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A Deviation Display Method for Visualising Data in Mobile Gamma-ray Spectrometry

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Abstract

A real time visualisation method, to be used in mobile gamma-spectrometric search operations using standard detector systems is presented. The new method, called Deviation Display, uses a modified waterfall display to present relative changes in spectral data over energy and time. Using unshielded ^{137}Cs and ^{241}Am point sources and different natural background environments, the behaviour of the Deviation Displays is demonstrated and analysed for two standard detector types (NaI(Tl) and HPGe). The Deviation Display enhances positive significant changes while suppressing the natural background fluctuations. After an initialisation time of about 10 minutes this technique leads to a homogeneous display dominated by the background colour, where even small changes in spectral data are easy to discover. As this paper shows, the Deviation Display method works well for all tested gamma energies and natural background radiation levels and with both tested detector systems.

1 Introduction

Many tasks in the field of emergency preparedness calls for mobile gamma-ray detecting systems. When searching for orphan sources (IAEA 2004) or mapping contaminated areas the search areas can be vaguely defined and vast. The pre-knowledge of source conditions, for instance, may range from none to almost complete information on source geometry, radionuclide identity and activity. Irrespective of whether air- or carborne, the search crew needs some guidance when interpreting the signal from the detector. The objective of this paper is to describe one such guidance method for visualising significant changes in the field of view of the detector.

Considering carborne platforms alone, the common recipe for mobile detecting systems is one or several large volume gamma-ray detectors, repeated short-term measurements and not too slow vehicle velocities. The detector platform itself needs special-designed computer software that deals with the constant information flow from the detector, positioning system and additional devices. Often, the Graphical User Interface (GUI) of such a program displays a wide range of user-defined parameters and graphs in real time. From simple parameters like intensity levels of specific radionuclides (Mellander 1998) or Potassium-Stripped Counts (PSC) in a Region of Interest (Hjerpe and Samuelsson 2003) via simple displays like the "waterfall" display (see "rainbow method" in Aage and Korsbech 2003), to more complex filtered displays (Cresswell and Sanderson 2009) and imaging routines (Ziock et al. 2003; Ziock et al. 2007). Many methods implemented in such programs have pre-defined alarm levels on different parameters, helping the search crew with indication. Alarms are, however, not within the scope of this paper.

The largest challenge when interpreting mobile gamma spectrometric information is the ever-changing radiation background. Ideally, both systematic changes and stochastic fluctuations in the photon field must be taken into account in order to achieve a sensitive and at the same time reliable search method. While stochastic fluctuations can be dealt with using statistical methods, incorporation of systematic changes into the search method is difficult and requires some knowledge *a priori*.

This paper describes a method to construct a straightforward and informative display - the *Deviation Display* (DD) - that enhances positive changes in spectral data. One purpose of this work was to construct a detector-independent method to display data in real time. This means that the Deviation Display should be suitable for all energies, both scintillator- and semiconductor-systems and at all naturally occurring levels of radiation. The method works with real time data and the Deviation Display functions both as a search tool and as an overview of background radiation trends. Consequently, this method could improve the search effort when searching for gamma-emitting sources using mobile platforms.

2 Theory and Methods

The signal processing problems present in mobile gamma spectrometry are virtually the same as in other fields of digital signal processing. Commercially available software, like MATLAB[1], offers a large set of tool kits for processing and presentation of digital data. One of the functions found in MATLAB is the waterfall window display. Conventional waterfall displays present consecutive colour-scaled data arrays side by side as seen from above. Individual bins within each array are mapped on a colour range consisting of contrasting colours. After each data acquisition the measured data is added as a coloured line to the

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[1] MATLAB is a software package produced and supported by The MathWorks, Inc, Natick, MA, USA.

display, making it flow with time (for a brief description see Aage and Korsbech (2003) or the MATLAB user manual).

2.1 The Deviation Display method

The proposed Deviation Display method is based on relative comparisons on a channel-by-channel basis. Let $m_{i,j}$ be the mean count rate (s^{-1}) in channel i after j measurements

$$m_{i,j} = m_{i,j-1} + \frac{c_{i,j} - m_{i,j-1}}{j} \tag{1}$$

where $c_{i,j}$ is the observed count rate using the same notation. The observed counts per time unit in channel i fluctuates about its mean with a sample standard deviation of

$$s_{i,j} = \sqrt{\frac{1}{j-1}\sum_{k=1}^{j}(c_{i,k} - m_{i,j})^2} \tag{2}$$

The dimensionless standard Z score, as computed by Tewari (1988), can then be used to find anomalous regions in the spectral data

$$Z_{i,j} = \frac{c_{i,j} - m_{i,j}}{s_{i,j}} \tag{3}$$

Here, a modified version of the Z score statistic is used. Let $q_{i,j}$ be the relative deviation from the mean plus n standard deviations.

$$q_{i,j} = \max\left\{0, \frac{c_{i,j} - (m_{i,j-1} + n \cdot s_{i,j-1})}{n \cdot s_{i,j-1}}\right\} \tag{4}$$

The observed j:th count rate is thus put in relation to the expected count rate based on the latest $j-1$ observations for that channel. For each sampled spectra j, the vector $\mathbf{q}_j = [q_{1,j}, q_{2,j}, \ldots, q_{n,j}]^{\mathrm{T}}$ is calculated. All negative elements in $\mathbf{q}_j$ are set to zero in order to enhance positive changes in the count rate. By storing the historical maximum positive deviation, $q_{\max}$, a relative deviation can be calculated. Using a colour scheme of C colours each $q_{i,j}$ is colour-coded, i.e. mapped in the range $[0, C]$ by scalar multiplication.

$$\mathbf{w} = \frac{C}{q_{\max}} \cdot \mathbf{q} \tag{5}$$

The weighted vector $\mathbf{w}$ represents a new column in the Deviation Display matrix $\mathbf{Q}$, which has m columns (histories) and n rows (channels). The Deviation Display algorithm takes as input parameter the weighted column-vector $\mathbf{w}$ and adds it to the display matrix $\mathbf{Q}$ ($m \times n$ elements), thus pushing out the oldest spectra if more than m measurements exist. In surveys with High-Purity Germanium (HPGe) detectors, using a conversion gain of $n = 4096$ channels or more is not uncommon. With $m = 250$ histories to display, this means that over

10^6 elements has to be evaluated and displayed for each new sampled spectra. But since a 4096 pixel column will not fit onto most computer screens, $\mathbf{w}$ can be scaled down to, for example, a 512 element vector by forming one new bin out of every eight channels.

