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Assessment and Accuracy Improvement of Pyroelectric Sensors (Eco-Counter) Based on Visitors Count in National Park. The Case: Monitoring System of Tourist Traffic in Stołowe Mountains National Park, Poland

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***Abstract* – The monitoring of tourist traffic helps to manage tourism in national parks. Today park managers and researchers use many different devices and technologies that facilitate data collection. Among these often used devices is the pyroelectric sensor. Despite its high degree of usefulness, this type of sensor can miscalculate. Therefore, there is a need to assess the magnitude of errors and the circumstances in which they occur. The purpose of the study was to evaluate pyroelectric sensor counting errors in relation to different visitor flow levels and time intervals between visitors. The study was based on a field experiment and on-site observations using pyroelectric sensors, part of the Monitoring System of tourist traffic (MSTT) in Stołowe Mountains National Park in Poland. The outcome of the assessment was the errors sizes and types and calibration formula. Pyroelectric sensors more often overcount than undercount. Errors occur in larger than 6-visitor groups and time intervals between visitors shorter than 3 seconds. Finally, the analysis of the causes of errors gave the ground to generate the typology of error circumstances. The calibration formula was generated based on a field experiment and on-site observation. The average error size was reduced from ±13 % to ±6 %. The calibration formula provided in the study is simple and universal and can be applied to other data.**

***Keywords* – Calibration; eco-counter; monitoring; national park; pyroelectric sensor; visitor flow**

1. INTRODUCTION

Global, nature-based tourism intensification is a trend that has been increasing in recent years, therefore creating the need to count visitors in more sensitive to human impact mountain ecosystems. This includes national parks, which are highly valuable natural areas and have the potential to attract large numbers of visitors. The sustainable management of vulnerable natural areas requires accurate measurement of visitor flow, especially in mountain areas and protected natural areas [1]. The monitoring of visitors is regarded as an important component of recreation management [2]–[6]. The aim of natural area management is to ensure the sustainability of sensitive natural areas such as mountain areas featuring important habitats and this demands accurate estimates of the number of visitors in specified

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time periods [1]. Many different types of automated systems for visitor flow counting are currently in use all over the world, but many tend to be used more often in urban spaces [7] and natural areas, especially in mountain national parks [4], [8]–[12]. According to Andersen *et al*. [1], the most often used counting system in Scandinavia (several hundred counters in use) and the United Kingdom (more than 2 000 counters in use) is a pyroelectric sensor that features a lens sensitive to heat radiation emitted by the human body (Eco-Counter model: PYRO sensor called counter). The aforementioned counter was selected for several important reasons: they are waterproof, function over a wide range of temperatures (from −40 °C to +50 °C), record the direction of visitors' approach, can both record and store data at either every 1 hour or 15 minutes, and maintenance is easy and cost-effective. An important challenge with automatic counting systems is their accuracy, since all types of counters are subject to counting errors [11], [13], [14]. Field tests conducted in this study as well as by other research teams showed that infrared sensors usually count significantly fewer visitors than their actual number [14].

This paper focuses on visitor counting accuracy in national parks situated in mountain areas that are also some of the most popular tourist areas. It illustrates the attention to detail required to carry out accurate visitor counting. The purpose of the study was to evaluate the accuracy of pyroelectric sensor measurement errors in relation to different visitor flow levels and different time intervals between visitors. This verification was based on field experiments and on-site observations of the pyroelectric sensors working as part of the Monitoring System of tourist traffic (MSTT) in Stołowe Mountain National Park (SMNP). The system consists of 39 pyroelectric sensors located in the vicinity of the most popular attractions in order to assess the spatiotemporal characteristics of visitor flow throughout the entire calendar year [15]. This evaluation of accuracy was performed to yield calibration formulas. The method for generating these formulas is shown at the further part of this article.

SMNP is located in the Sudety Mts. chain found in southwestern Poland. The unique physical appearance of the Stołowe Mts. stands in stark contrast to many other mountain massifs in the Sudety Mts. chain. The SMNP is the second most popular tourist destination in the Sudety Mts. According to the MSTT, is visited by about 900,000 tourists per year. The highest and most popular attraction is Mount Szczeliniec Wielki, where the MSTT recorded almost 300 000 visitors per year [16], [17]. In mountain areas, it is difficult to collect data over a longer period of time. In addition, field and weather conditions may yield a higher error rate.

2. Literature Review

Accurate and reliable visitor traffic data are an essential component of science-based protected area management [18]. Several studies have documented the fact that there is some amount of error associated with all visitation data collected via automated visitor monitors [13], [19]. Counter accuracy is subject to qualitative errors caused by physical movement that does not represent actual visitors, and technical errors caused by certain characteristics of the given counter and the installation site itself [6]. For the calibration of automatic counters, a human performed manual counting was used [19]–[22]. Another approach used to calibrate automatic counters is to use a video- or camera-based system triggered by a traffic counter [22] or step counter [23].

