Monitoring the environmental radiation by using a new gas-filled proportional counter probe as a quasi-spectroscopic system

Dirk Peter Schmalfuß[1], Uwe Hoffmann, Julia Glück, Andreas Meister

VacuTec Meßtechnik GmbH, Dornblüthstraße 14, 01277 Dresden, Germany

Abstract: The "VacuTec Meßtechnik GmbH", specialised in manufacturing radiation detectors since 1956, provides an economic, innovative quasi-spectroscopic proportional counter probe (hereinafter referred as to PCP) that combines a conventional Geiger-Mueller probe (hereinafter referred as to GMP) with a gas-filled proportional detector of high efficiency towards photon radiation. By means of a sophisticated deconvolution algorithm, the continuously updated pulse height spectra are reconstructed into a natural and a non-natural part. To be more precisely, the PCP evaluates the local background by comparing a current spectrum with a set of response vectors containing the radiometric fingerprint of the location where the PCP is installed stationarily, whereby a reliable differentiation is obtained between the local background and non-local spectral contributions of artificial origin. Additionally, χ^2 is calculated as well being extremely sensitive to deviations from the general spectrum shape, for example due to present contamination. Natural background radiation may vary in intensity, for example as a result of precipitation regardless of whether rain or snow, however without the spectrum shape changing. Accordingly, a natural increase of intensity can be well-distinguished from a non-natural increase following a contingent nuclear incident. To obtain additional dose rate data, two Geiger-Mueller tubes are attached. They are operated in an innovative dead-time independent measuring mode. Neutron detection using ^{3}He proportional counters is available optionally. In this paper, we present results of on-going measurements under real environmental and "non-natural" conditions.

Keywords: natural radiation; monitoring network; spectroscopy; gas-filled proportional counter

1 Introduction

To evaluate the composition of complex gamma-fields, spectroscopic systems are increasingly gaining in significance in environmental monitoring especially triggered by the Fukushima incident in 2011. Nowadays, commercial solutions that provide accurate and valid information concerning the potential nuclide vector are based upon scintillators and semiconductors. However, the cost of acquisition and maintenance of such systems are high-priced aside from general stability problems if operated under ambient conditions. Therefore, it is illusory to implement a continuous and comprehensive monitoring network solely equipped with such spectroscopic systems. To mention an example, the German monitoring network is currently operated by using conventional GMP's measuring dose rates only, and on a limited scale, the application of scintillator-based spectrometers is taken into consideration exclusively for selected locations being exposed to a higher nuclear risk. In this context, the "VacuTec Meßtechnik GmbH" has developed a quasi-spectroscopic probe based upon a large volume gas-filled proportional detector to meet the demand of low-cost spectroscopic devices providing at least basic information about the composition of the local radiation registered. The PCP allows a rough analysis of spectra as to the contingent presence of non-natural radiation components. Naturally occurring events such as rainfall can cause a temporary increase of the radiation level. In this case, the increase would be identified as natural variation of the local background, whereas a GMP at best would register merely an unspecific gain of the dose rate not being distinguishable from a possible increase caused by a nuclear incident. Additionally, due to the comparable high efficiency of the PCP towards photon radiation, the data to be obtained are much less interfered by statistical effects. The PCP is thought to be a potential substitute for commonly used GMP's for the comprehensive application under ambient conditions.

---

[1] Dirk Peter Schmalfuß: Dirk.Schmalfuss@vacutec-gmbh.de

2 Formalism

The proportional detector response to photon radiation of different energy constitutes the system matrix A, where the number of rows is given by the number of channels m. Consequently, each column of matrix A represents a certain energy. The number of columns n corresponds to the number of different energies taken into account. Generally, the number of rows is greater than or equal to the number of columns: $m \geq n$. Alternatively, the system matrix A may also be defined in such a way that each column represents the specific photon radiation emitted by a certain nuclide. Thus, each column represents a certain nuclide. Within our approach the natural background radiation is considered as one of these nuclides reflecting the contamination-free situation locally. The choice of the other nuclides depends on which nuclide one would expect to be released in the event of a nuclear incident. Mathematically, the detector response defines a set of basis vectors. Each basis vector can be understood as a discrete probability distribution. In its simplest version applied here, A is composed of $n = 2$ basis vectors only, i.e., the natural component and a pre-set non-natural component. The natural component must be measured on-site initially. Considering the non-natural component, we have chosen the response to 30 keV X-ray photons representing a typical radiation to be expected if ^{137}Cs is accidentally released. To photon energies lower than 100 keV the PCP responds very sensitively. Taking into account the natural constraint $x \geq 0$, the following equation has to be solved:

