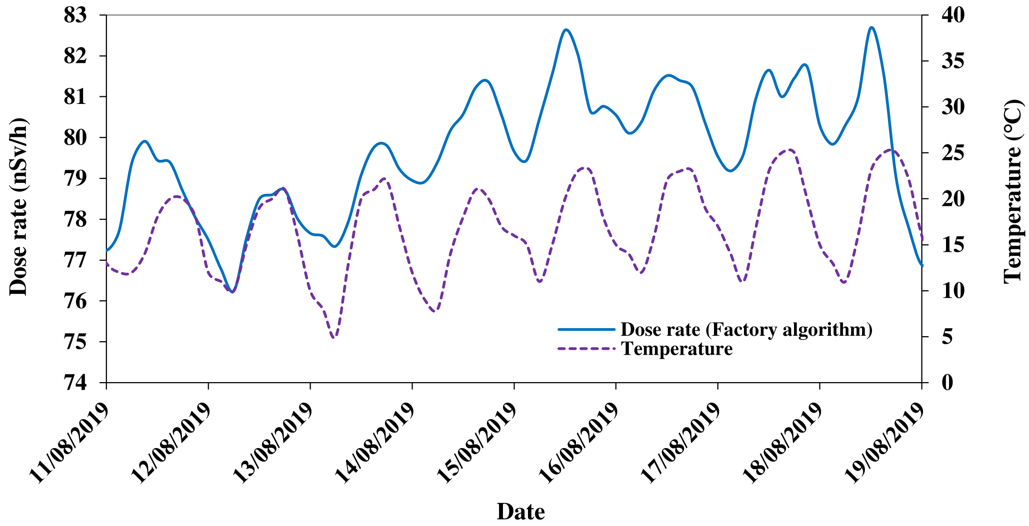



**Figure 4.** Daily variation of dose rate from high activity radioactive source calibration algorithm (indicated in blue) as a function of atmospheric temperature (indicated in violet).

same conditions, the dose rate calculated by the factory's algorithm was higher. This is not expected to be the case because the level of gamma radiation in the environment is the same, hence the dose rate measured is expected to be the same or with a very small uncertainty. This shows that a NaI (Tl) gamma detector calibrated using a highly radioactive source does not give accurate results when used to measure radiation with a low gamma background.

Figures 5 and 6 were replotted using the experimental algorithm (equation (2.4) obtained by calibrating the detector with a low-activity calibration source for a time interval of 5 minutes.

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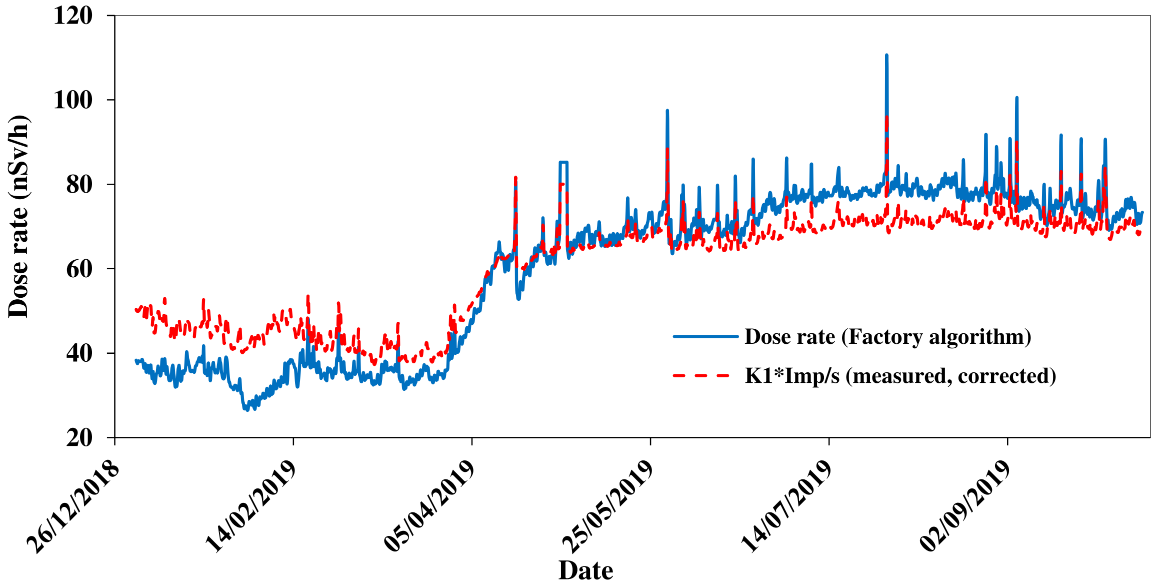