Despite the prevalence of studies involving the use of automated visitor monitors and the inherent error in visitor use counts recorded with these devices, few studies have documented specific calibration methods to convert raw data to reliable visitation estimates. Watson *et al*. [22] provide the most thorough description including discussion of sampling methods to

calibrate monitors as well as basic statistical analyses to estimate visitor counts from automated counter data. Bates *et al*. [24] used pyroelectric monitors to estimate visitor counts in Rocky Mountain National Park (NP) in the U.S.A. and conducted observation-based calibration counts over three days during the 2004 summer season. Both studies [22], [24] conclude that it is necessary to calculate accurate estimates of visitors. Calibration of automated visitor counters through direct observations is performed in order to calculate accurate visitor numbers. Factors that contribute to data errors include the physical aspects of the monitoring locations (e.g., trail gradient and width) [11]. Hlavackova *et al*. [25] indicated sources of deviation between the measured and actual number of passages: (i) road width – the wider the passage, the more probable it is that more persons would pass aligned; (ii) nature of visitor arrivals – large groups or individual visitors; (iii) nature of the terrain – stony road, uphill road; (iv) counter type – the accuracy of counting is affected by the recording technology used. Other potential causes of deviation in calibration include: (i) recording angle of sensor; (ii) exact nature of individuals who have passed by i.e. mushroom pickers, herbalists, people walking dogs, etc.; (iii) too many visitors at a time where many park visitors pass by aligned. Andersen *et al*. [1] investigated the effects of technical errors on the accuracy of counters used to record the number of visitors in natural settings in wintertime, which is especially important in ski areas.

Automated visitor counters are typically calibrated via human observation. Arnberger *et al*. [5] collected a variety of data on visitor traffic. Results from this study indicate that at high levels of overall use (more than 120 visitors per hour) field observers reported 20 % fewer visitors compared to video interpreters. In their study, Greene-Roesel *et al*. [26] collected pedestrian count data. Observers collected overall visitor use counts. Zwijacz-Kozica *et al*. [27] used manual counting for the purpose of verification of pyroelectric sensors and photo-traps in Tatra National Park in Poland. He states that the practical use of manual counting in visitor monitoring in the field faces a number of limitations. The studied pyroelectric sensor counted 30 times fewer visitors than those via manual counting. In another study, Hlavackova *et al*. [25] used statistically processed data. The results of regression analysis show that visitor arrival monitoring carried out using a pyroelectric sensor differs just slightly from that performed via manual counting. The auto-calibration used in the study consisted of three pyroelectric sensors located on three hiking trails heading towards the Śnieżka summit – the highest peak of the Karkonosze Mts. in western Poland. The auto-calibration process consisted of the counting of all visitor entrances (IN) onto trails leading to the Śnieżka summit as being equal to the sum of visitor exits (OUT) from the aforesaid trails. The average error rate was 10 %, while the median error rate was 6 %. As a result, the additional assessment factor should equal 10 % [28]. Trail counts by Wolter *et al.* [29] obtained with infrared counters in Indiana suggested that the sensor systematically undercounted trail users by 15 %. The study of Jones *et al.* [30] found a nondetection rate of 15 % to 21 % for active infrared counters and one of 12 % to 48 %. Greene-Roesel *et al*. [31] tested a dual-sensor passive infrared pedestrian counter and reported that the sensor consistently undercounted pedestrians by 9 % to 19 %. This is well above the undercounting rates of 2 % to 5 % obtained from tests on sidewalks in Montpelier, Vermont [32]. Yang *et al*. [33] found that the infrared undercounting error can be more than 20 % at sites with high volumes.

Pyroelectric sensors have also been used in urban areas. Yang *et al.* [14] presented the most important applications of these sensors and used the bivariate bootstrap sampling procedure to obtain correction factors for new counts – instead of the traditional regression-based approach.

3. METHODS AND METHODOLOGY

Popular methods of remote visitor data collection include active pyroelectric sensor-type counters affixed along tourist trails that record each time an infrared beam oriented across a trail is blocked, and also passive infrared trail counters, which record each time a temperature differential is detected [4], [34]. The data presented in this paper were collected in the summer seasons 2018 and 2019. PYRO Sensors by Eco Counter devices were used in the present study. The PYRO, with its passive-infrared, pyroelectric technology and a high-precision lens, counts people passing within the range of its sensor by detecting their body temperature. The pyroelectric sensor takes into account the direction of movement. In the configuration used for testing, data were recorded every hour. In a situation where the observer is equipped with a mobile device within Bluetooth range, it is possible to view the counts in real time.

Pyroelectric sensor accuracy was investigated in three steps:

1. A field experiment aimed to determine how the number of volunteers passing continuously and with various time gaps in front of the sensor affects the count result;
2. On-site observation in Szczeliniec Wielki of how the sensor works in visitors flow;
3. Calibration formulas based on field hourly measurements were then generated.

Pyroelectric sensor data analysis concentrated on the following variables: each visitor's passing configuration, time intervals between passing visitors, number of visitors in groups. Statistical measures were used to characterize error rates: average error size, error standard deviation, and average error ratio, median of error size. Pearson linear regression was employed to yield the calibration formula discussed extensively in the present study.

3.1. Field experiment under prearranged conditions

The field experiment conducted in the study was carried out in a prearranged environment to verify the general conditions of the experimental site and the devices used. A pyroelectric sensor was placed at a height of 90 cm, perpendicular to a path 60 cm wide. In order to manually verify the number of volunteers passing by, a video camera placed at a height of 2.5 m above the sensor recorded volunteers passing by in front of the sensor. Volunteers walked single-file at a speed of about 4 km/h along a designated path at a distance of 2 m ±30 cm from the pyroelectric sensor, perpendicular to it. The weather was windless, temperature within 18–22 °C, with variable cloud cover.

In the first stage of the field experiment, volunteers walked continuously (without a time gap) in a group of 10 (Fig. 1). It was measured that one volunteer appeared in front of the sensor per every second. In the second stage of field experiment, various numbers of volunteers walked single-file one by one with a time gap (Fig. 1). At first, the volunteers walked by one by one with 1-second time gaps (Stage 2a), which means that a volunteer appeared once per two seconds. Next (Stage 2b), two volunteers passed by with a 1-second time gap. Later (Stage 2c), similarly, three volunteers with a 1-second time gap walked by the sensor. Similarly, in the third stage of fieldwork, volunteers walked with a 2-second time gap (Stages: 3a, 3b, 3c and 3d) in order to check if the time separation and volunteer configuration make a difference.