$$\nabla_{x,\lambda}[(y - Ax)^T(y - Ax) + 2\lambda v^T(y - Ax)] = 0. \tag{1}$$

That way the measured spectrum y is approximately reconstructed as linear combination Ax of the underlying basis set. The Lagrange multiplier λ ensures pulse number conservation. This means that the number of pulses in the measured spectrum is exactly the same as in the reconstructed spectrum. To express the conservation of pulse numbers compactly, an auxiliary vector v is introduced. Its m entries are set to be 1 to sum up the contents of all m channels according to $N = v^T y$. Eliminating λ the solution of (1) reads as follows:

$$Ax = P\left(1 + \frac{vv^T(1 - P)}{v^T P v}\right)y \tag{2}$$

with $P = P^2$ being the corresponding projection matrix given by

$$P = A(A^T A)^{-1}A^T. \tag{3}$$

Obviously, the invertibility of $A^T A$ must be assumed. To obtain count rates, the solution has to be divided by the acquisition time. The conservation of pulse numbers can be easily shown. Right multiplying the transpose of v by (2) yields first $v^T Ax = v^T y = N$. Because of the probabilistic character of the basis set, summing up the entries of A generates the transpose of a new vector u, whose n entries are equal to 1. Accordingly, the conservation of pulse numbers is evident: $N = v^T y = u^T x$. Basically, (2) implies an interesting geometric aspect. Neglecting the pulse conserving term, (2) can be rewritten as follows:

$$A^T Ax = A^T Py. \tag{4}$$

Furthermore, y may be understood as being composed of two contributions, i.e., the parallel part $y_{\parallel}$ and the perpendicular part $y_{\perp}$. The projection matrix acts on both parts differently: $Py_{\parallel} = y_{\parallel}$ and $Py_{\perp} = 0$. Accordingly, one obtains $A^T Ax = A^T y_{\parallel}$. The right-hand side of this equation represents a vector, whose entries are identifiable with the projections of $y_{\parallel}$ onto each basis vector, by definition the covariant components of $y_{\parallel}$. The matrix product $A^T A$ on the left-hand side defines the metric, more precisely, the covariant components $g_{\mu\nu}$ of the metric tensor. Consequently, the solution x represents the set of contravariant components of $y_{\parallel}$. It is evident that the co- and contravariant components of $y_{\perp}$ vanish identically. For that reason, they may be reintroduced formally with the result that (4) can be reformulated according to

$$g_{\mu\nu}y^{\nu} = y_{\mu} \text{ or inverse } y^{\nu} = g^{\nu\mu}y_{\mu} \text{ with } g^{\mu\eta}g_{\eta\nu} = \delta^{\mu}_{\nu}. \tag{5}$$

In summary one obtains the known transformation rules between co- and contravariant vector components within a space characterised by a given metric. This means that basically deconvolution may be considered as transforming the covariant components of y into the corresponding contravariant components.

The relation between both the covariance matrix of x and the covariance matrix of y is given simply by following equation

$$AC(x)A^{T} = P\left(1 + \frac{vv^{T}(1-P)}{v^{T}Pv}\right)C(y)\left(1 + \frac{(1-P)vv^{T}}{v^{T}Pv}\right)P \tag{6}$$

with $C(y) = y_i\delta_{ij}$ being diagonal due to the Poisson statistics that governs the buildup of spectra. Differentiating of $N = v^{T}y = u^{T}x$ yields first $\Delta N = v^{T}\Delta y = u^{T}\Delta x$. By averaging the square of this expression one finds $\langle\Delta N\Delta N\rangle = v^{T}\mathrm{C}(y)v = u^{T}\mathrm{C}(x)u$ with $C(y) = \langle\Delta y\Delta y^{T}\rangle$ and $C(x) = \langle\Delta x\Delta x^{T}\rangle$. Apparently, the sum of all matrix entries of $C(y)$ equals to the sum of all matrix entries of $C(x)$. This sum is nothing but the total number of pulses what agrees with the variance $\langle\Delta N\Delta N\rangle = N$.

