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Confidence
Coping with uncertainty for improved modelling and decision making in nuclear emergencies

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D9.8 – Database of smartphone app / dosimeter evaluation*

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*** Despite the title of the deliverable, this document is not a database of evaluation results of smartphone apps and external dosimeters but a report on the evaluation of apps that turn the camera of the smartphone into a dose-rate meter.**

Abstract

The present deliverable reports on the characterization of two applications that enable dose-rate measurements with an ordinary smartphone, using the CMOS sensor of the in-built camera as a radiation detector. Scope of this scientific work is to investigate the reliability of the so-called "citizen measurements" performed with a widely spread consumer device such as a mobile phone. All tests were carried out at room temperature and in different reference fields at the Secondary Standard Dosimetry Laboratory of the Helmholtz Zentrum München (HMGU). Investigated properties were the response at different dose-rate levels, influence of integration time, background, energy dependence and angular dependence. The report concludes with recommendations on minimal requirements for the "RadioactivityCounter" app for field measurements.

Contents

1 Introduction

1.1 Citizen measurements following nuclear emergencies

Nuclear emergencies, which have occurred in the past, combined with the more recent threat of potential terrorist attacks with radioactive materials, are the main reasons for an increasing public awareness of ionizing radiations. In fact, radiation and its environmental and health effects are perceived as risks not only by the countries where nuclear power plants are located but worldwide. Technological enhancement in the last years has made it possible for lay people to approach a possible unplanned exposure from another perspective. Affordable devices for radiation detection are becoming more and more common and some of them have been already tested during an emergency scenario such as the Fukushima Daiichi power plant accident in 2011. In such circumstances, collecting environmental monitoring data by the public and sharing them through a network can help to better understand the radiological situation and the operational picture. Collaboration with citizens may be fruitful in both the above-mentioned scenarios and people would feel empowered to be actively involved in self-protective operations. However, from a scientific point of view, the reliability of such kind of measurements it still an open issue.

1.2 Brief description of Sub-subtask 9.1.2.1 objective

Nowadays two categories of devices for measurement of environmental radiation are available on the market. On the one hand, there is expensive professional equipment, mostly dedicated to technical experts; on the other hand, an increasing number of cheap instrumentation is becoming available, which do not require any particular scientific expertise. Often the latter category is supported by smartphone technology.
As modern mobile phones come with a multitude of functionalities, they are not restricted to be only used for communication but can also be used as radiation detectors through:

- *External hardware*: plug- in or wireless, based on solid state or gas detectors
- *Software*: dedicated applications, that make use of the built-in camera sensor of the phone

Sub-subtask 9.1.2.1 of the CONFIDENCE task (9.1) focuses on the reduction of uncertainties in exposure assessment based on environmental monitoring data, with the aim to derive individualized exposure histories in order to improve the awareness of the radiological situation following a nuclear emergency. While a large part of the activities therefore concentrates on the characterization and optimization of (professional) stationary and mobile environmental monitoring networks, the sub-subtask also addresses the potential participation of the general population in producing (lower quality) monitoring data. In this context, the emphasis is on software applications for smartphones, since in terms of cost they might appear as particular attractive to citizens. In fact, anyone who owns a smartphone could invest in a low-priced tool that turns the Complementary Metal Oxide Semiconductor (CMOS) camera sensor into a dose-rate detector.
Scientific effort was put into the characterization of this technology in laboratory irradiations, whereas the social impact of the technology and characterization in field tests is addressed by the CONCERT task SHAMISEN SINGS (9.8).