2.2 Background estimation

As the number of collected spectra j grows, each channel mean $m_{i,j}$ will approach the true background mean as long as there is no systematic changes in the background radiation level. This will result in a homogeneous Deviation Display dominated by the background colour of choice. In other words, the stochastic background fluctuations within each channel will be suppressed, enhancing significant positive changes in the count rate.

The optimal size of the set of spectra, j, can vary depending on the prerequisites of the measurement situation. Normally more samples give a better estimation, but this is not always the case in mobile gamma spectrometry, since the samples are not drawn from the same distribution. If the background radiation level is drastically changing over short distances (hundreds of metres), as in many urban areas, a high spatial resolution can be favourable, thus limiting the number of samples, j, which can be used to build up a representative background. In the other extreme, a background where the fluctuations are purely stochastical, allows for a large j giving a very good estimation of the background level in each channel. This situation, or at least a good approximation of it, can be found when the detector is stationary, like in most laboratories.

A number of different background subtraction techniques exist. In a recently published study, independent of this work, Cresswell and Sanderson (2009) used a rolling average background constructed from filtered difference spectra. The filtering was based on both full spectrum count rates and count rates for the spectral windows used in the standard windows stripping analysis. Spectra passing all the filters were added to the rolling background. In this work, the filtering is instead done on a channel-by-channel (or bin-by-bin) basis as shown in Eq. (4), rejecting only negative $q_{i,j}$. Furthermore, as described below, the background approach here is different from that of Cresswell and Sanderson (2009). To make the method detector-independent it is necessary to allow for a fairly large number of background spectra j. While 30s of background sampling might be enough for large NaI(Tl) that is seldom the case for HPGe and small NaI(Tl) detectors, given moderate background levels.

In the field experiment (see next section) the same methodology for background sampling as described in Hjerpe et al. (2001) was used. Here, instead of deciding alarm levels, the background measurements were used to sample the relative deviations, $q_{i,j}$. Hjerpe and Samuelsson (2003) showed that a representative background distribution could be estimated after about 45 minutes by driving around the area where the experiments should take place. Since the field experiment in this work was undertaken at the same site, this result applies here as well. Hence the natural background distribution, shown in Fig. 1, was sampled by driving around the area in question for about 45 minutes.

3 Materials and Experiments

3.1 Spectrometry systems

In the field experiment a P-type High-Purity Germanium (HPGe) detector[2], model no. GEM 100-S, with 123 % relative efficiency from Ortec[3] was mounted in a GMC van at a height of approximately 2 m above the ground. The detector's cylinder axis was horizontally orientated with the end-cap facing the rear of the van. A digital, portable, Multi-Channel Analyser (MCA, Ortec Digidart), with the conversion gain set to 4096 channels was used. The MCA communicated with a laptop-PC over the USB (Universal Serial Bus) interface, sending a new pulse height distribution when requested. To reduce microphonia due to the roughness of the road, the detector was mounted on a layer of approximately 10 cm of foam rubber.

The NaI(Tl) spectrometry system used in the laboratory experiment is a portable backpack solution. It uses a 7.62 x 7.62 cm cylindrical detector[4] from Saint-Gobain[5] , model no. 3M3/3, equipped with a 14-pin PMT (PhotoMultiplier Tube), integrated Bias Supply, pre-amplifier and digital MCA manufactured by Ortec (Ortec Digibase). The system was made for field use and assembled by Gammadata[6].

3.2 Field experiment

To test the sensitivity of the method described in this work on a strong point source far away, a field experiment was undertaken at the military training ground near Revingehed, 15 km east of Lund, Sweden. An isotropic ^{137}Cs source with an activity of 1.8 GBq, sealed in a 2 mm thick steel capsule, was used to represent an orphan source.

The Critical Distance (CD) is defined by Hjerpe and Samuelsson (2003) as "the distance from the road at which a source can be detected with 50% probability when driving by". Here, the source was placed at $D = 130$ m perpendicular to a 400 m long straight stretch of the road and driven by 10 times at a speed of 50 km h^{-1}. This distance was not arbitrarily chosen, it equals the CD of a 2 GBq ^{137}Cs source using a 7.62 x 7.62 cm NaI(Tl) system and the PSC-method, as shown by Hjerpe and Samuelsson (2003).

With the source sealed in the steel capsule and at a distance of 130 m, the primary photon fluence rate at the road was approximately 10 % lower than that for the same distance in Hjerpe and Samuelsson (2003). This difference is balanced by the slightly larger detector used in this work, making the experiment carried out in this work comparable to those of Hjerpe and Samuelsson (2003), in terms of sensitivity.

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[2] s/n p41629A

[3] Ortec, 801 S. Illinois Ave., Oak Ridge, TN, USA.

[4] s/n 60004-02515-1

[5] Saint-Gobain Cristaux, 104 Route de Larchant, Nemours, France.

[6] Gammadata Instrument AB, Vallong. 1, Uppsala, Sweden.

3.3 Laboratory experiment

To demonstrate the cross-detector application of the Deviation Display method a small-scale experiment with a ^{241}Am source (70 kBq) was done using the NaI(Tl) backpack system described above. By choosing a primary photon energy in the X-ray band (60 keV), the natural background level is substantially increased due to scattered photons. This energy was chosen to demonstrate the ability of the DD-method to enhance positive changes in an energy band with higher background noise, where a weak signal is harder to distinguish.

A plastic tube containing the sealed ^{241}Am source was carried ten times past the detector at close range ($\simeq$ 10 cm) and at a slow constant speed ($<$ 5 km h^{-1}). After every passage there was a pause for a few seconds to make each passage distinguishable. The sampling rate was 0.5 Hz. In this experiment the natural background distribution, shown in Fig. 2, was sampled for about 10 minutes. This relatively short time results in greater uncertainties in the measured channel means. However, when the detector is stationary, 10 minutes of measurements will suffice to give a rough approximation of the natural background.