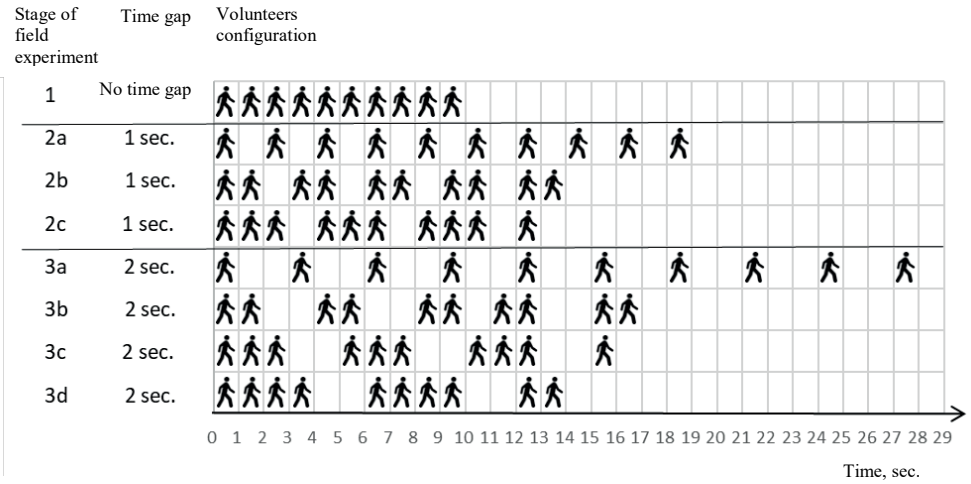


Fig. 1. Stages of field experiment with configuration of volunteers.

3.2. On-site observation of visitor flow

The aim of on-site observation was to observe in real conditions how the pyroelectric sensor counting of visitor flow in Szczeliniec Wielki works. The sensor was selected for three reasons:

1. Szczeliniec Wielki is the highest peak of the Stołowe Mts. and the most frequently visited attraction in the corresponding national park; according to MSTT data, in 2017 there were a total of 283 214 visitors on the mountain out of 871 344 in the national park. The density of visitor flow on Szczeliniec Wielki varies from zero to 300 people per hour [17];
2. The selected pyroelectric sensor was mounted – according to the manufacturer's recommendations – in a narrow passage in a rocky gorge on Szczeliniec Wielki at approximately 0.9 meters above ground. The width of the tourist passage in front of the sensor was approximately 0.6 m. The narrow trail forced visitors to walk single-file only and pass the pyroelectric sensor one at a time, increasing the chances that all the passing visitors will be detected by the sensor;
3. According to national park regulations, the trail on Szczeliniec Wielki is one-way.

The on-site observation of visitor flow was performed on a single day, August 3, 2019, during high season. The weather on that day was similar to weather during the field experiment under prearranged conditions. The visitor profile of the studied trail shows a high variability of visitor flow density ranging from 0 to more than 400 persons per hour, with individual visitors passing by or in groups. The number of visitors and errors was recorded from 9 a.m. to 7 p.m., and included 97 % of the daily number of visitors. In order to reduce the risk of observer error, a paper form was prepared in advance to be completed by the observer. The calibration work consisted of reading data from pyroelectric sensors after every visitor or group of visitors who walked by with simultaneous manual counting including the direction from which the visitor came and recording the time of each visitor's passage. Although the trail is officially one-way, some visitors walked in the opposite direction. The analysis of the minimum sample size showed that with the collected 428 measurements with the variance of 0.12, the expected error is not greater than 4.3 % ($P < 0.01$).

3.3. Calibration based on hourly counts

The aim of the calibration was to minimalize measurement errors. Hourly periods were used because this is how the data from pyroelectric sensors are collected in many areas. The data set used for calibration contains manual counting results for hourly periods and corresponding to the totals obtained from the pyroelectric sensor from May 4–5 and August 2–3, 2019.

4. RESULTS

4.1. Field experiment results

For groups up to 6 volunteers per passage, the pyroelectric sensor counted flawlessly (Appendix: Table A1). For all group sizes over 6-volunteers (55 passages), the most common problem was overcounting (95 % of passages). In the case of 7-volunteer groups, the error was ±1 (8 times over- and 1 time undercounted). Increases in the average error size for bigger groups were noted. The average error size for 16-volunteer groups was ±1.6, and 28-volunteer groups ±6.0. The average error ratio was in the range from 14.3 % to 21.4 %.

There were no errors for groups up to six volunteers. For 7- and 8-volunteer groups, the median error size was 1. For 10- to 18-volunteer groups, the median error size was 2–3. For bigger groups the median error size reached maximum 6.5. Average error size, error standard deviation and average error rate generally increased with increasing numbers of volunteers per group.

When volunteers walked with a one-second time gap (Stages: 2a–2c), we observed the inaccurate counting in all groups. Counting were correct only in 1 of 48 passages. In this time the most common issue (92 % of passages) was undercounting. Overcounting was observed only in 3 cases (Appendix: Table A1). For 10 measurements for 9-volunteer groups, 9 measurements were found to be incorrect. For 9-volunteer groups, the average error size was ±1, while for 29-volunteer groups it was ±5.2. An increase in the average error size for bigger groups was noted in the study. The average error size for 18-volunteer groups ranged from ±1.9 to 3.2, and the median of error size ranged from 2 to 3. For 28-volunteer groups, the average error size was ±5.2. The error standard deviation increased in the same way from 0.43 to 1.78 (values are similar to those from the first experimental conditions).