2 Materials and methods

A preliminary market research helped to identify smartphones applications for detecting ionizing radiation that are currently available on the two main portals (Google Play Store and App Store), for Android and iOS systems, respectively. The following chart summarizes the results of this research, and contains information about developer, prices and number of downloads:

Name	Developer	# of downloads	Rating	Price	Availability
Radioactivity Counter	Rolf-Dieter Klein	>10.000	4.1	3.49 €	Android/iOS
GammaGuard	Environmental Instruments Canada	>5.000	3.6	free	Android/iOS
GammaPix (FULL VERSION) Gamma Radiation Detector	Image Insight Inc.	>1000	3.4	3.79 €	Android/iOS
GammaPix Lite Gamma Radiation Detector	Image Insight Inc.	> 50.000	3.3	free	Android/iOS
Radioactivity-Meter	SpitConsult	>100	3.3	3.56 €	Android
RadSensor (Geiger counter)	Zhang Hong	>1000	3.2		Android

Table 1: Radiation detection applications and their specifications

Some of the softwares known from the past ("WikiSensor", "iRad") were no longer available or not available on both operational systems, while some of them have changed features. For instance, developers of "GammaGuard" removed camera detector functionality. Now the application requires an external device to plug-in, therefore it was discarded from the selection.

"RadSensor" app performs only on a qualitative level since it does not show dose-rates after a measurement but a "level of danger" instead. Its working principle is based on taking photos before and after irradiations, so it was not suitable for real-time purposes.

From preliminary tests "RadioactivityMeter" software showed an unreliable behaviour, therefore only two applications were considered as useful for further testing: "GammaPix" (full version) and "RadioactivityCounter".

The choice also reflects the intentions to better investigate the most widely spread tools, which is reflected in the number of downloads in Table 1.

Both the above-mentioned applications have the same operating principle: the CMOS sensor is sensitive to visible light but can also detect ionizing radiation when shielded with adhesive black tape. After covering the camera, the user may run a measurement that consists of a video record where every interaction of radiation (photons) with the chip is observed as an intense signal in a certain pixel (bright spot). The dedicated software analyses each video frame by counting the number of spots, at a frame rate depending on the smartphone model.

The sum of detected particles in selected time periods is given as number of counts.

"GammaPix" and "RadioactivityCounter" APPs were both downloaded and installed on a total of 14 different mobile phones. The variation in models allowed to investigate the variability in sensitivity of the CMOS sensors and the quality of the app-specific calibration values.

The majority of phones chosen were recent models of most common brands sold in 2017, covering the low, medium and high price range.

In Table 2, the list of smartphones tested and their specifications are reported.
In most cases, manufacturers did not provide information on type of camera sensor and sensor size, therefore this can be only shown for a few models. No information is given for front cameras, since most tests were performed on the back cameras only, as they generally show a higher sensitivity. Exception is the measurement of energy dependence, for which the relative response of the front and back camera was compared for four models.

Brand	Model	Back Camera Resolution [Mp]	CMOS Sensor
APPLE	iPhone 6S	12	No info
ASUS	Zenfone2	13	No info
ASUS	Zenfone3	16	SONY IMX298 Exmor S 5.22 x 9,92 mm /0,26 inches
HUAWEI	P8 lite	13	OV13850 Size 1/3.06"
HUAWEI	P10 lite	12	Size 1/2.8"
HUAWEI	Mate 10	20 + 12	LEICA 1/2.9"
KODAK	Ektra	21	Sony IMX230
LENOVO	K6	13	Sony IMX258 Exmor RS 4,71 x 3,49 mm /0,23 inches
MOTOROLA	E4	8	No info
NOKIA	1	5	No info
SAMSUNG	Galaxy J3	13	No info
WIKO	Lenny3	8	No info
XIAOMI	Mi A1	12	OV12A10 5,11 x 3,84 mm/ 0,25 inches
ZTE	Blade	8	No info

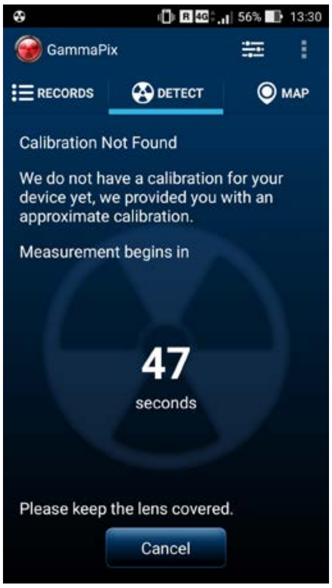
Table 2: Brand, model, back camera resolutions and CMOS sensors specifications of the tested phones