The quantity χ^2 tests the hypothesis that both the reconstructed spectrum Ax and the measured spectrum y match as to shape. To illustrate the basic properties of χ^2 clearly, we consider a simplified A composed of one basis vector only, where the quantity to be studied actually is the mean $\langle\chi^2\rangle$. As usual $\langle\chi^2\rangle$ is defined as a sum covering all m channels according to

$$\langle\chi^2\rangle = \sum_k \frac{\langle(y_k - NA_k)^2\rangle}{NA_k} = \sum_k \frac{\langle {y_k}^2\rangle - \langle y_k\rangle^2 + (\langle y_k\rangle - NA_k)^2}{NA_k}. \tag{7}$$

Due to Poisson statistics the variance of y_k is equal to $\langle y_k\rangle$. Introducing $\langle y_k\rangle = NB_k$ one obtains

$$\langle\chi^2\rangle = \sum_k \frac{B_k + N(B_k - A_k)^2}{A_k}. \tag{8}$$

Equation (8) allows a simple interpretation. If B_k equals A_k for each channel both spectra match and $\langle\chi^2\rangle = m$ complies with the number of channels, namely independent of N. Then, the variance of χ^2 is given by $2m$ in the limit of large N. Otherwise, $\langle\chi^2\rangle$ is growing linearly with the number of pulses registered. For a fixed count rate it becomes a linear function of acquisition time indicating that there are existing spectral contributions not being consistent as to the basis. The growing is controlled by the squared difference $B_k - A_k$. The smaller these difference the longer the acquisition time to be needed to reveal residual spectral discrepancies. Without any restriction, all the results apply to the general case of a multicomponent basis.

As mentioned above, the attached low and high dose Geiger-Mueller tubes are operated in a dead-time independent measuring mode based upon the idea of measuring time intervals between consecutive pulses instead of counting pulse numbers per time which would be interfered by dead-time effects. After every single pulse the tubes are quenched and restarted automatically with a defined recovering time much larger than the intrinsic dead-time. This method results in a linear count rate-dose rate relationship, which expands the usable measuring range by one to two decades. As is known, the time up to the next pulse obeys an Exponential distribution with a mean being the inverse pulse rate

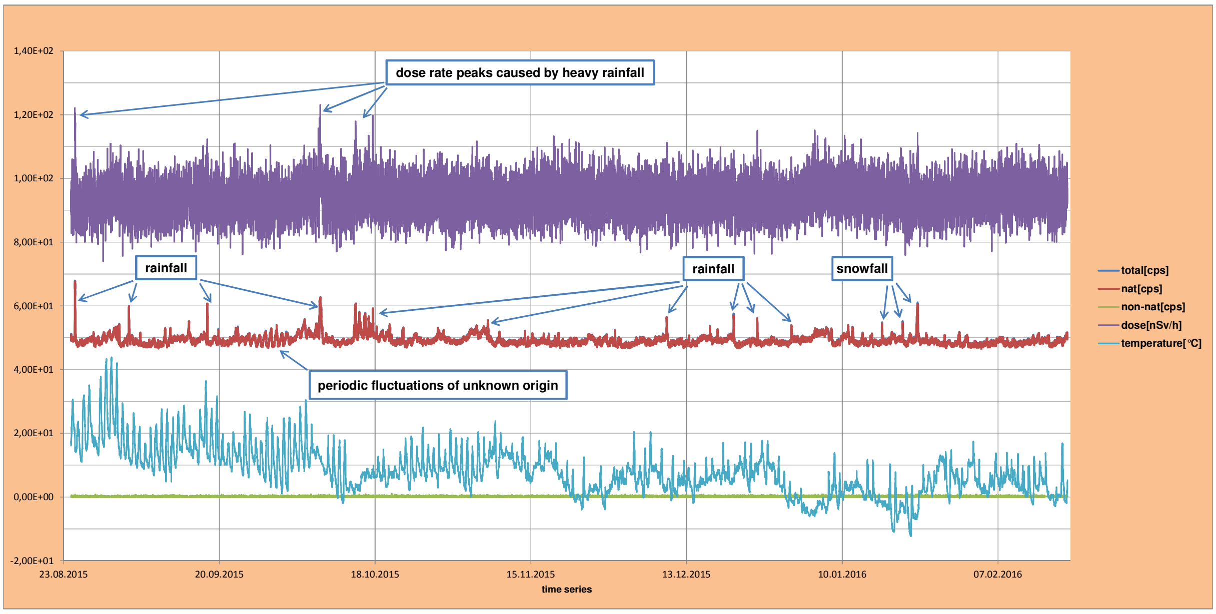
$$\langle\Delta t\rangle = \int_0^{\infty} R\Delta t e^{-R\Delta t}\, d\Delta t = R^{-1}. \tag{9}$$