3.4 MOBCAL-08 exercise

During 2008 the Swedish Radiation Protection Authority organised an exercise (MOBCAL-08) in the surroundings of Gävle in central Sweden. One task was to measure the background radiation levels using carborne gamma-ray spectrometry. As this area holds many places with high concentrations of radiocaesium due to Chernobyl fallout (NKS, 2002), the focus of the exercise was mainly on ^{137}Cs.

An excerpt of the background measured in the exercise by a team from the Swedish Customs is presented here to show some of the relative strengths and weaknesses of the DD compared to the normal waterfall display. The data were measured with a GR-460 system manufactured by SAIC Exploranium[7], which uses a 4L NaI(Tl). Raw data for the 512 channels were extracted from the save files produced by the GR-460 software. The sampling rate was 1 Hz and the car held a speed of about 30 km/h. The background gross counts along with the ^{137}Cs-window gross counts of the excerpt are presented in Fig. 6, for comparison with Figs 1-2.

4 Results and Discussion

Three examples are presented to elucidate the behaviour of the Deviation Display method, the field experiment represent a strong source far away and the laboratory experiment represent a weak source close to the detector, lastly an example from a more challenging background environment is presented.

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[7] SAIC Headquarters, 1710 SAIC Drive, McLean, VA, USA.

4.1 Background distributions

The background gross count rates presented in Figs 1, 2 and 6 were used to characterise the background environments. The $\pm 2\sigma$ dashed lines in the figures should contain about 95% of the samples given a single pure Poisson distribution. As expected, the variances are greater in the outdoor background distributions, where the detector is constantly moving around, thus sampling from a large number of different Poisson distributions. About 52% and 34% of the sampled counts are within the $\pm 2\sigma$-region for the field experiment and the MOBCAL-08 exercise backgrounds respectively, while this region contained about 95% for the laboratory experiment. A good agreement with the theoretical Poisson distribution was expected in the laboratory experiment since the detector was stationary.

The statistical dispersion of the natural radiation background sampled at the field experiment site is still fairly low when compared to, for instance, that of an urban area (Jarman et al. 2008) or that of the MOBCAL-08 exercise (Fig. 6). This relative homogeneity in the background radiation levels also allowed for a large j, without increasing the risk of estimating the channel means from samples of an unrepresentative background distribution when driving around. A direct consequence of this "low-background" is that a CD measured at Revingehed with a certain method and detector system should be quite close to the ideal CD for that configuration.

A much more fluctuating background environment is seen in Fig. 6, showing some systematic changes which leads to a non-poissonian behaviour. As only 34% of the full spectrum counts fall within the range of $\pm 2\sigma$, finding an representative estimate of the channel means valid for the whole set is difficult if not impossible. The strong correlation between ^{137}Cs window gross counts and the full spectrum gross counts, both shown in Fig. 6, also confirms that Chernobyl fallout constitutes most of the background in the area. High and heterogeneous ^{137}Cs levels characterise this area, favouring a higher spatial resolution, thus favouring a relatively short background i.e. small j.

4.2 Deviation Display method

The result from the HPGe field experiments at Revingehed is shown in Fig. 3. Several γ-lines from the natural background can be seen in the conventional waterfall display in the left half of Fig. 3. Among them, the 1.46 MeV line from ^{40}K is the most prominent. Colours are calculated with Eq. (5), so that $q_{\max}$ is displayed in white in the Deviation Display. In the conventional waterfall display the maximum count rate measured is displayed in white.

To avoid the influence of previous passages in the subsequent all statistics (m, s, j, q and $q_{\max}$ in Eqs. (1-5)) were reset to their background values after each source passage. The background value is simply a value stored immediately before the first source passage. This procedure, used in both the field and laboratory experiments, gives each run the same basic conditions in terms of deviation from the mean, and hence detection. This procedure is necessary to make each individual source passage comparable to the others as well as to Hjerpe and Samuelsson (2003), where the moving background was free of any source influence by the time of next passage.

As can be seen in Fig. 3, the image produced using the Deviation Display method is much more homogeneous than the normal waterfall display. The natural background is effectively suppressed, so that the lines disappear, leaving a display dominated by the background colour of choice. At the same time the method enhances positive significant changes over the whole energy range covered by the display, leaving the ten dots from the ^{137}Cs source passages.

The choice of n in Eq. (4), i.e. the number of standard deviations, is a balance between sensitivity and statistical strength. The DD images in Figs 3 and 5 are produced using $n = 2$, which gives a reasonable balance between the background noise level and the enhancement of changes on the positive side. For comparison, Fig. 4 shows the first four ^{137}Cs passages (rightmost in Fig. 3) from the field experiments, for three different n. As can be seen in the figure, the background suppression works better for the two higher values of n. On the other hand the source passages are "sharpened", covering smaller and smaller areas around the peak's centre channel with increasing n.

Fig. 5 shows the output from the low-energy region from the laboratory NaI(Tl) experiment. Again, the source's passage can be seen in both displays, but are more prominent in the Deviation Display. The poorer resolution of the NaI(Tl) detector results in broadened full energy "peak-lines" rather than the "peak-dots" observed in the HPGe-measurements (Figs 3 and 4). The slightly higher noise level seen in Fig. 5 can be explained by the incomplete background estimation prior to the source passages and by the zoom level of the figure. This experiment shows that the Deviation Display method works well after about 10 minutes of background sampling for a stationary detector of this size, even in this high background regime.

The last 200 s from the 4L NaI(Tl) MOBCAL-08 exercise excerpt are shown in Fig. 7. The difference solely from the choice of background algorithm are presented in Fig. 7, showing two Deviation Displays produced using both a long (>300 s) and a short (50 s) background. The high ^{137}Cs levels at the beginning of the excerpt leaves a band of void in the long background DD, while the short background DD displays some variations in ^{137}Cs levels. The DDs in Fig. 7 are also less homogeneous than the ones in Figs 3-5, mainly due to drastic changes in the background level fluctuations (compare Figs 1-2 and Fig. 6), but also due to the choice of n. The DDs in Fig. 7 were produced using $n = 1$, which better shows the differences between the background algorithms.