Irradiations were carried out at the Second Standard Dosimetry Laboratory of the HMGU (Helmholtz Zentrum München) with calibrated ^{137}Cs and X-ray sources, the latter with ISO narrow spectrum qualities from N30 to N300. Further investigations with other radionuclides, emitting higher energy photons (e.g. ^{60}Co) were not performed since in case of a nuclear emergency, ^{137}Cs will be the highest photon energy emitting radionuclide contributing to the post-depositional environmental dose-rate.

3 Results

3.1 Results for the App "GammaPix"

After installing "GammaPix" on a device and covering the camera with a black adhesive tape, users have simply to follow first to-do steps guided by some messages.
On all the tested phones, the same communication was shown: "Calibration Not Found" (see Figure 1). After that, the software automatically initializes a three-step procedure for assessing the background and providing an approximate calibration value (see Figure 2).



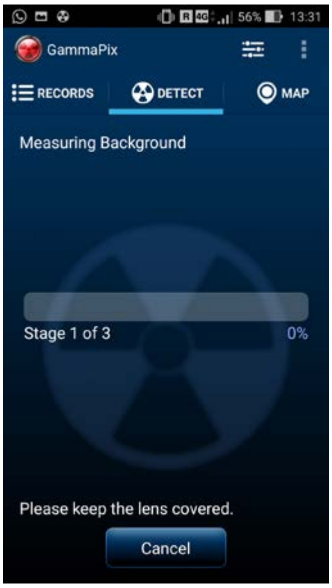
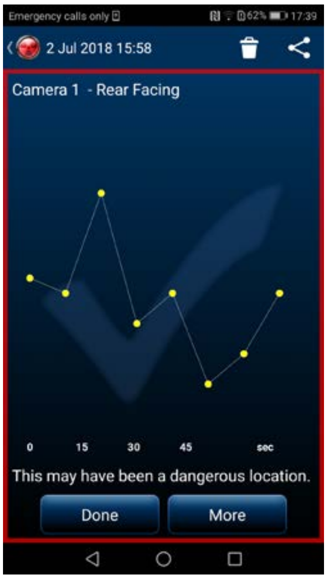


Fig.1 (left) "GammaPix" display of "calibration not found"; Fig.2(right) "GammaPix" background assessment

The same procedure must be repeated in case the user decides to switch camera in the "Options" menu (front to back or vice versa). Afterwards a measurement can be performed in two different modes: "Real Time" or "Three Stage". "Real Time" allows the user to watch the results as a reading is being taken while "Three Stage" quickly gives a warning of danger. In this work, the "Real Time" mode was selected.

Fig.3: "GammaPix" is set ready for detecting ionizing radiation

Also in “Real Time” mode users may set up the “number of measurements” they would like to perform, choosing from a minimum of 5 up to 50. This selection has impact on the duration of a run (e.g. 40 measurements corresponded to around 10 minutes).
The following figures illustrate how an actual measurement display looks like:



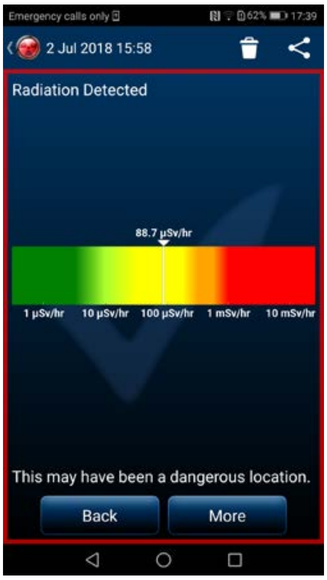


Fig.4 (left) Measurement displayed; Fig 5 (right) Results of a measurement

Measurement is visualized as a series of dots in time where a single dot represents the mean value of the recorded dose-rate in the respective time interval. At the end of the measurement, the average dose-rate detected over the whole time period is represented as a single line in colour-coded, log-scaled dose-rate bar chart.
In fact, after a session three different “alert messages” may be displayed:

1. *Reading Unclear*: means that a low-level source was potentially detected.