Both tubes are energy-compensated. Knowing the pulse rates, the corresponding ambient dose rates $\dot{H}^{*}(10)$ can be calculated. The dose rate values of both tubes are used to deduce an overall dose rate taking the statistical precision of the measurements into account.

3 Results

One PCP was installed outdoors on the rooftop of our company building. Dresden, localised in the proximity of known uranium deposits, is characterised by a comparative high natural radiation level. Since August 2015 the PCP has been exposed to various weather conditions with temperatures ranging from +40 °C in late summer down to nearly -20 °C in winter.

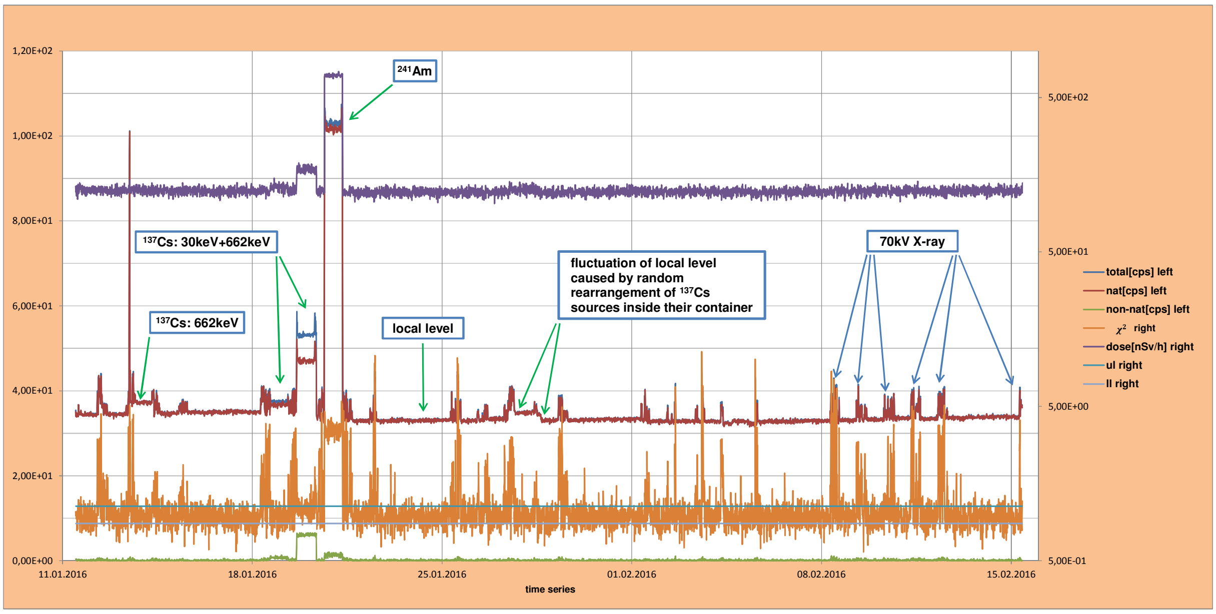
Figure 1: Selection of ambient data recorded during a period from August 2015 to February 2016.



