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SAFECAST – CITIZEN SCIENCE FOR AMBIENT DOSE RATE MONITORING

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Abstract. *Citizen Science has raised much interest for the last decades. In many scientific disciplines, citizens contribute to acquisition of field data mostly out of scientific interest. Institutional science used to look sceptically upon laypeople, but the attitude has largely changed as the benefits of Citizen Science for both active citizens and scientific institutions became apparent. One very successful project is SAFECAST, devoted to monitoring ambient ionizing radiation. The paper introduces the project and its measurement tool. Benefits and problems are discussed, the latter consisting primarily of uncertainty introduced by deviations from standard measurement protocol, in turn contributing to problems of interpretability. Altogether, measuring ambient dose rate is easy, but interpretation of results is not trivial and prone to spurious conclusions. One should have in mind that especially in case of real emergency (like Chernobyl and Fukushima accidents) the measurements of ambient dose-rate level only are not sufficient for proper decision-making on protective measures.*

Keywords: *Ambient dose rate, Citizen Science, SAFECAST, quality assurance*

1. INTRODUCTION

SAFECAST [1, 2] was founded in Japan in 2011 after the Fukushima accident. Its motivation was the distrust in the perceived unreliable and incomplete information by Japanese authorities and the NPP operator (TEPCO) about the radiation situation. Measurements of ambient dose rate (ADR) performed by citizens were supposed to verify and to complement official data. A standard instrument, easy to use and to operate and relatively inexpensive (compared to similar instruments), was designed for the purpose. An on-board GPS receiver records geographical position and writes it into a log file together with date/time and the dose rate reading. It can be submitted to SAFECAST database in order to be displayed on the freely accessible on-line SAFECAST map.

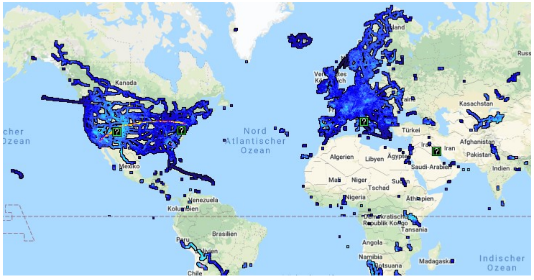

Figure 1. Screenshot of the SAFECAST map
(https://map.safecast.org/)

SAFECAST soon expanded internationally. Today (August 2021) its database includes over 168 million ADR measurements world wide acquired with about 3000 detectors.

However, measurement density is very variable, with high densities mostly in Japan, some European countries and the U.S., see the screenshot, Fig. 1, for more details see webpages Safecast.org.

This paper is organized as follows: In section 2, the concept of Citizen Science (see below) is introduced, together with a discussion of its benefits and problems. Section 3 presents the standard device used in SAFECAST; section 4 deals with quality assurance (QA) issues and section 5 discusses problems which arise in interpretation of CS generated results.

2. CITIZEN SCIENCE

Citizen Science (CS) means scientific research conducted by citizens who are not professional scientists. Their involvement can range between participating to different degree in defined projects and setting up entire projects. A particular class of CS is sometimes called Citizen Sensing, focused on data acquisition, typically in environmental monitoring. (Text inspired by the very comprehensive Wikipedia entry about CS, [3]) A large compendium of CS across fields of science Czech is given in *The Science of Citizen Science* [4].

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2.1. Advantages and benefits of CS

(i) Involving citizens who are not trained scientists, in general, adds to science education - in this case to better understanding of radiation physics and effects in general and radiation protection altogether, the nature of natural radiation, ADR and its geographical variability, and of what measurement means, including the importance of observation protocol and uncertainty. It may also help understanding the problems of repeatability and reproducibility, uncertainty of different types and other statistical issues. Quite naturally, the possibility to participate and to contribute visibly stimulates scientific curiosity and interest. Additionally, it helps in communication with professional radioprotection institutions, including appeasing possible mutual distrust, and in adopting their knowledge.

In order to promote public education and awareness on environmental radiation, SAFECAST organizes workshops and public events; an international on-line conference was held in March 2021, see the “news/10th anniversary” tab on the Safecast.org website.