A local ^{232}Th feature, visible in Fig. 7 through ^{208}Tl (2.61 MeV) and scattered radiation, appear after about 420 s. It is clearly visible and easily identifiable in the DDs alone. The normal waterfall display reveals a high contribution in the lower parts of the energy spectrum due to scattered photons from ^{232}Th daughters, with a slight enhancement to the 2614 keV ^{208}Tl peak. But the signal above about 1.5 MeV is clearly visible in the DDs only.

Background sampling times from 50 s to 45 minutes were used in this work. The initialisation time required for the DD method to produce an acceptable display depends on the detector type and size, the number of bins used and the background radiation level. However, as shown in the examples above, 10 minutes of sampling is enough for all but the most extreme scenarios.

5 Conclusions

The superior resolution of a HPGe-system compared to a NaI(Tl)-based system results in a narrower full energy region and thus a lower inherent background, giving a much sharper display. Hence, a source placed at the Critical Distance of a specific NaI(Tl)-system should be clearly observable when using a HPGe-system of equal size. This is confirmed on a qualitative level by the ten clearly visible dots produced by the Deviation Display, seen in Fig. 3. The results presented here are thus in line with those of Ziock and Nelson (2007), who argued that a semiconductor system will out perform a scintillation-based system of comparable size, given that spectroscopy can be used to limit the background (which is the case in this work).

The Deviation Display method gives satisfactory results for all tested systems, and at all tested energies. This method should, in fact, work with any detector used in mobile gamma spectrometry today, since it is based on relative comparisons. Furthermore, as a consequence of the relative comparisons, there is no need to rewrite the software when switching between detector types. The key to a good result using this method is stability in energy over time, since each channel (or bin) has its own statistics.

The initialisation time for the method depends on both internal (detector type and size and the number of bins) and external (background environment and shielding) factors. From the results of this work we conclude that 10 minutes of sampling, stationary or mobile, would be an sufficient initialisation time for all but the most extreme detector/background scenarios.

Depending on the characteristics of the background environment, the choice of background sampling technique giving the best Deviation Display differ. When the detector is stationary, a large number of background spectra yields a more representative mean, hence giving a more homogeneous and “eye friendly” display. The same conclusion applies when mobile in areas with small to moderate systematic changes in the background radiation levels, for example that of the field experiment presented in this work. Conversely when mobile in more challenging environments a small number of background spectra is preferable. A conservative choice when searching for anomalies in an unknown area would be to start with a fairly small rolling background. The size may then be gradually increased (decreased), manually or by an algorithm checking the background variations, if the variations are low (high).

The Deviation Display method can also be a quick and convenient way to ensure that the detector system is working properly and that it is stable. Energy drift or microphonia can be readily spotted in the display as perturbations in the background levels. A slight energy calibration drift would appear as a new thin false source line in the DD. This should draw the attention of the operator, who then can identify the perturbation by studying the normal waterfall display.

When searching for orphan sources or mapping contaminated areas, the new semi-automatic Deviation Display method presented here could assist the operator. It is automated in that the method continuously sorts out significant changes on the positive side. On the other hand the operator will have to study the display at all times to be able to detect an orphan source or increased levels of radioactivity. In conclusion, the search operation could benefit from combining the Deviation Display method with some fully automatic real time alarm method (see for example: Hjerpe and Samuelsson (2003) or Jarman et al. (2008)).

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fig 1

Full spectrum gross count rates of background measurements from the field experiment at Revingehed. The dashed lines mark ±2 standard deviations about the mean (solid line) of a Poisson distribution.

fig 2

Full spectrum gross count rates of background measurements from the laboratory experiment. The dashed lines mark the ±2 standard deviations about the mean (solid line) of a Poisson distribution.

fig 3

Normal waterfall display (left) and new Deviation Display (right) from HPGe detector measurements, when passing the ^{137}Cs source ten times. Each pixel-column shows data sampled during 6 s. Data is pushed from left to right so that the oldest spectra is on the far right side of the figure.

fig 4

Detailed view of the first four ^{137}Cs source passages from the field experiment, plotted for three different number of standard deviations, i.e. three different n from Eq (4). Bottom $n = 1$, middle $n = 2$ and top $n = 3$.