**Figure 5.** Annual variation of dose rate from high activity radioactive source calibration algorithm and the constant coefficient algorithm.

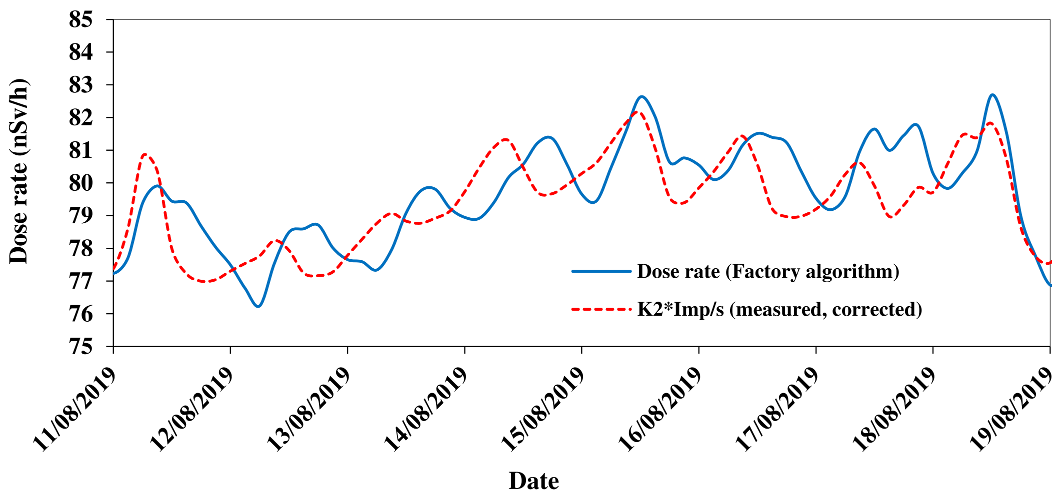



**Figure 6.** Comparison of the daily measured dose rate calculated using the factory algorithm (high activity radioactive source) and the constant coefficient algorithm.

They were used to calculate the dose rate instead of the factory's algorithm to aid in investigating the influence of calibrating a detector with a high and low radioactive source when using the BDKG-03 scintillation detector for gamma radiation monitoring. Figures 8 and 9 compare the dose rate calculated from the experimental algorithm (indicated in green) and the constant coefficient (indicated in red) for both annual and daily variation, respectively. From the graph, the spectrum of the experimental algorithm overlapped with that of the position of the constant coefficient. This is because the detector was calibrated with gamma radiation of low activity, which allowed us to obtain a temperature correction coefficient (equation (2.7) that can remove the effect of temperature