In **Figure 1** recorded data are shown, i.e., the dose rate “dose”, all rate components and the temperature. Due to pulse conservation, the natural component “nat” and the non-natural component “non-nat” provide the overall count rate “total” exactly. The overall count rate displays distinct peak structures. These structures definitely may be attributed to precipitation events regardless of whether rain or snow. During a heavy thunderstorm in late August 2015 the overall count rate increased by nearly 40 % temporarily, however without any effect on the associated non-natural component. Generally, the non-natural component did never exceed its own statistical noise level. Hence, the natural count rate equals the overall count rate approximately. Any increase of the overall count rate is clearly allocated to the natural component so far. In parallel, the associated χ^2 remained within its statistical limits, emphasising that the observed fluctuations were not caused by present contaminations. Another remarkable event occurred in early October 2015 related to a heavy downpour after a longer period of dry weather. The individual characteristic of a precipitation induced radiometric event results from the interplay of various factors such as duration, intensity and frequency of precipitations. Thanks to its extreme sensitivity, the PCP allows a fairly precise insight into the dynamics of a radiation field. The fact that not only precipitation influences the intensity of natural radiation is illustrated in **Figure 1** as well. During a period in September 2015 a cyclical, nightly increase of the background intensity in connection with a recurrent decrease back to the initial level during the daytime was observable. At that time rain could be excluded. Without being able to allocate the concrete causes for the observed fluctuations occurring that time, the data emphasise the sensitivity of the PCP in the face of numerous factors such as geologic, topographic and meteorological conditions along with the omnipresent cosmic background of variable intensity, which influence the natural radiation level directly or indirectly. However, eye-catching dose rate peaks are only to be ascertained in connection with exceptional precipitation events. Otherwise, the course of dose rate is dominated by statistical noise and at best indicates general trends.

To simulate the “worst case scenario”, the PCP was tested next to our calibration facility which is used regularly for development and manufacturing purposes. It provides various photon irradiation devices including ^{137}Cs and ^{60}Co sources of different activity as well as an X-ray system. The measuring setup was installed in an adjoining room ensuring, if any, the PCP would register just a small amount of additional radiation. Prior to the actual test, the natural basis component being typical for the local conditions was recorded during a weekend when the facility usually is not in use.

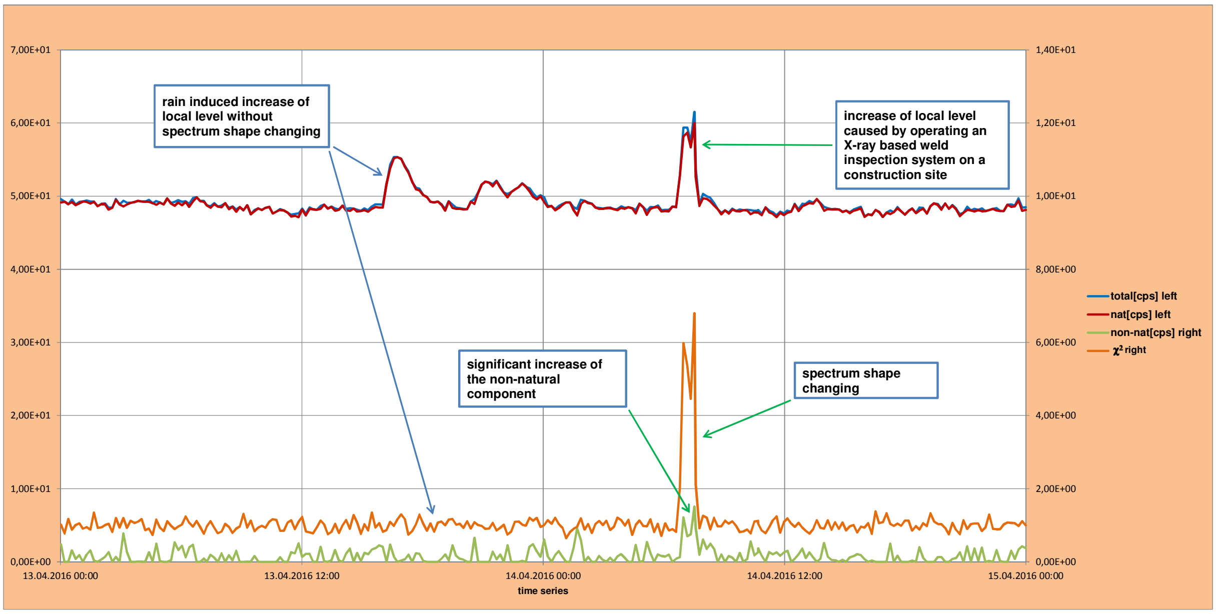
Figure 2: Selection of data recorded next to our calibration laboratory: count rates (left axis); dose rate, normalised χ^2 including its statistical limits (right axis).