fig 5

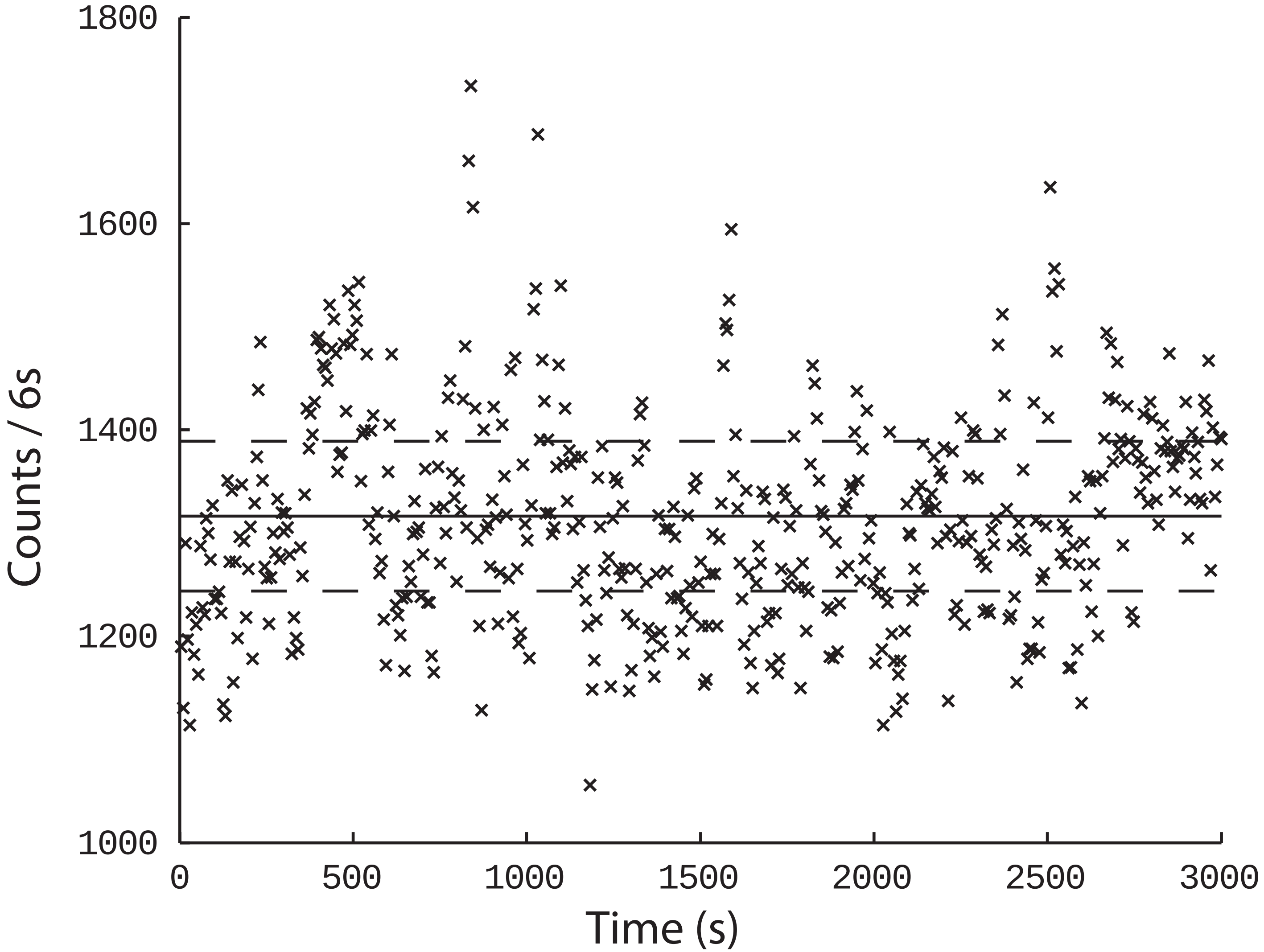
Normal waterfall display (left) and new Deviation Display (right) from the laboratory experiment. The ^{241}Am source passes the detector ten times at a slow speed. Each pixel-column shows data sampled during 2 s. Data is pushed from left to right so that the oldest spectra is on the far right side of the figure.

fig 6

Full spectrum and ^{137}Cs window gross count rates from the MOBCAL-08 exercise excerpt. The dashed lines mark the ±2 standard deviations about the mean (solid line) of a Poisson distribution.