(ii) A great advantage of CS-based over institutional monitoring surveying is that it can acquire amounts of data which the latter can hardly do. Thus it can detect phenomena and geographical patterns of ambient radiation which may have elapsed institutional attention, and help in effective utilizing of capacities of professional monitoring teams.

2.2. Drawbacks and problems

(i) Since citizens are usually not familiar with quality assured metrology, their results are affected by uncertainty due to deviations from standard measurement protocols. These are difficult to quantify and may impair the reliability of results, but analysis of large amount of data generated by citizens can help in understanding and even quantifying these uncertainties. This important aspect will be further discussed in section 4.

(ii) Since CS projects often lack an overall sampling design, results are in general not representative. Instead, they tend to reflect preferences of participants. On the other hand, the example of the Czech Republic where CS-based ADR monitoring has been integrated into education schemes [5], [6], [7], [8] and [9] shows that a systematic approach can lead to near representative coverage. Similarly, increasing number of participants and data points may lead to asymptotic representativeness, if statistical methods for de-clustering are applied, e.g. [10].

(iii) Establishing and maintaining infrastructure such as a web platform is a long-term and possibly demanding effort, which requires an institution willing and capable of doing it reliably.

(iv) A caveat which should be kept in mind is that especially in case of real emergency (like Chernobyl and Fukushima accidents), ADR measurement alone is not sufficient for appropriate decision-making on protective measures, but should be considered as indicative for motivating professionally QAed measurement and action.

3. THE ‘BGEIGIE NANO’ DEVICE

SAFECAST’s standard instrument for ADR measurement is called ‘bGeigie Nano’, see Figure 2. It is based on a pancake-type G-M detector with thin window (theoretically able to record α and β rays, if the detector is taken out of its sturdy case; but field measurement of gross α and β rates is difficult to interpret and we discourage this). Geographical position (by GPS) is written into a log file every 5 seconds together with date/time and the ADR reading. The log file is stored on a SD card in text format. Apart from submitting to SAFECAST it can be processed using GIS software, such as QGIS, utilising a plug-in provided by SÚRO [11] (you can view Safecast and other CS measurements performed in the Czech Republic on www.suro.cz/aplikace/ramesis/). All data are publicly accessible for viewing and download.

Several shortcomings of the device have been identified during usage. This has led to the development of a conceptually very similar, but technically improved version by SÚRO. First series of a few pieces are expected to be available at the end of 2021, much more during next two years.

Figure 2. The ‘bGeigie Nano’ device

4. ASPECTS OF QUALITY ASSURANCE

We distinguish between two essentially different aspects:

(1) QA related to the physical properties of the detector;

(2) QA of detector handling and measurement protocol.

4.1. Detector properties, calibration

The “classical” part of QA deals with metrological characterization of a measurement instrument. For dose rate meters, topics are response to a known radiation field (calibration); angular dependence or response isotropy; energy dependence of response (ideally independent); dependence of response on true dose rate (should be linear); internal background (due to electronic noise and radioactivity within components); response to cosmic radiation (mostly muons, to which a detector reacts differently, in general, than to environmental gamma rays); possible dependence on ambient temperature; variability between devices of same brand (because components are always slightly different).

Classical metrological characterization is done in dedicated laboratories. An important complement is testing measurement instruments in inter-comparison exercises, to compare performance of different brands of instruments of same type (here, ADR measurement). One element of characterization is establishing an uncertainty budget, so that accuracy and precision of the readings can be assessed.

Regarding the bGeigie Nano, the instrument has only been partly characterized by its designers and some topics are still under investigation, among others by the authors. For example, by measuring above appropriate water bodies, where terrestrial radiation is almost entirely shielded, the internal background has been found to be about 10 nSv/h. Some technical details and references can be found in [10]. The detector is calibrated to yield ambient dose equivalent rate (ADER, μSv/h H*(10); see also section 5). Unfortunately, calibration and other QA issues are not very well documented on the SAFECAST page.