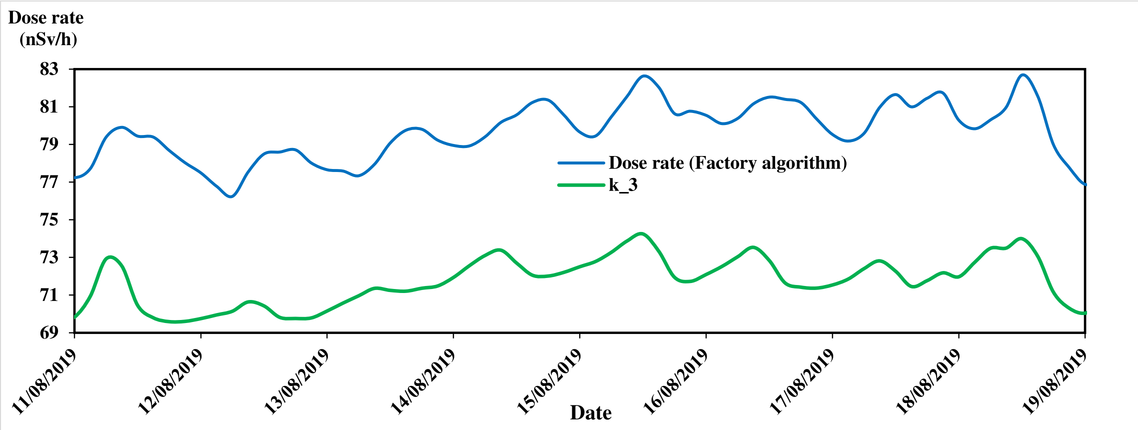



**Figure 7.** Comparison of the daily measured dose rate calculated using the experimental algorithm (low activity radioactive source) and the factory algorithm.

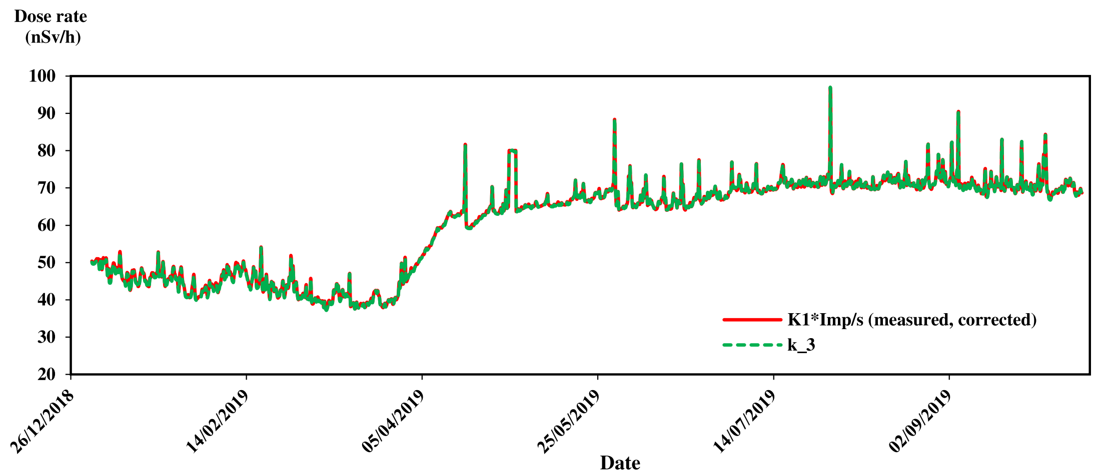



**Figure 8.** Comparison of the annually measured dose rate calculated using the experimental algorithm and the constant coefficient algorithm.

change and can be used to calculate low dose. This demonstrates that when a NaI (Tl) gamma detector is calibrated with a gamma radioactive source of low activity, it can only be used for monitoring low-level gamma radiation and that the effect of temperature change on the detector during measurement has been removed. Furthermore, when calibrated with a high activity radioactive source, it can be used to monitor only high-level radiation.

### 3.4 Duration of measurement

Time duration is a very important factor when it comes to the taking of measurements for dose rate. The annual dependence the of dose rate calculated using the temperature correction coefficient (equations (2.5) and 2.6) for measurement of time intervals of 1 minute is shown in figure 10. The results obtained showed that there was a shift in the spectrum of the dose rate calculated using the temperature correction coefficient in equations (2.5) and (2.6) to that of the position of the constant