When volunteers walked with a 2-second time gap (Stages: 3a, 3b, 3c and 3d), we observed much less of inaccurate counting in all groups. When the number of volunteers in groups was 9, and 18, in stage 3a (one person passing every 3 seconds), all measurements were found to be correct. In bigger groups (Stages: 3b, 3c and 3d), half of measurements, while in stage 3b–3d, 54 % were correct, while 32 % were under- and 14 % were overcounted. However, errors were not higher than 1 person (average error rate 1.7–3.9 %, error standard deviation 0.46 – 0.50, which means 3 % of group size). It seems that to achieve the correct value from counting via the studied pyroelectric sensor, a 2-second time separation between groups is necessary.

4.2. On-site observation

On a sample day from 9 a.m. to 7 p.m., the pyroelectric sensor posted on Szczeliniec Wielki recorded a total of 1740 visitors entering (IN) or leaving (OUT) the area, whereas an observer counted only 1525 visitors. This number of counted visitors was one of the highest in 2019. The sensor overcounted visitors by about 14 %. The significant Pearson correlation coefficient with $r = 0.946$ ($N = 428$, $P < 0.001$) calculated for manual counting and pyroelectric sensor counting indicates a very strong relationship.

Of 428 measurements, 248 (58 %) were correct, 159 (37 %) were overcounted and 21 (5 %) were undercounted. The average error rate was ±19.4 %. The error rate here varied from +300 % (one visitor was counted by the pyroelectric sensor as four) to –100 % (one visitor was not counted). Detected errors were described using time and the number of visitor passes. The most common problem occurred when 2 visitors walked continuously in front of the sensor – in 31 % of cases – or individual visitors and a group of 3 or 4 appeared: in 13 % – 17 % of cases. Thus, groups smaller than 5 persons in a row accounted for 75 % of the total, while groups of 5 to 10 persons accounted for 24 %, and groups bigger than 10 persons – less than 1 %. The biggest number of visitors walking together was 13. Due to the high density of tourist flow, the time interval noted between groups of walking visitors (treated here as separate measurements) was not long. In 76 % it was 1 minute or less (324 measurements), in 17 % (72 measurements) 2–3 minutes and in 7 % (32) it was longer.

4.2.1. Visitor passages per hour

Results of on-site observation were compiled into 1-hour periods because pyroelectric sensors counted in hourly periods. Here, the number of measurements reflects the number of groups of visitors walking. The largest number of measurements were noted in four 1-hour periods between 10 a.m. and 2 p.m. (Appendix: Table A2). The largest number of visitors were counted at this time. Incorrect measurements were noted most frequently between 12 p.m. and 1 p.m. (36 of 73 measurements – 49 %), and error standard deviation was higher (1.06), but most frequently between 2 p.m. and 3 p.m. 23 of 34 (68 %), and the error standard deviation was 0.91. In the period between 2 p.m. and 3 p.m. occurred the highest average error size (±1.00), which means that each measurement was either underestimated or overestimated by about 1.00. The average error rate for each measurement in this period was ±32.5 %. The highest error size was 12:21 when one visitor was counted by the studied pyroelectric sensor as four. In this case, the error rate was +300 %. Three times were noted when two visitors were counted by the pyroelectric sensor as five. The error rate was +150 %. It was noted at 11:18, 13:46, and 14:43. The highest error rates applied most often to small groups of visitors walking, usually when these groups walked a short time (1 minute or less) after the group during high flow of visitors.

Differences between manual and pyroelectric sensors counts per 1-hourly periods were compared with visitor-use levels (Fig. 2). The highest error ratio was noted in the period between 2 p.m. and 3 p.m. Incorrect measurements were noted the least in the morning and evening. The average error size in these periods was smaller than ±0.5 (i.e. 10 a.m. – 11 a.m.: ±0.22; 9 a.m. – 10 a.m.: ±0.35). The number of incorrect measurements was the smallest in periods between 10 a.m. and 11 a.m. (16 % of hourly measurements), 9 a.m. – 10 a.m. (24 %), and 6 p.m. – 7 p.m. (35 %). Medians for almost all 1-hourly period were 0. Only in the period between 2 p.m. and 3 p.m. was the median equal to 1.

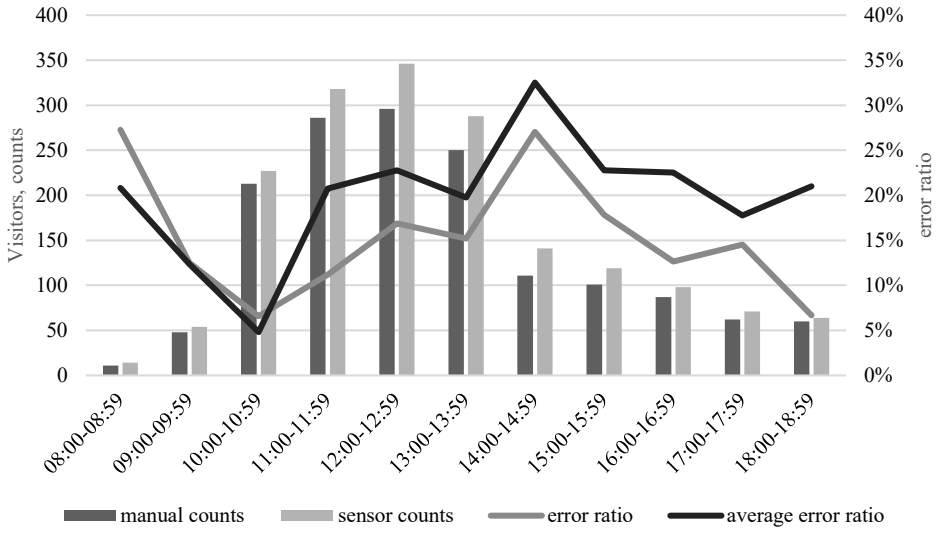


Fig. 2. Error counts by the pyroelectric sensor, aggregated hourly (Szczeliniec Wielki, August 3, 2019).