4.2. Detector handling, measurement protocol

The non-classical part of QA deals with the measurement procedure. In professional usage, instruments are used by persons trained in metrology according to defined protocols. This cannot be assumed in CS usage, even if measurement protocols are recommended to users. In practical “field use”, deviations from an ideal protocol are inevitable, be it by ignorance, negligence or because in a situation the standard protocol is impractical. Three examples of deviations:

(1) Measurement 1 m above ground is recommended (this is the standard for ADR measurement). In practice, however, devices are often carried in backpacks (typically 1 – 1.5 m above ground), mounted on bicycles (typically 70 – 80 cm above ground) or in cars e.g. close to the windscreen or side doors (50 – 80 cm). Fig. 3 shows the calculated dependence of ADR on measurement height above ground, taken from data reported in [12]; see also [10] (actual measurements with the bGeigie Nano are still missing). The graph shows that deviation of ±0.5 m from the standard height, 1 m, leads to errors of less than 5%, which appears negligible in practice.

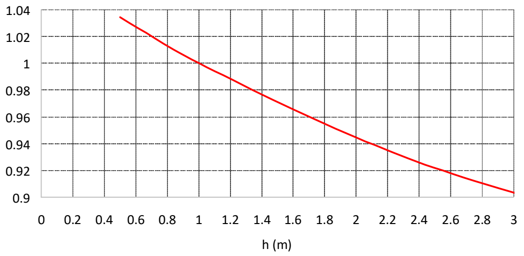


Figure 3. Dependence of ADR on height of measurement above ground. (y-axis: ADR Normalized to 1 for standard height, 1 m)

(2) The detector should not be shielded during measurement. Obviously this is not fulfilled in a car, but also the person who carries the device in a backpack shields to some extent, but also contributes a radiation signal mainly due to ^{40}K content in the body.

(3) The pancake G-M detector has a high form factor, meaning that its diameter (45 mm) is larger than its depth (13 mm). This results in strong angular response anisotropy for environmental gamma and for cosmic rays (in different manner). We recommend using the device with the disk-shaped detector in vertical position but in reality it may be positioned differently or if carried in a bag, inadvertently change its tilt position, and other deviations from standard.

Although users are encouraged to submit a “field protocol” together with the data, indicating height above ground, tilt against vertical, manner of carrying the device and possible shielding, the reliability of such information is often limited. Therefore, one must assume additional uncertainty due to deviation from standard protocol or from altogether missing metadata.

5. AMBIENT DOSE RATE

ADR is the energy deposited by ambient radiation into a volume per unit time. Usually, monitors are calibrated to report ambient dose equivalent rate dH*(10)/dt, (ADER, referring to tissue equivalence); see ICRU 51 [13], chapter I.4.3.1 (p.6) for details. Sources and composition of observed ADR have been discussed, among other, by 14] and [15], chapter 4.2.1 (p.93). In short, components which contribute to the reading, are cosmic radiation (mainly muons), natural terrestrial radiation (^{40}K, ^{238}U and ^{232}Th progeny), anthropogenic terrestrial radiation (from nuclear fallout, mainly ^{137}Cs), radionuclides in air: radon and thoron progeny, cosmogenic radionuclides and after nuclear accidents, anthropogenic airborne radioactive pollution. Additionally, other radiation sources may be present in the environment. Importantly, there is always an internal background contributing. See figure 4 for a schematic visualization, taken from [15].

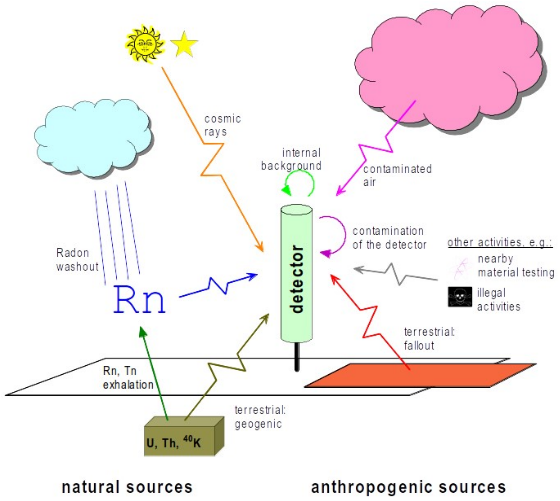


Figure 4. Sources of ambient radiation contributing to the reading of an ADR detector.