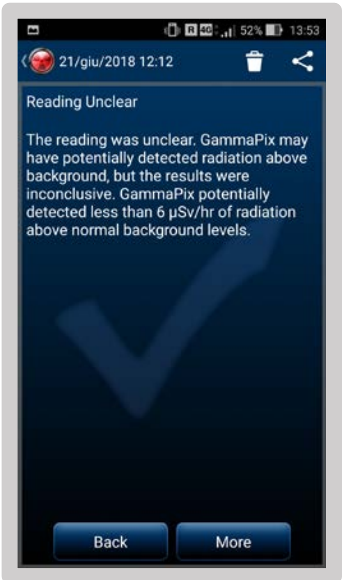


Fig.6: “GammaPix” potential alert

2. *All clear*: no radioactivity was detected, the area is safe.

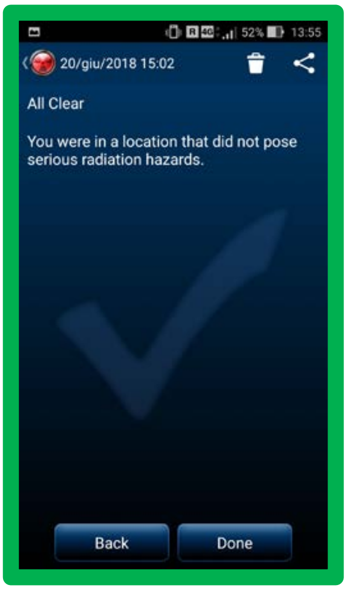


Fig.7: "GammaPix" second type of potential alert

3. *Radiation detected*: an area with high level of radiation was identified.

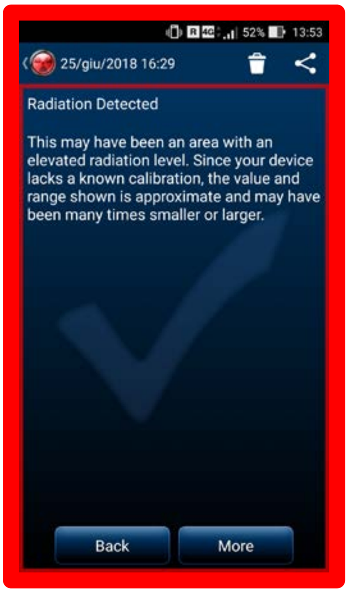


Fig.8: "GammaPix" third type of potential alert

Different "numbers of measurements" for dose rates ranging from 10 µGy h^{-1} to 1 mGy h^{-1} were explored, but "GammaPix" resulted in underestimating the nominal reference values on most of the phones by at least an order of magnitude. In addition, even though a "warning message" represents a fast and clear way to communicate people radiation levels and effects, it sometimes happened, that dose-rates in the order of 50 µGy h^{-1} were categorized as "All clear". Consequently, potentially dangerous misinterpretations may occur.
For these reasons, investigations into this app were stopped at this stage and more efforts were put into evaluating the "RadiaoctivityCounter" app.

3.2 Results for the App "RadioactivityCounter"

The "RadioactivityCounter" app was actually tested at the Second Standard Dosimetry Laboratory of the Helmholtz Zentrum München, before it was launched into the market.
After covering the camera with a black tape, users are requested to "Set the noise" level as shown in the following picture:

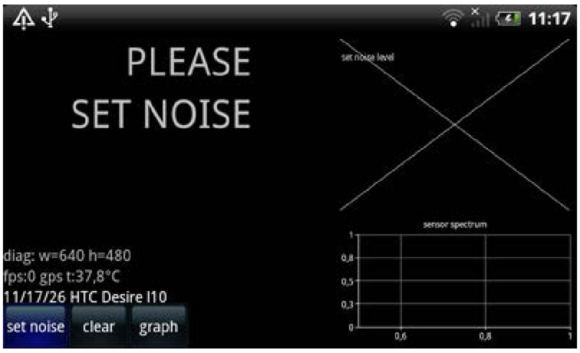


Fig.9: "Set the noise" function display

This procedure allows users to assess the local background radiation level (expressed in "CPM0" = counts per minute at 0 level) and it may vary in time depending on the sensor sensitivity.
Less sensitive phones take around 4 minutes, whereas high sensitive models take around 15 minutes.
This procedure is requested to be completed for both front and back cameras.
Unlike "GammaPix", "RadioactivityCounter" allows the user to perform his own calibration. This is done through a menu section named "Adjust", where it is possible to input calibration factors for converting Counts Per Minute (CPM) to dose-rates values (Figure 10).

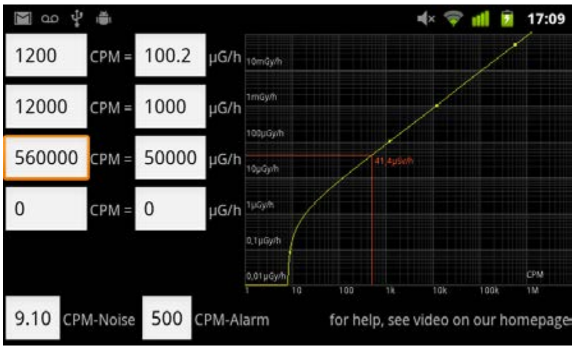


Fig. 10: "Adjust" menu and calibration curve

Developers supply some values in a conversion list on their website, but unfortunately it has been not updated for a longer time, so that currently values for modern smartphones are not available (see Figure 11). It's also true that smartphone technology is rapidly and constantly developing such that is not easy to maintain an up-to-date database.
Therefore, all the tests conducted on the 14 models in this study show results in CPM, apart from the iPhone 6S. In fact, only iOS version of the software has been brought up to date, up to iPhone 8.

RadioactivityCounter Data

The values for n,border and CPM-Noise are set **automatically** after the first calibration - the table is a reference for values we had.

Achtung: Apple iOS User brauchen keine Daten zur Eingabe - **attention** iOS user don't need to enter values, update for iPhone 6 and some other models comming soon (depends on the App Store valdiation process - expect Feb 2016)

tested phones (mean values)	rating	n auto	border	CPM-Noise automatic	CPM for 100 µGy/h	CPM for 1000 µGy/h	CPM for 50000 µGy/h
Sony Xperia D2303 frontcam	*	3	-4	0	0	not yet measured	
Sony Xperia D2303 backcam	***	15	-4	8	180	1800 estim	
Samsung Galaxy Grand Prime	in Test						
Samsung SMT-100	in Test						
Google Nexus 6P	in Test						
Samsung S6	in Test						
Samsung S5	in Test						
Nexus 5 - frontcam	***	2	2	0,3	600	6073	331311
Nexus 5 - backcam	*	1	2	0,3	12	162	7400
HTC ONE - frontcam	**	5	-2	0,1	73	766	34223
HTC ONE - backcam	not working						
Nexus 4 - frontcam	**	12	-2	1,6	48	493	25540
Nexus 4 - backcam	***	4	2	3	148	1609	78199
Samsung S4 - frontcam - GT-I9505	***	6	-2	6,4	200	2025	103666
Samsung S4 - backcam - GT-I9505	***	4	-2	0,2	220	2202	111965
HTC Desire S backcam	******	4	2	2	3225	30421	1617666
Samsung Galaxy Mini GT-S5570 ++	******	3	2	3	2711	27310	1345327
HTC Desire	*****	4	2	2	1933	19058	966015

Fig. 11: Calibration factors listed on "RadioactivityCounter" developer's website

A measurement carried out with "RadioactivityCounter" is shown in Figure 12.