fig 7

The last 200 s of the MOBCAL-08 4L NaI(Tl) excerpt showing a local ^{232}Th feature. Normal waterfall display (a) and Deviation Displays sampled with approximately 300 s of background (b) and a rolling background of 50 s (c).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1600
1400
1200
1000
Counts / 6s
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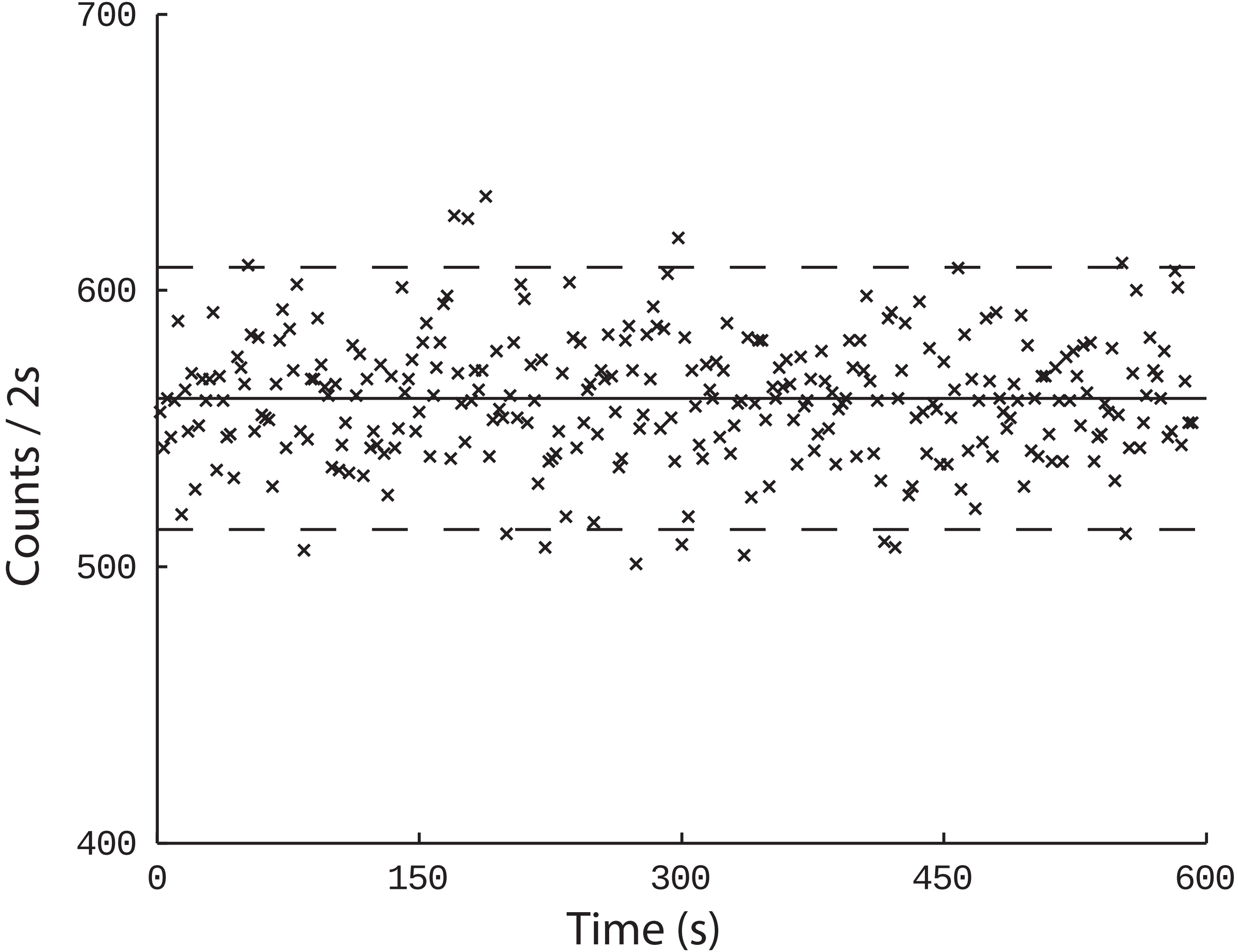
500
1000
1500
2000
2500
3000
Time (s)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Counts / 2s