4.2.2. Visitor group size

On a sample day, visitors passed individually or in small groups counting between 2 and 13 persons per passage (Appendix: Table A3). The largest number of measurements were noted for 2-person groups (132), 3-person groups (71) and 4-person groups (60). The number of incorrect measurements increased with group size. The largest number of incorrect measurements were noted when the biggest groups passed, those with more than 10 persons (and 11 persons, 12- and 13-, etc.). Of 9 measurements made of groups with more than 10-persons, 7 were incorrect (78 %). Of 11 measurements of 9-person groups, 8 were incorrect (73 %). Conversely, of 56 measurements of individual visitors, only 11 were incorrect (21 %). The lowest average error size for individual visitors was equal to ±0.25. This means a 25 % error rate – underestimated or overestimated for every individual visitor. The highest average error size was ±1.60 for groups with more than 10 persons. This means, for each group with more than 10 persons, the average error size was underestimated or overestimated by 1.60.

The highest error size occurred twice, with overcounting by 4: for a 13-person group the pyroelectric sensor counted 17, and for a 12-person group the sensor counted 16. The differences between manual and pyroelectric sensor counts for groups were correlated with visitor-use levels. The highest error ratio was noted for the biggest groups. The median of error size for the smallest group and individual visitors was zero; however, for the group with more than 6-persons it was equal to 1. The majority of measurements were correct for 2 or 3 visitors groups. However, an excess of 1 person means a +50 % or +33 % error. Therefore, the error rate for these groups is 17.4–19.3 %.

4.3. Calibration based on hourly counts

The results of the field experiment performed in the study as well as on-site observations serve as guidelines for the generation of a calibration formula. We found that the pyroelectric sensor more often overcount, especially when more than 6 persons walk at the same time in

front of it and the time gap is shorter than 3 seconds. Therefore, samples with no fewer than 20 persons per hour were used in the calibration process. Based on all available error data, the average error ratio, which is an overcount of 13 %, can be calculated.

In order to generate a calibration formula, data from the pyroelectric sensor and manual counting in 1-hour intervals showing a linear trend were compared. The data set contained 33 pairs of results from manual and sensor counts. The calibration procedure is summarized as follows:

1. Creation of data pairs (X, Y) consisting of manual counting and pyroelectric counting in 1-hour periods and ordering from minimum to maximum – by pyroelectric counting;
2. Use of linear regression to give a linear trendline $y = mx + b$. The correct pyroelectric count should be the same as the manual count and should yield the linear trendline $y = x$;
3. Recalculation of hourly pyroelectric counts with respect to the calibrated counts using a regression formula.

Pearson linear regression data were produced based on the above data. R^2 equals 0.9933 ($r = 0.997$), and the calibration formula is as follows: $y = 0.9416x - 5.4010$. Calibrated counts were rounded to whole numbers. The calibrated count trendline is closer to the correct count trendline than the pyroelectric count trendline (Fig. 3.)

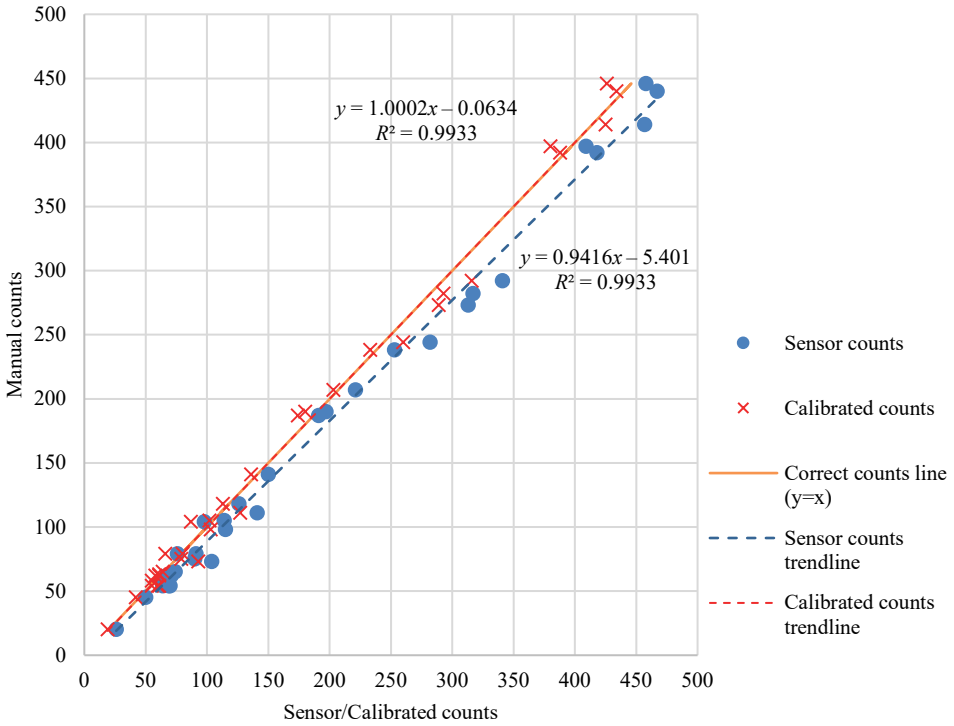


Fig. 3. Manual, pyroelectric and calibrated counts before and after hourly observation calibration.