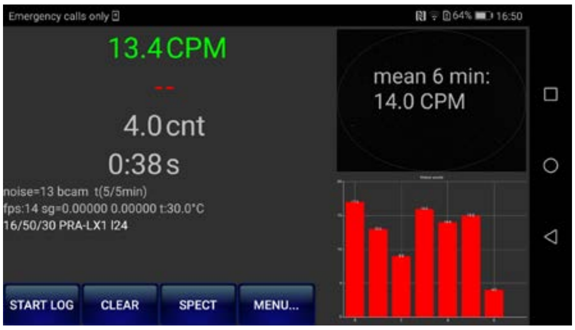


Fig.12: Example of a "RadioactivityCounter" measurement display

Each histogram is built up of counts collected in a one-minute time interval and mean values are also shown. Users can visualize every session of measurement, store it through a "Start log" function and to eventually send the results as a .csv file attached in an email.

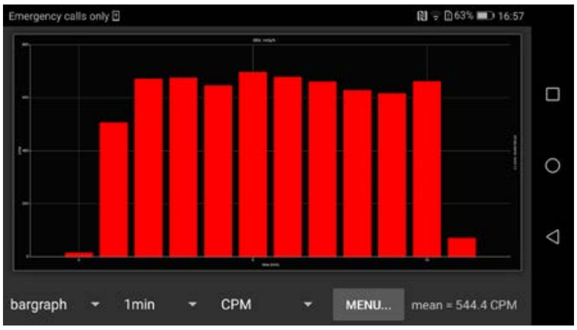


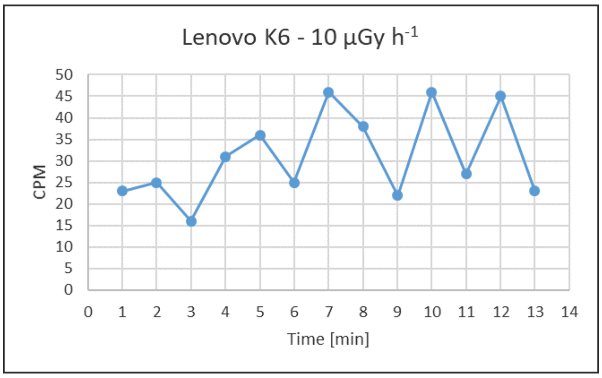
Fig.13: Closer view of a 10 minutes based measurement

The file recorded comprehends details on the phone (brand, model, camera sensor noise…) and on the measurement (date, time, noise level, sensor temperature).
In the following paragraphs results are presented for:

- Dose- rate responses
- Background assessment
- Energy dependence
- Angular response

3.2.1 Dose-rate responses

As first study, dose-rate responses from 5 µGy h^{-1} to 1 mGy h^{-1} on all phone models were investigated. The number of counts detected showed a fluctuating trend that was more evident when a weak source was used (Fig. 14). Mean values started to stabilize over the time for dose-rates above 50 µGy h^{-1} as shown in Fig. 15.



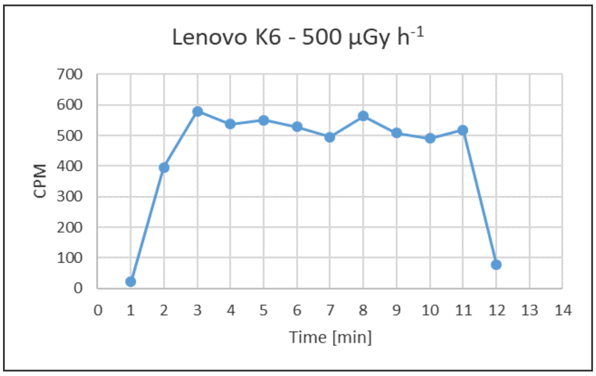


Fig. 14 (left) Counts recorded with Lenovo K6 for 10 µGy h^{-1} irradiation;
Fig.15(right) Counts recorded at 500 µGy h^{-1} with the same phone. During the second time interval, irradiations started and stopped during the last time interval.