The data shown in **Figure 2** comprise the dose rate “dose”, both rate components “nat” and “non-nat”, the overall count rate “total” as well as χ^2 divided by m, measured during four weeks of normal business. Both horizontal lines “ul” and “ll” denote the upper and lower limit respectively, within χ^2 may fluctuate provided the spectra are consistent with the basis set. Obviously, distinctive effects were observed when the X-ray system was operating. Depending on the applied tube current, both the overall and the natural count rate increased considerably while the non-natural count rate responded in a rather modest way. However, the concurrent risen χ^2 indicates the presence of spectral contributions being different from the contamination-free local background. The radiation of a ^{137}Cs source emitting 662 keV photons only has induced a slight gain of pulses registered. Neither the non-natural component nor χ^2 has been affected noteworthy, which presumably is due to low additional intensity connected with the fact that the detector responds to photons of higher energy in a rather uniform way. Equation (8) would provide an explanation that therefore χ^2 seems to be widely unaffected. Nevertheless, considering the distance, the separating wall and the source being used inside a massive lead shielding, it is astonishing that there has been a measurable effect at all. Even the random rearrangement of ^{137}Cs sources inside their storage container has raised the overall count rate significantly. Free ^{137}Cs emits 662 keV photons along with 30 keV photons. To reproduce an accidental release of ^{137}Cs on the laboratory scale, the PCP was irradiated additionally using small ^{137}Cs sources of different activity. These sources have thin windows allowing low energy photons to escape. According to **Figure 2**, as expected both the natural as well as the non-natural component increased obviously depending on the additional intensity provided. Evidently, the gain of χ^2 has been a matter of intensity as well. Because of the spectral similarities mentioned above, it would take a longer acquisition time to indicate the presence of free ^{137}Cs solely by the increase of χ^2. Furthermore, the PCP has been exposed to the radiation of a fairly strong ^{241}Am source emitting 60 keV photons. Apparently, this radiation did not fit to the underlying basis set which is clearly visible regarding χ^2. Except for radiation originating from those sources, the corresponding dose rate has proved widely to be much less sensitive to fluctuations of the radiation level.

In April 2016 the PCP on the rooftop registered the concurrence of two radiometric events of different origin within a 24-hour period, which is well-illustrated in **Figure 3**. The first radiometric event was induced by a thunderstorm in the evening of April 13th. Due to heavy rainfall the overall count rate and its natural component increased temporarily, however without having any effect being visible neither on the non-natural component nor on χ^2, whereby the observed increase of radiation may be considered as natural variation of the normal background level. As opposed to this, the increase of radiation the next morning was accompanied by a significant gain of both χ^2 and the non-natural component suggesting the temporary presence of artificial spectral contributions. The further investigation revealed that the additional radiation arose from an operating X-ray based weld inspection system on a construction site nearby.

Figure 3: Concurrence of a natural and a non-natural radiometric event within a 24-hour period: the data shown comprise the overall count rate and its natural component (left axis), its non-natural component and normalised χ^2 (right axis).



4 Conclusions

Applied to monitor environmental radiation, the introduced PCP enhances the extent of available information. By deconvoluting continuously updated pulse height spectra, the PCP is capable of differentiating between natural and non-natural radiation components. The PCP may be integrated into monitoring networks as a substitute for conventional counting probes based upon Geiger-Mueller tubes. In addition to dose rate data, it provides basic evidence of the spectral constitution of the radiation being detected. Where ordinary GMP's at best would register just unspecific fluctuations of the background level, the PCP allows a rough spectroscopic classification. For example, a temporary increase of radiation, typically induced by naturally occurring events such as precipitation, will be identified as a non-hazardous variation of the natural background, whereby man-made causes may be excluded. Being very sensitive to any deviation from the local background, the PCP indicates the presence of air or surface contaminations, however without analysing the hypothetical nuclide vector itself.