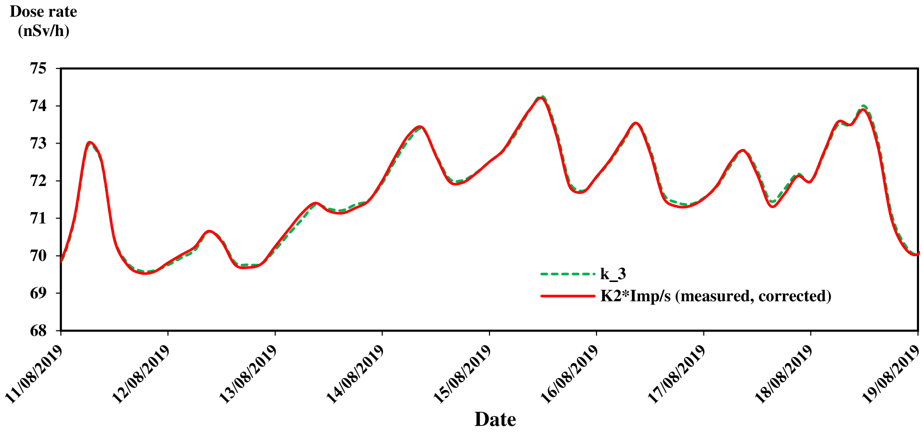
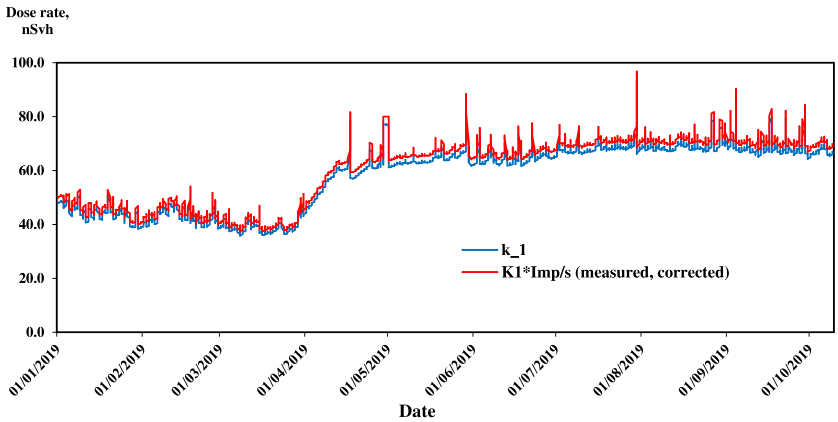
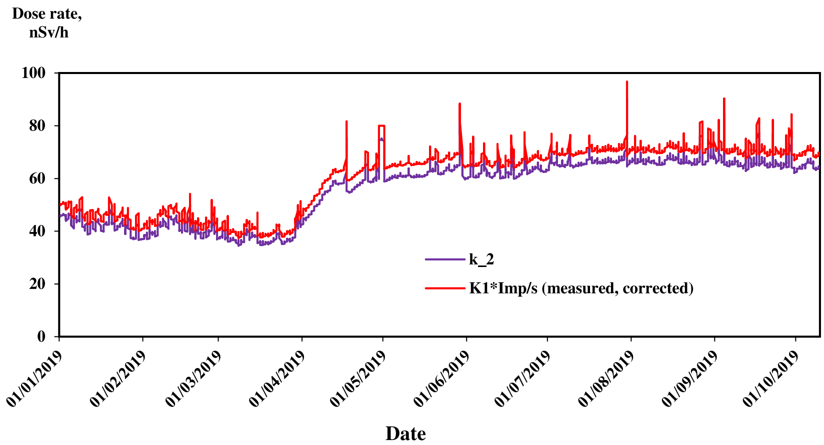



**Figure 9.** Comparison of the daily measured dose rate calculated using the experimental algorithm (low activity radioactive source) and the constant coefficient algorithm.




(a)




(b)

**Figure 10.** Dose rate calculated using temperature correction coefficient for time interval of 1 minute a) for $k_1(T)$ b) for $k_2(T)$

coefficient even though the detector was calibrated using a gamma activity of low background. Though the deviation between figure 8 and figure 10 is very small, the shift was due to the duration of the time interval of measurement. This shows how the time duration interval for the measurement of dose rate is very important.

### 3.5 Temperature correction coefficient

The high and low activity radioactive sources are used to calibrate the NaI (Tl) detector in order to obtain a temperature correction coefficient to correct the peak shift caused by temperature variations. The dose rates were calculated by multiplying the temperature correction coefficient by the count rates. Figure 11 compares the temperature correction coefficients of the detector when calibrated with a high and low gamma radioactive source. The graph shows that the temperature correction coefficient of the low gamma radioactive source corrects the peak shift, whereas the temperature correction coefficient of the high radioactive source does not correct the peak shift when used to measure low-level gamma radiation. This demonstrates that the temperature correction coefficient is strongly influenced by the type of radioactive source used in detector calibration. This also demonstrates that the detector calibrated with a high activity radioactive source can only be used to monitor high-level radiation and not low-level radiation.