Integration time seemed to play a key role in counts fluctuations. Reasonable agreement between reference and measured dose-rates were observed when integrating over more than 10 minutes, whereas large fluctuations occurred for one-minute-based measurements.
Quantitative assessments down to lower dose-rates required longer measurement times.
Therefore, for dose-rates below 10 µGy h^{-1}, a comparison between 10 minutes and 60 minutes based measurements was carried out.

This resulted in a slightly improved match in the lower dose-rate range between nominal and measured dose-rate for four different models (see Figure 16).

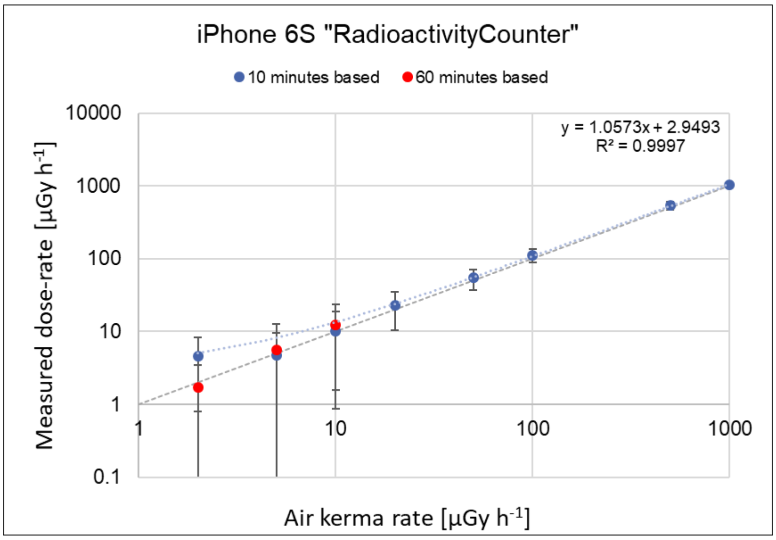


Fig.16: Results of comparison 10 minutes to 60 minutes based measurement on iPhone 6S

Dose-rate responses investigations were also performed in order to contribute to updating the "RadioactivitiyCounter" calibration factors list. Results are reported in Table 3.

Brand	**Model**	**CPM for 50 µGy h^{-1}**	**CPM for 500 µGy h^{-1}**	**CPM for 1000 µGy h^{-1}**
APPLE	iPhone 6S	60	603	1165
ASUS	Zenfone2	476	1865	3620
ASUS	Zenfone3	82	791	1577
HUAWEI	P8 lite	45	363	660
HUAWEI	P10 lite	36	345	671
HUAWEI	Mate 10	585	5311	11229
KODAK	Ektra	166	1491	3148
LENOVO	K6	80	531	993
NOKIA	1	105	749	1640
SAMSUNG	Galaxy J3	85	658	1280
WIKO	Lenny3	95	770	1672
XIAOMI	Mi A1	72	548	1256

Table 3: Calibration factors

3.2.2 Background assessment

The developer for assessing the background radiation level recommends one-hour measurement. In this way, users may vary the CPM0 value determined during "Set the noise" phase and replace it with a more accurate estimate of the influence of the environmental radiation field on the count rate.

The 60 minutes background assessments carried out on all the phone models showed a general agreement with the "Set the noise" values. If the use of an improved background assessment also leads to an improvement in the performance of the app at detecting dose-rates lower than 10 µGy h^{-1} remains to be investigated.

Even though a long integration time is generally recommended, a confounding effect may occur during this procedure. In one model, counts did not statistically fluctuate around a constant background value but continuously increased with time, leading to a count rate at the end of the background assessment, which was two orders of magnitude higher than the count rate at the beginning. An equal trend was observed when the same model was irradiated at a dose-rate of 10 µGy h^{-1}. Checking the .csv file, it could be observed that the temperature of the sensor increased in time as well and in parallel with the count rate.
Therefore, users should be aware that if such a tendency is observed during a background assessment, temperature variation and temperature sensitivity of the sensor might be the cause and not variation in the background dose-rate.