The results of calibration show that the calibration formula successfully reduced errors in 82 % of measurements. As the manual counts increases, the calibration error size increases, but more importantly, the calibration error rate decreases. This means that greater accuracy is achieved through the proposed calibration.

Using the proposed calibration formula, the estimated overall error is smaller than that for pyroelectric counting (Table 1). The average error size was reduced from ±16.1 to ±6.6, average error rate from ±13 % to ±6 %.

TABLE 1. CALIBRATION OF MEASUREMENTS BASED ON CALIBRATION FORMULA

	Average error size	**Error standard deviation**	**Average error rate**
Pyroelectric sensor counting	16.1	13.3	13 %
Calibration result	8.3	6.6	6 %

Taking into account the reported manufacturer error of ±5 % for the pyroelectric sensor, need to verify to ±13 %, which is close to the analysis indications in the Karkonosze Mt. [28].

5. DISCUSSION

This study demonstrates the extent of incorrect pyroelectric sensor counts for a given mountain area. The field experiment and on-site calibration provided the basis for a calibration formula.

The field experiment provided the following results:

1. The studied pyroelectric sensor can both overcount (visitors walking continuously) and undercount (1-second time gap);
2. For the passage of more than 6 persons walking continuously, generated errors occur in the range from 10.0 % to 21.4 %; passages up to 6 persons do not generate errors;
3. For passages with shorter than 3-second time gaps between persons walking by, a generated error occurs: walking with a 2-second time gap yields an average error ratio of 2.8 % for a maximum of 3.9 %; walking with a 1-second time gap yields an average error ratio of 14.0 %, it may range from 10.6 % to 17.9 %; walking continuously yields an average error ratio of 16.1 % for a maximum of 21 %.

On-site observation was pursued to check how the pyroelectric sensor works under real-world conditions of visitor flow. Various intensities of visitor flow yield an opportunity to observe low and high numbers of persons walking by per hour. On-site observation provided results as follows:

1. Ratio of incorrect measurements and average error size increase with increasing number of persons walking by continuously;
2. In groups smaller than 6 persons per passage, an error occurred in the process of real-world conditions observation, although not in the field experiment;
3. In a group as small as 2 or 3 persons per passage, overcounting one person yields a bigger average ratio, thus the error ratio was bigger for this group – the average error ratio is 18.3 %. For comparison, in a group with 4 to 10 persons, the error ratio was 11.9 %, and in a group with over 10 people per passage – it was 15.5 %;
4. The pyroelectric sensor counted most accurately in the morning and in the evening. In these times of the day, the number of visitors did not reach more than 120 people per hour and weather conditions were most favourable, as temperatures did not exceed 20 °C;
5. The highest number of, and biggest error size for, incorrect measurements happened around midday (from 11 a.m. to 2 p.m.) and reached from 50 % to 68 % of total hourly measurements. In this period of time, the density of visitors was highest, and reached more than 200 visitors per hour;

6. At a high visitor traffic site (more than 200 visitors per hour) during one day of observation the studied sensor overcounted by 14 %.

The analysis of the causes of errors of the pyroelectric sensor provided the basis for a typology of error circumstances gave the ground to generate the typology of error circumstances:

1. Visitors passing simultaneously in both directions (IN and OUT) or next to each other in front of the pyroelectric sensor. This is due to the fact that the device counts only the person who at the moment passes the closest to the sensor, concealing those passing a further distance away;
2. The difference between the temperature of the human body and that of outdoor air is lower in periods characterized by the daily maximum temperature;
3. In high visitor flow indicated by a large number of visitors in 1-hour periods, when the following situations are more frequent:
    a) Groups of visitors are large (reaching more than 6 visitors per group);
    b) Visitors passing continuously, which means that there is no break between consecutive visitors;
    c) There is a delay in the pyroelectric sensor counting of the previous group, causing an overestimation in current counting;
    d) Previous, usually large or numerous, groups passed the sensor shortly before (see the fatigue effect described below).

Above supplemented and confirmed selected aspects of deviation noted by Hlavackova *et al.* [25], the main factor of error occurrence was density of visitor flow.

In the course of the field experiment and on-site observation, unique situations were noted, which were related to errors made by the studied sensor:

1. Opposite-direction counting;
2. Fatigue effect;
3. Impact of higher air temperature on counting errors.

It is important to note that even when people were walking in one direction, sometimes situations of counting opposite-direction passage was observed. In the course of the field experiment with 168 passages, this occurrence was noted 17 times (10 %). In the case of 11 times, this was just 1 person, while in a group of 29 volunteers opposite-direction error size equalled 3 or 4, but the rate ranged from 3 % to 14 %.

The most frequently noted (14 times) time gap between visitors was 1 second (2a stage of experiment). During on-site observation, opposite-direction counting was noted 19 times (5 times – 2 visitors, 14 times – 1 visitor) – for 4.5 % of all observations. This did not affect the result significantly because sum of errors was 24 – of 1 525 visitors counted manually or 1.5 %. This error was noted 14 times (73 %) during high visitor flow hours (persons per hour >200). This situation needs more precise observations in order to draw additional conclusions.