The different contributions cannot be separated if gross ADR is measured, such as done with a G-M counter. If one wants to estimate one component, the others have to be subtracted, which requires to know them. However, usually they are known only approximately, at best. For example, internal background is device specific and can be found through specific experiments. The cosmic component depends essentially on altitude above sea level and can be calculated, if the cosmic response characteristic of the detector is known (a task which is part of QA).

The lesson is that ADR is easy to measure but difficult to interpret, except if one component is known to be dominant above all others, as is typical in emergency conditions.

6. INTERPRETATION OF CS GENERATED RESULTS

The uncertainty of reported results leads to difficulties of interpreting them. This pertains to local values which are visible in the map as well as to larger-scale pictures. On the other hand, large-scale pictures, say ranging over countries or entire Europe, appear quite reliable because of averaging immense numbers of data. For example, the SAFECAST map of Europe clearly reflects European base rock geology (in general, granite has higher ADR than most sedimentary and calcareous geology). In the following, four topics are addressed and examples given.

6.1. Ill-measurement

Systematic. Closer analysis of data retrieved from the SAFECAST repository has revealed an example ([10], fig.11 of that paper) of several tens of thousands of measurements evidently wrong (reason unknown). If they are included in statistical evaluation, bias is the consequence. Identification of such erroneous data is not always easy, sometimes indeed impossible.

Correlated random. Occasional detector mis-handling is inevitable (section 4.2). If this happens only concerning a few measurements in a sequence, one may consider it as a random error which cancels in the mean by virtue of the central limit theorem, only resulting in larger random uncertainty. But for a long sequence, say thousands of measurements deviating from protocol, the result is clearly a biased picture. Identification is possible only by comparing with other measurements performed along the same transect.

6.2. Repeatability

This term means that repeated measurement with same instrument under (ideally) same condition yields the same picture, up to statistical fluctuation. If one has two or more measurements of one site or of a transect, how can one decide whether individual pictures are different? Fig. 5 shows the ADR profiles measured by bGeigie Nano mounted on a bicycle for 34 journeys (some incomplete) of the same route in the upper graph. (Each value is the mean in a sliding window of 100 m radius, centred along the transect.) The lower graph shows the average of a number of journeys as indicated in the legend. One can see in the lower graph that there is indeed an ADR profile, although not very distinct, with maxima at about 250 and 1200 m and a minimum at about 800 m; but this cannot be recognized from data of individual journeys (upper graph). The reason is of course statistical uncertainty. This demonstrates that interpretation of individual transects is problematic, if (i) mean ADR is low (here: Berlin, but quite typical for European cities) and (ii) differences along the transect are small (here between 106 and 125 nSv/h, lower graph, "all" curve). The lesson is that individual transects are prone to statistical artefacts and mis-interpretation. Deciding whether two pictures (measured transects) are truly different apart from statistical effects is a non-trivial statistical task.

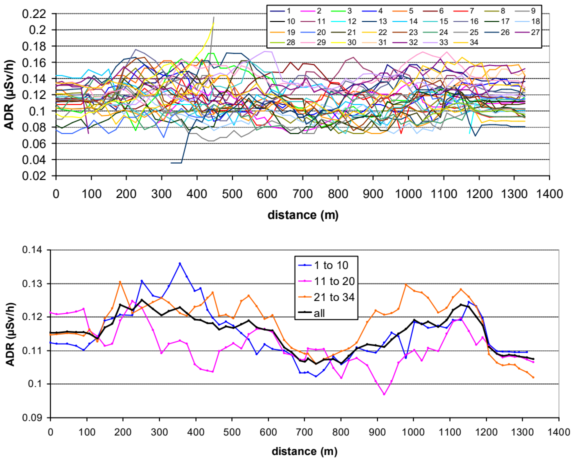


Figure 5. Top: ADR profiles of 34 journeys along the same transect; Bottom: Profiles averaged. (for details see text)