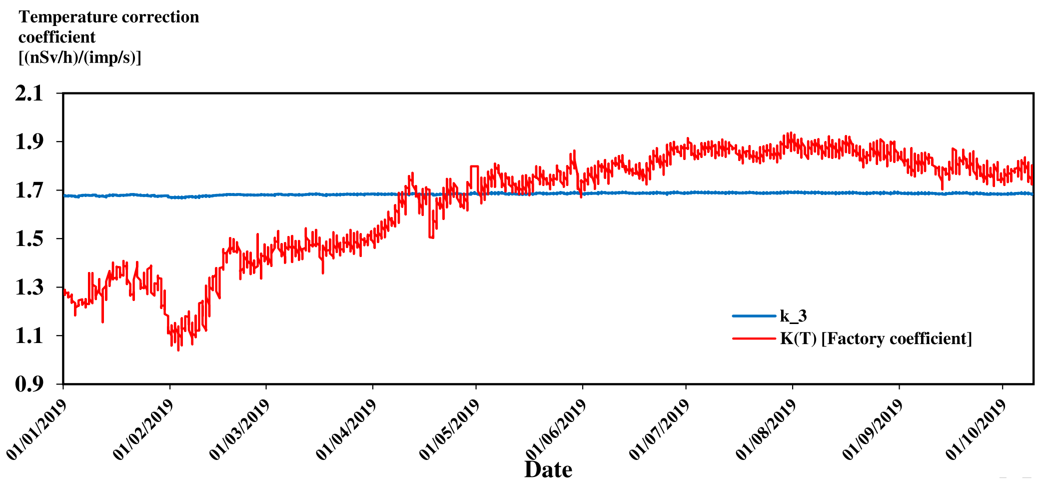



**Figure 11.** Comparison of the detector's temperature correction coefficients when calibrated with a high and low activity radioactive source.

## 4 Conclusion

In this work, we presented a method for investigating the effect of calibrating a detector with a low or high activity radioactive source on background gamma radiation monitoring based on daily and annually measured dose rates as well as the effect of the time duration of the measurement interval on readings of gamma dose rates.

This study shows that the count rate and dose rate for the measurements taken at a time interval of 1 minute were more distorted with greater uncertainty than those taken at 5 minutes. This demonstrates that to get an accurate reading of dose rate with less error, the time duration for each measurement



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has to be longer. The built-in algorithm gave unreliable results, hence the need for a new expression for the temperature correction coefficient. In addition, temperature has an effect on the readings of a scintillation radiation detector because the coefficient for calculating dose rate is temperature dependent. The temperature correction coefficient, which is used to correct peak shifts caused by temperature variations, is dependent on the type of radioactive source used to calibrate the detector.

The fact that there was a shift in the spectrum of the daily and annual dose rates calculated using the factory algorithm to the position of the constant coefficient indicates that the factory algorithm was unreliable. This is because the detector was calibrated with a high activity radioactive source, whereas the constant coefficient is used to calculate dose rate with a low activity radioactive source. Furthermore, the difference between the dose rate calculated using the experimental algorithm and that of the constant coefficient was relatively small, demonstrating the importance of the radioactive source used in the calibration of the NaI (Tl) detector. This demonstrates that the temperature correction found in this study can only be used for calculating the dose rate of low gamma dose and that the temperature correction coefficient embedded in the detector during manufacture can only be used for calculating the dose rate of high gamma dose.

In order to obtain accurate results when using the NaI (Tl) scintillation detector (BDKG-03) for gamma radiation monitoring, it is crucial to know the type of radioactive source used in calibrating the detector.


## Acknowledgments

The work was performed using equipment of TPU and IMCES SB RAS.

**Funding.** This research was supported by TPU development program.


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