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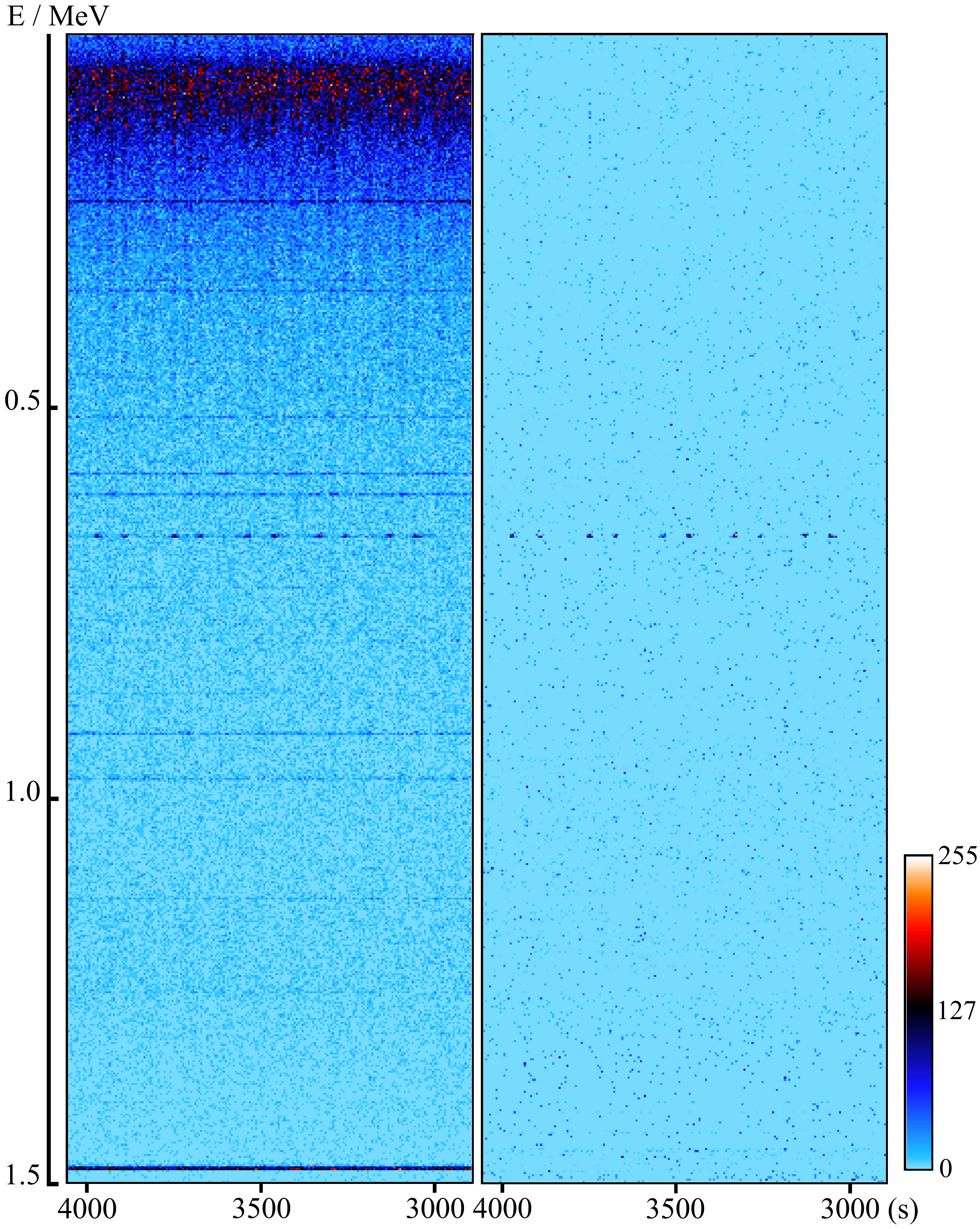
150
300
450
600
Time (s)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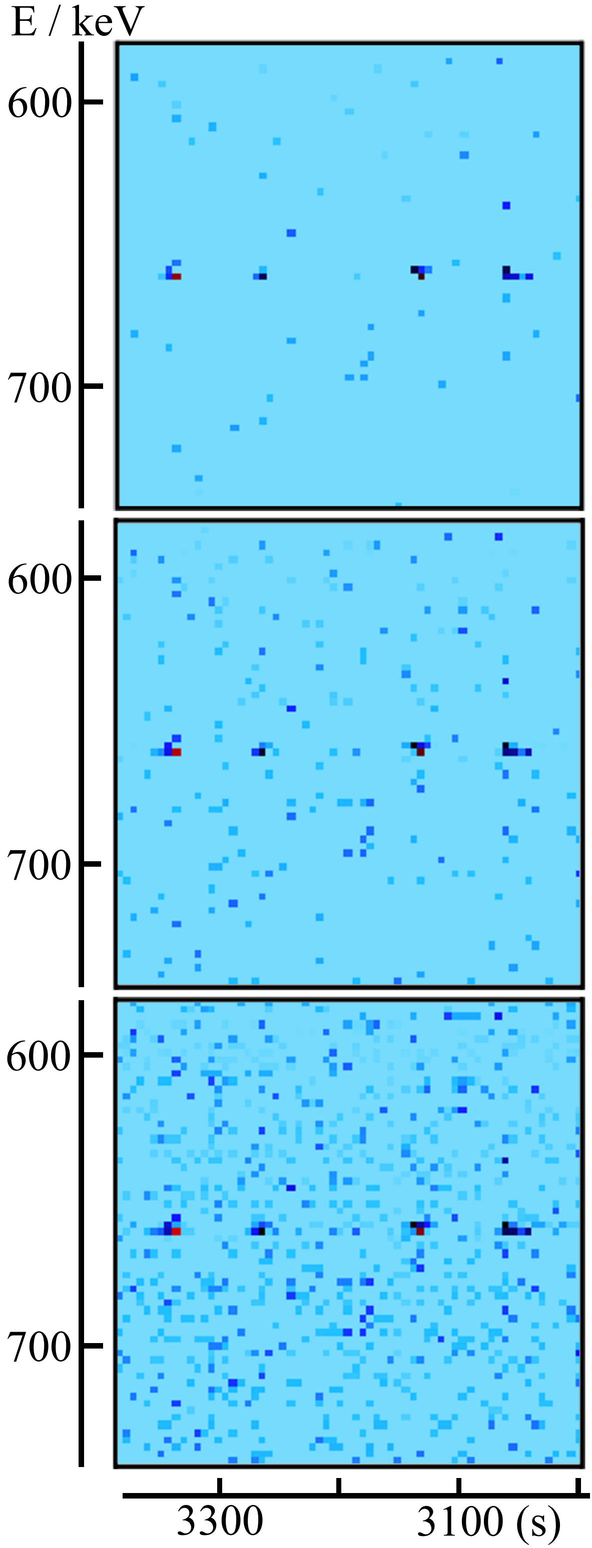
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600
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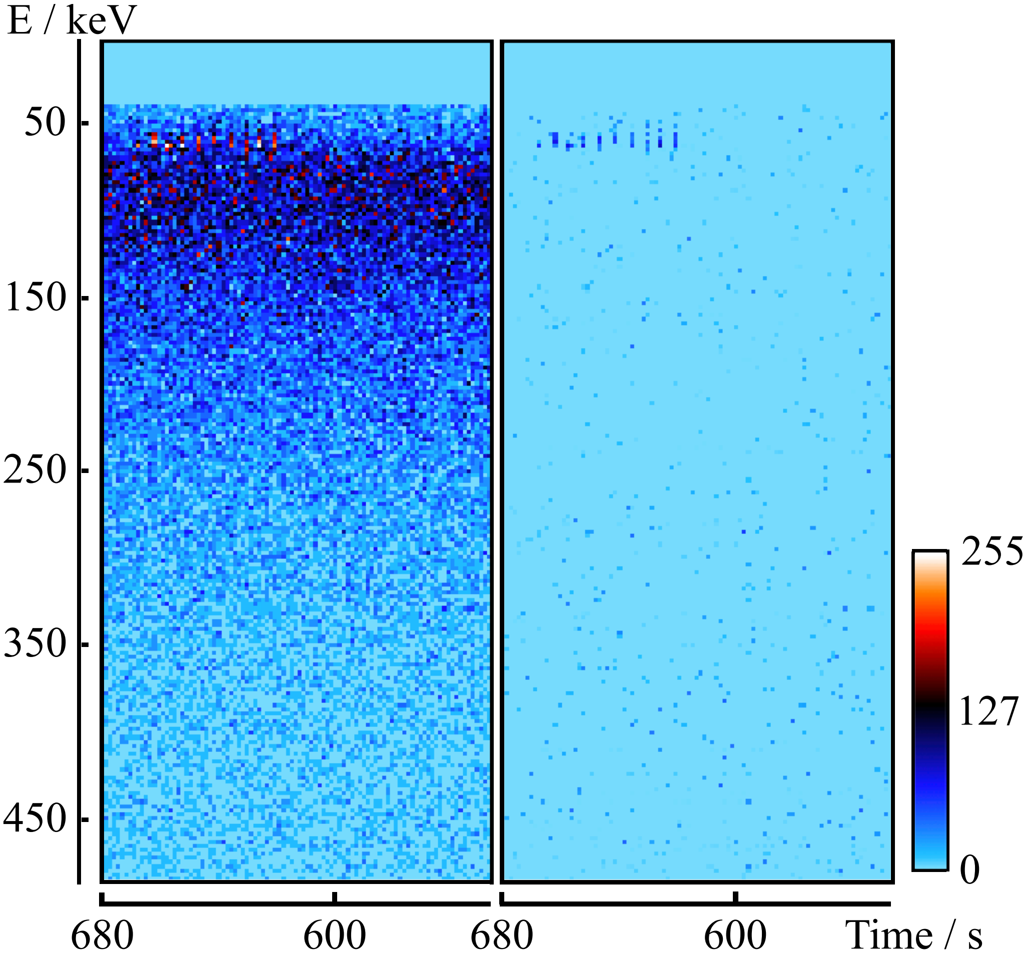
600
700
3300
3100 (s)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Time / s
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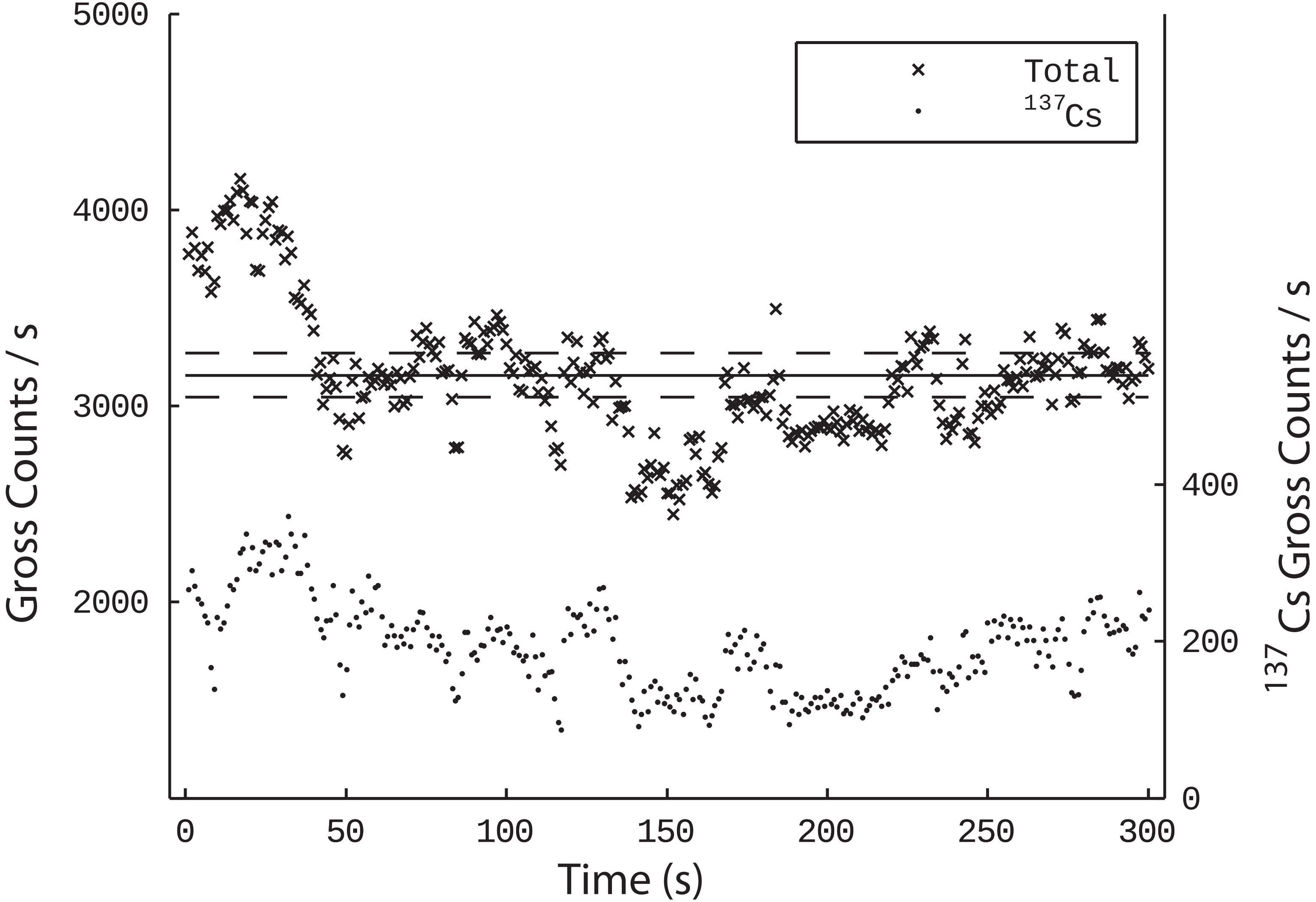
0