6.3. Effect of averaging

The bGeigie Nano has a measurement cycle of 5 s. Due to low sensitivity, the number of counts in this period is between 1 and 6 in usual ambient radiation environments (see [10]). Since counting statistics follows the Poisson distribution, variance equals mean, which leads to very high statistical uncertainty within 5 s: for mean per 5 s equal to 3 counts, relative standard deviation is equal to √3/3=0.58 i.e. 58 %. Therefore, 12 readings are pooled to yield a 12 × 5 s = 1 min mean, which leads to 58%/√12=17% uncertainty in the same example, which appears tolerable. However, the price to pay is lower spatial resolution, because within 1 min, one can move a distance in which the radiation environment changes. Applying a 12-values moving average, as implemented in the bGeigie and displayed in the SAFECAST map, blurs the local ADR picture. Moreover, averaging windows are not centred on the actual location, but represent the past 12 locations. This is inevitable if the 12-values mean has to be calculated "on the fly" and written sequentially into the log file. However, it can lead to misleading pictures on a local scale, as shown in the example, Fig. 6.

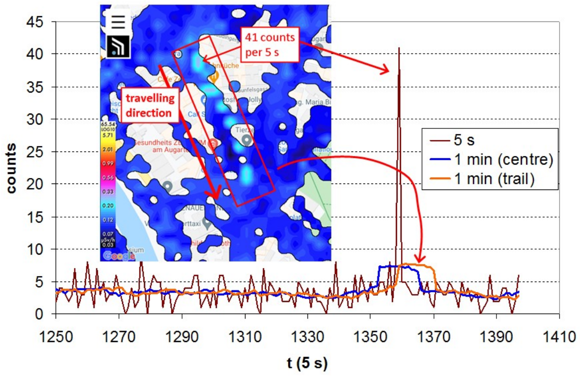


Figure 6. Artificial "trail" (marked by the red rectangle in the inset map) generated by averaging over 1 minute ADR values measured over 5 s, as consequence of the presence of an isolated anomaly.

The graph shows the 5 s-readings, revealing an isolated anomalous value (41 counts) whose physical reason is unknown; perhaps caused by a radioactive source locally used for material testing, or a person undergoing nuclear medicine treatment. Averaging leads to an apparent trail of elevated ADR, shown in the inset, a screenshot from the SAFECAST map. In this case, it was known that the street (in Vienna) had no elevated ADR, so the log file was inspected (which contains the raw 5 s-count numbers) and the isolated anomaly found and the ADR trail identified as artefact.

The example shows that finding segments of transects with high ADR (here about 200 m long) do not necessarily reflect true radiation conditions and should therefore be interpreted with caution.

Similar findings in Rome, e.g. on St. Peter's square and at the Forum Romanum (Fig. 7a), easily seen on the SAFECAST map, have been interpreted by inadvertently having the instrument pass through security X-ray.

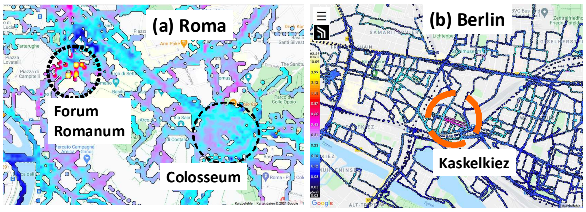
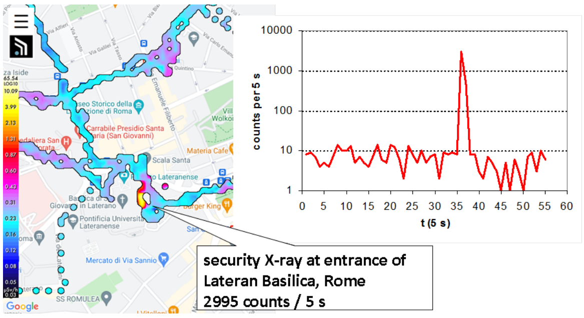


Figure 7. (a) Rome, unexplained hot spots at the Forum Romanum (X ray machines?); the circular structure of the Colosseum is also clearly visible (partly made of tuff with relatively high radium content);
(b) Berlin, some streets with Ra-rich pavement.

On the other hand, ADR anomalies in Berlin (also easy to see on the SAFECAST map; Fig. 7b) have been confirmed as generated by a certain type of street pavement containing relatively high concentrations of radium.

However, one anomaly in Rome has been confirmed to originate from X-raying, Fig. 8. In this instance, the detector has been passed deliberately through the security X-ray.



security X-ray at entrance of
Lateran Basilica, Rome
2995 counts / 5 s

Figure 8. Dose rate caused by deliberate irradiation in an X-ray machine. Beware the logarithmic scale in the graph.