When analysing data, there appears to be a sensor fatigue effect. It consists of the fact that the size of the error depends not only on the volume of visitors in a given time period, but also that in preceding periods. For instance, error rates in the first hour of intensive tourist traffic were lower than those noted in the first or second hour of reduced traffic (Fig. 2). In addition, on the scale of individual group passages, the appearance of a given group increases the probability of error occurrence after the previous group. A more precise determination of this relationship requires further research.

In summer, at higher air temperatures, there is a possibility of measurement errors due to the reduction in the difference between the temperature of the human body and that of the ambient environment. As a result of such a narrowing difference, there is a likelihood of larger sensor reading errors. This also requires further research.

The calibration formula produced in the present study is as follows: $y = 0.9416x - 5.401$. Results are rounded to whole numbers. The formula may be used for groups of at least 20 persons per hour. This calculation is based on hourly observation data from manual counting and pyroelectric sensor counting. Further research requires verification of this formula for other sensor placement locations. For data obtained in real-world conditions, the original overall error rate was 12.6 %. By using the proposed calibration formula, the estimated overall error rate becomes 6.3 %. Each calibrated error ratio was reduced overall about half. These results show that the calibration formula is useful

The calibration formula procedure proposed in this study is simpler than the calibration procedure proposed by Yang *et al*. [14] whereas the results are similar. The calibration procedure successfully reduced the overall counting errors to the range of ± 5 %. Furthermore, the present study was performed in a mountain area, where it is more difficult to obtain accurate data than in an urban area. Previous regression-based calibration require the collection of a relatively large amount of ground truth data to build a robust regression model to identify a reliable correction factor. The presented procedure does not require the collection of a large amount of data. The error rate of calibrated data by Andersen *et al*. [1] is 5 %, which is only about 1.3 % smaller than that in this study. Andersen *et al*. [1] completed his study in wintertime when the difference between air temperature and that of the human body is higher. This is why Anderson *et al*. [1] worked on more accurate data. The herein obtained results are also comparable with results from Karkonosze National Park, although the average error rate was higher [28]. This may have been caused by the way tourists walk due to safety reasons. In Szczeliniec Wielki, it is easier to walk along the trail, therefore, time intervals between tourists are very small. Similar study of Watson *et al*. [22] received a 95 % confidence that the results will be accuracy of ± 5 %. Another field tests [35], [36], [37] indicated that the performance of these devices under ideal conditions identified by the vendor, that is, counts of ± 5.0 % the true counts, was not always guaranteed.

Linear regression achieves values between manual counts and calibrated data $R^2 = 0.9933$, which is comparable to similar work by Muhar *et al*. [19] who evaluated results as a very strong correlation between sensor counts and observed counts ($R^2 = 0.94$), but no details on observation methods to correct sensor counting errors are provided. Pettebone *et al*. [11] confirmed a strong statistical relationship between observation-based visitor counts and sensor counts ($R^2 > 0.95$), which yields confidence in the use of sensors to estimate recreational use in national parks and protected natural areas. Results of post-analysis showed that 5h of direct observations would produce an error of approximately 15 %. This finding is partially substantiated by Greene-Roesel *et al*. [26] that found Eco-Counters to undercount pass-by events by −9 % to −19 % and suggested that correction factors be developed via direct observation to derive accurate estimates of pedestrian volumes. The highest values of the correlation coefficient (close to 1) were calculated for sensors installed in forest areas and the lowest (below 0.75) in high mountain areas, where the devices were hidden among rocks in Tatra National Park [27]. Counter error rates were slightly higher in outdoor versus indoor tests, but still accurate within 5 %. Error rates increased with increasing visitor traffic. The findings in the present study yield methodological implications for researchers and forest managers using automated visitor counters to estimate wintertime visitor use in mountain areas [1]. Analysis shows that almost of half errors reach a maximum of ±5 %. The smallest errors were noted in summer. The average error rate was 10 % and median 6 % [28]. The presented procedure may be applied to other natural sites with a high density of visitor flow and in the case of a variety of other data.

6. CONCLUSIONS

Research results show that the herein proposed procedure could improve the quality of pyroelectric sensor data by reducing the discrepancy between sensor counts and ground truth. To improve the quality of pyroelectric counts, an adjustment of raw pyroelectric sensor output is needed. Previous works discussed in the literature require the use a complicated calibration procedure. The main strength of the proposed calibration formula is its simplicity and ease of using due to its reliance on a trendline. No calibration procedure will eliminate measurement errors, but will reduce them.

Sensor errors depend on both type of visitor flow and measurement conditions. They occur as a result of the intensification of visitor flow, and therefore it is important to provide threshold values, the exceeding of which causes an increase in errors. This intensification causes both the merging of visitors into larger groups passing continuously in front of the sensor as well as a reduction of time intervals between the groups. The thresholds of measurement accuracy is:

1. Passing of more that 6-visitors group in front of pyroelectric sensor;
2. The time interval between each visitors is shorter than 3 seconds.

Appeal to literature review [5], [14], pyroelectric sensors can overestimate and underestimate. Results from our study indicate that pyroelectric sensors over calculate at the highest numbers of visitor passages (>200 visitors per hour). The errors mainly reached during walked continuously or with 1-seconds time gap. Even though overcounting happened more often, while time gap was 1 second the sensor mostly undercount.

Thanks to the calibration formula provided in the present study the average error ratio was reduced to a range of ±5 %. No universal calibration formula is available for all data collected from various study areas. A calibration formula may vary due to differences in time and physical location, which means that a calibration formula identified for one location might not be easily applicable for other locations without manual counts for verification purposes at those other locations. It seems that it would be beneficial to create a typology of sensor location sites. In light of this type of approach, instead of calibrating each sensor, one could do it for any type of geographic location.