Total
^{137}Cs
Gross Counts / s
^{137}Cs Gross Counts / s
Time (s)
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3000
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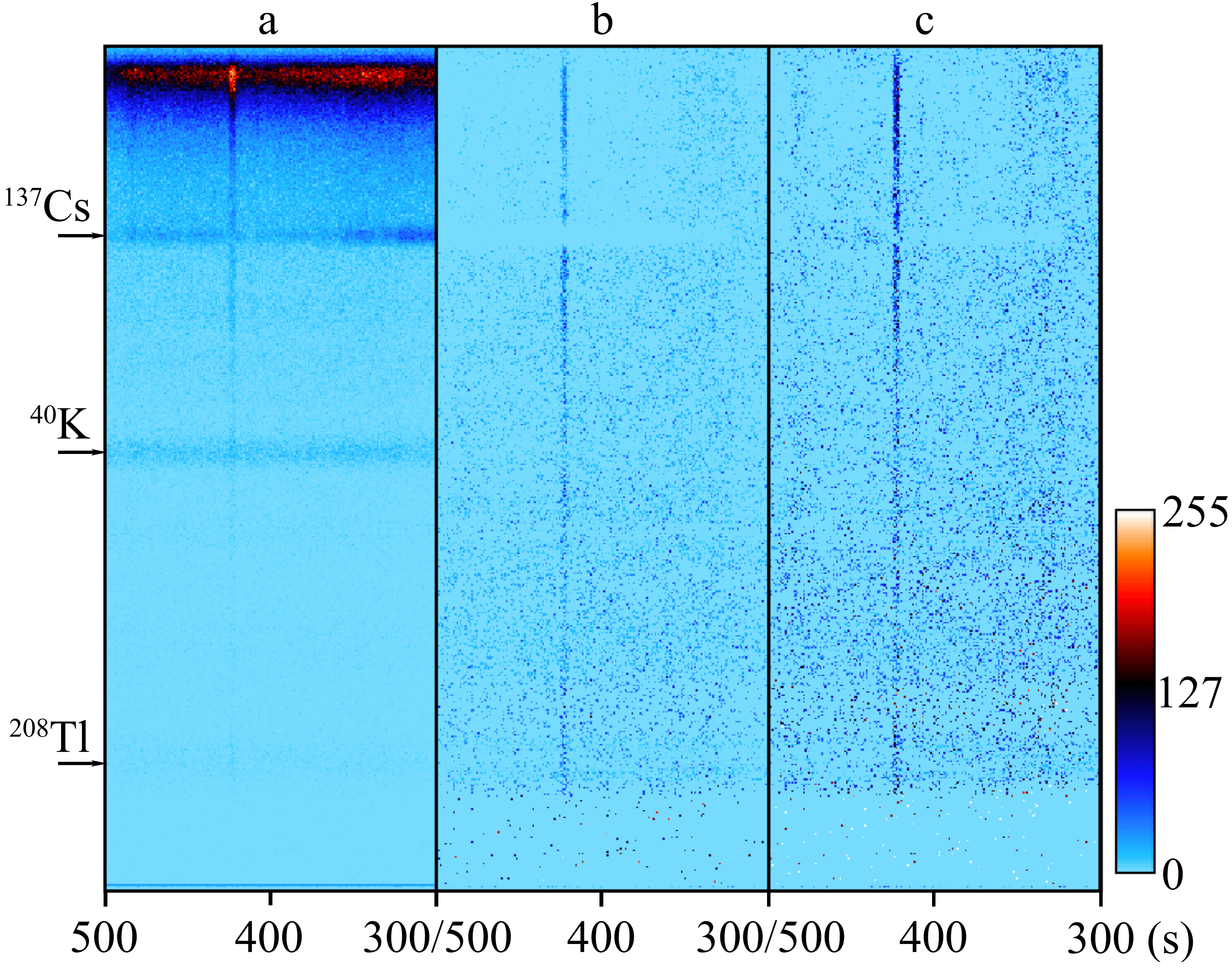
300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b
c
^{137}Cs
^{40}K
^{208}Tl
255
127
0
500
400
300/500
400
300/500
400
300 (s)