3.2.3 Energy Dependence

Investigations on the energy response were performed on all the phone models in order to assess any energy dependence of the CMOS sensor.
Irradiations were carried out with N30 to N300 X-ray narrow series beams and the response of the sensor normalized to the response at 662 keV, for the same air kerma value. In general, all phones showed the same behaviour, regardless of the quality of the camera sensor: a strong over-response of up to a factor of 15 for a photon energy of around 60 keV. In addition, the relative response of the back and front camera was compared for four models, leading to the conclusion that there was no difference in the response when either camera sensor was facing the source. When the front camera was turned away (180°C) from the source, a slightly improved (i.e. reduced) energy dependence was observed, due to shielding effects. However, this advantage is more than compensated by the disadvantage of a reduced sensitivity of the front camera sensor. Therefore, it is still recommended for users to perform measurements in the field using the back camera.

3.2.4 Angular Response

Further investigations were performed on four phones irradiated from different angles. Scope of this test was to assess any difference in the performance in the app when using either point sources for characterization or extended surface sources in an actual field measurement, where radiation will be coming from all different directions. 0° degree orientation corresponded to the back camera facing the source whereas 180° corresponded to the camera turned away from the source. Data showed an overall variation of the measured signal at maximum about 10%, whereas a sharp decrease in the detector response was observed for an angle of incidence of 90°. This is caused by shielding properties of the smartphone material but has no practical implications for field measurements as such extreme angles of incidence would only be realized by infinitely remote contaminated areas.

4. Recommendations for an improved performance when using "RadioactivityCounter"

The goal of the scientific investigation on smartphone applications in this deliverable was to be able to judge the quality of data produced by such apps following a nuclear emergency. At the same time, the results can also be used to give lay people without any expertise on radiation monitoring some minimum criteria for performing more reliable measurements.
Citizen measurements can be a powerful instrument with technical experts' guidance.
Recommendations are given for the "RadioactivityCounter" app only, since this was the only app for which an in-depth test was performed.

- As a first step, closely follow the developer's instructions on the webpage: ensure to have the camera well covered with black tape (exposing the camera to a bright light source and looking for any increase in the count rate is a good test for this) and start the "Set the noise" function accurately. Even though calibration for Android's systems are more difficult to accomplish, it is recommended to first have a look on the developers' website list.

- Insert calibration values in the "Adjust" menu, if provided by the developer. An updated list for new phone models is reported on paragraph 3.2.1 of this deliverable but it is still a small number compared to the large amount of available phones today. Maintaining the list of phones with calibration values can also be seen as the primary responsibility of the app developer. It will be very difficult, even close to impossible, for lay people to have access to proper calibration sources.

- Before starting a real measurement on field, a background assessment with a one-hour long detection is highly recommended. Such test may help to recognize unusual counts or low dose-rates trends, as observed on one phone model.

- If an increasing tendency is noticed, it is advisable to check the temperature in the correspondent .csv file. It might happen that the sensor sensitivity is particularly dependent on the sensor temperature in the low dose-rate region. If this occurs, then the app cannot be used for reliable measurements below tens of µGy h^{-1}.

- Measurements reliability is influenced by integration time. To reduce count fluctuations, it is strongly recommended to use a minimum measurement time of 10 minutes, preferably 60 minutes (i.e. average 10 or 60 consecutive one-minute based measurements). "RadioactivityCounter" app showed a general accuracy when detecting high dose-rates, whereas for dose-rates below 10 µGy h^{-1}, only averaged values over sufficiently long measurement times were reasonably close to the nominal values. Field-mapping based on one-minute measurements are unreliable and should not be performed. It is further recommended to not only report the average value but also the standard deviation of the measurements. This can be done with e.g. standard Microsoft Office software (e.g. Excel) or LibreOffice.