The calibration formula discussed in this study was used to process pyroelectric sensor data generated by MSTT, a system used to monitor visitor flow in Stołowe Mts. National Park. The said formula represents one potential way of using data from MSTT for sustainable tourism management in a middle mountain national park [15]. Finally, the said calibration formula is simple and universal.

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ANNEX

TABLE A1. RESULTS OF FIELD EXPERIMENT: VOLUNTEERS PASSED THE PYROELECTRIC SENSOR CONTINUOUSLY

Time gap	Stages of field experiment	Persons per passage	Number of passages	Correct measurements	Undercounted measurement	Overcounted measurement	Sum of errors	Average error size	Error standard deviation	Average error rate	Maximum of errors	Median of error size	Sum of manual counts	Sum of sensor counts
No time gap	1	4	8	8	0	0	0	0.00	0.00	0.0 %	0	0.0	32	32
		6	9	9	0	0	0	0.00	0.00	0.0 %	0	0.0	54	54
		7	9	0	1	8	9	1.00	0.00	14.3 %	1	1.0	63	70
		8	8	0	0	8	10	1.25	0.43	15.6 %	2	1.0	64	74
		10	8	0	0	8	13	1.63	0.48	16.3 %	2	2.0	80	93
		16	10	1	0	9	16	1.60	0.92	10.0 %	3	2.0	160	177
		28	10	0	1	9	60	6.00	1.84	21.4 %	8	6.5	280	325
		29	10	0	0	10	55	5.50	1.36	19.0 %	7	6.0	290	345
1 sec.	2a	9	10	1	7	2	10	1.00	0.45	11.1 %	2	1.0	90	88
	2a	18	8	0	8	0	18	2.30	0.70	12.5 %	3	2.5	144	129
	2a	29	10	0	10	0	52	5.20	1.78	17.9 %	7	5.0	290	256
	2b	18	10	0	10	0	32	3.20	1.40	17.8 %	6	3.0	180	148
	2c	18	10	0	9	1	19	1.90	0.70	10.6 %	3	2.0	180	165
2 sec.	3a	9	10	10	0	0	0	0.00	0.00	0.0 %	0	0.0	90	90
	3a	18	10	10	0	0	0	0.00	0.00	0.0 %	0	0.0	180	180
	3b	18	10	5	4	1	5	0.50	0.50	2.8 %	1	0.5	180	177
	3c	18	10	7	2	1	3	0.30	0.46	1.7 %	1	0.0	180	180
	3d	16	8	3	3	2	5	0.60	0.50	3.9 %	1	1.0	128	127

TABLE A2. ERROR COUNTS BY THE PYROELECTRIC SENSOR, AGGREGATED HOURLY (SZCZELINIEC WIELKI, AUGUST 3, 2019).

Period	Number of measurements (n)	Correct measurements	Undercounted measurements	Overcounted measurements	Average error size	Error standard deviation	Average error rate	Sum of manual counts	Sum of sensor counts	Hourly error rate
09:00–09:59	17	76 %	0 %	24 %	±0.35	0.76	±12.4 %	48	54	12.5 %
10:00–10:59	63	84 %	0 %	16 %	±0.22	0.58	±4.8 %	213	227	6.6 %
11:00–11:59	72	54 %	8 %	38 %	±0.64	0.79	±20.8 %	286	318	11.2 %
12:00–12:59	73	51 %	7 %	42 %	±0.82	1.06	±22.8 %	296	346	16.9 %
13:00–13:59	65	52 %	5 %	43 %	±0.68	0.88	±19.8 %	250	288	15.2 %
14:00–14:59	34	32 %	6 %	62 %	±1.00	0.91	±32.5 %	111	141	27.0 %
15:00–15:59	30	53 %	3 %	43 %	±0.67	0.83	±22.8 %	101	119	17.8 %
16:00–16:59	31	58 %	6 %	35 %	±0.55	0.71	±22.5 %	87	98	12.6 %
17:00–17:59	19	63 %	0 %	37 %	±0.47	0.68	±17.8 %	62	71	14.5 %
18:00–18:59	20	65 %	10 %	25 %	±0.40	0.58	±21.0 %	60	64	6.7 %
Total:	**424**	**58 %**	**5 %**	**37 %**	**±0.61**	**0.85**	**±19.4 %**	**1514**	**1726**	**14.0 %**

TABLE A3. ERROR COUNTS BY THE PYROELECTRIC SENSOR BY GROUP SIZE (SZCZELINIEC WIELKI, AUGUST 3, 2019).

Persons per passage	Number of measurements (*n*)	Correct measurements	Undercounted measurements	Overcounted measurements	Average error size	Error standard deviation	Average error ratio
1 ppp	56	79 %	7 %	14 %	±0.25	0.54	±25.0 %
2 ppp	132	66 %	2 %	32 %	±0.45	0.71	±22.3 %
3 ppp	71	55 %	4 %	41 %	±0.63	0.83	±21.1 %
4 ppp	60	63 %	5 %	32 %	±0.57	0.84	±14.2 %
5 ppp	32	50 %	6 %	44 %	±0.75	0.94	±15.0 %
6 ppp	19	37 %	5 %	58 %	±0.89	0.79	±14.9 %
7 ppp	22	27 %	18 %	55 %	±1.09	0.90	±15.6 %
8 ppp	16	38 %	0 %	63 %	±1.00	1.06	±12.5 %
9 ppp	11	27 %	9 %	64 %	±1.18	0.94	±13.1 %
≥10 ppp	9	22 %	0 %	78 %	±1.67	1.41	±14.7 %