Since the bGeigie Nano is not calibrated for the energy of X-rays (few keV, compared to 100-2600 keV for usual ambient gamma radiation), the count rate cannot be easily recalculated into dose rate.

6.4. Interpretation of ADR maps

Interpretation caveats. Since acquisition of geo-referenced data is so easy with the bGeigie Nano, it is tempting to generate local radiation maps. We show an example that this can go quite badly wrong without statistical consideration. A meadow in Berlin has been covered twice. The same measurement protocol was observed, external conditions (weather) were the same. Point density and areal coverage was somewhat lower at first trial, left map of Fig. 9.

The maps were produced by simple moving average method, grid size 2 m, circular search windows with 10 m radius.

At first sight, a pattern appears to exist in both maps; however the patterns are different (except from edge effects, SW edge, due to the vicinity of buildings), confirmed by correlation analysis (not shown here).

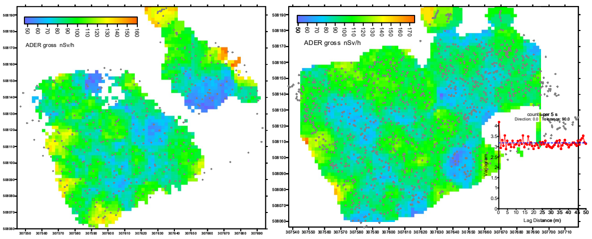


Figure 9. Two ADR maps of the same meadow. Insert: Variogram. Axis ticks: 10 m. North is up.

The variogram (insert of the right map) of the original values reveals that no autocorrelation structure exists, i.e. no true pattern. In other words, the apparent patterns are statistical artefacts generated by the interpolation method. (It can be shown analytically that applying moving average smoothing or interpolation generates spurious autocorrelation; an effect also to be kept in mind for time series. In this case, the variogram of the interpolated values, not shown here, has a correlation length of 20 m, corresponding to the diameter of the averaging window.)

Again, the lesson is that apparent patterns should not be trusted and taken for real without detailed analysis. A danger may be seen in that while such results can be generated very easily, the analytical tools necessary for validation may be beyond knowledge of citizen scientists.

Interpretable maps. A positive example of how ADR maps can give qualitative clues about an effect is shown in Fig. 10. (Similar to the example in Fig. 7b.) Two screenshots from the SAFECAST map are shown, city centre of Vienna, taken early 2020 and mid 2021. The increased coverage is obvious. In particular, in 2019-2020 one street (red rectangle) has been remade by laying granite pavement instead of asphalt. The granite used (from a quarry in the Bohemian massif) has relatively high radium content, which becomes apparent in increased ADR. (Also the pavement SE of the rectangle is of that type.)

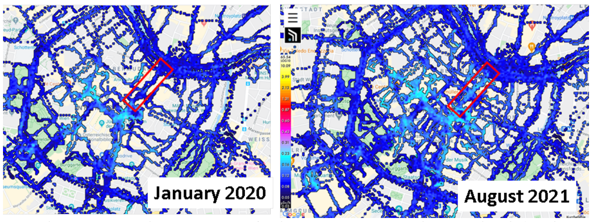


Figure 10. City centre of Vienna. A street is marked (red rectangle), in which the pavement has been changed from asphalt to granite. Screenshots from the SAFECAST map.

7. CONCLUSION

Citizen Science is a powerful concept which complements institutional science. SAFECAST is a particularly successful example: measurements on its platform have been performed in many regions around the world and an impressive world map of ADR has been generated. However, interpretation of individual and mapped ADR values is not trivial. Reasons are the varying mix of contributions from different ambient radiation sources and uncertainty, whose source is in the physical nature of radiation measurement, but perhaps more importantly, in that values generated by non-professionals are subject to higher probability of deviation from standard measurement protocol. This is an important, but so far little investigated source of uncertainty. Still, benefits of CS based radiation monitoring are considerable, from the educational aspect to its contribution to extensive databases. In our opinion, this justifies detailed investigation of CS-characteristic uncertainty and how to deal with it to improve interpretability of CS generated data.

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