Data Acquisition and Analysis

Signal Processing

How do I know what I know?, (a question that has driven me for a very long time), practically defines the motivation for all scientific endeavors. As a volunteer operator I am interested in the working details of the EPA's RadNet Air Monitoring System. I have written this document to highlight how we extract and interpret information from the electronic devices supplied with the RadNet monitoring system.

The equipment used is pictured in Figure 1:

Figure 1: Ludlum detector/photomultiplier/scaler

Ludlum:
43-1-1 scintillator/photomultiplier Serial Number (swapped out annually.)
2241-2 general purpose ratemeter/scaler Serial Number (swapped out annually.)
Disc MV: (alpha) $\approx$ 100 milliVolts
Disc MV: (beta) $\approx$ 10 milliVolts

1.1 Ionizing Radiation

Ionizing radiation passing through material generates a track of ionized atoms. Surprising!, no? Ionizing radiation manifests in two forms: Charged particles in motion, and Electromagnetic waves.

In the presence of an external magnetic field some ionization tracks curve. Early researchers used this observation to categorize the types of radiation.

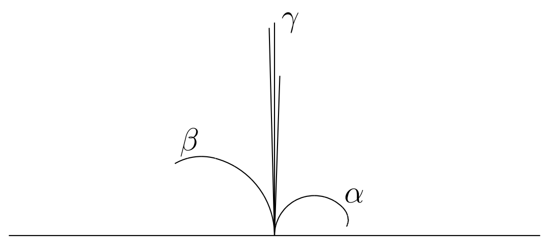

Figure 2: Ionization Tracks

The α-tracks are thick and short suggesting many ionization events per distance traveled (large "Linear Energy Transfer" to the medium). The β-tracks are thiner and longer, while the γ-tracks are very thin and very long suggesting fewer ionization events per distance traveled (small LET to the medium). This rate of energy transfer is quantifiable under proper conditions.

1.2 Scintillators

Several natural minerals and constructed compounds fluoresce when ionizing radiation passes through. Since its inception, ZnS(Ag) has become an important phosphor for quantifying the energetics of α and β detection. The radiation generates a track of ions as it passes through the phosphor. As the ions recombine photons carry away the "binding" energy. These photons are what we detect to determine the energy of the particle. As with all phosphors, self quenching is a concern. The photons, generated by ion recombination, strongly interact with the surrounding phosphor material. If the phosphor is too thick and/or too uniform the "liberated" photons get quenched, the phosphor heats up: This is not the “proper conditions” for quantifying the energy transfer rates for the incident particles.

The phosphor must be thin and must have defects to work. The silver doping provides sites for which the ion recombination process generates a photon that interacts weakly with the bulk of the phosphor. The phosphor acts like a light-pipe for these photons.

Optically attached to a photomultiplier tube, the phosphor is a transducer (It converts the signal “Amount of Ionization” into the signal “Amount of Photons”.) that presents these photons to the photo-electric circuitry of the photomultiplier.

1.3 Photomultiplier Basics

Photons enter through a transparent window to travel through a plastic “light-pipe” to the photoelectric element of the photomultiplier.

This element is kept at a high negative potential. As the photons knockoff electrons, the electrons are accelerated toward the first dynode where each electron collides and liberates N electrons (secondary emission),where N is a number greater than one. A sequence of dynodes at ever less negative potential comprise the “multiplier” of the photomultiplier. At the output terminal we are presented with a number of electrons proportional to the number of photons that entered the transparent window.

The photomultiplier (PMT) is a transducer (It converts the signal “Amount of Photons” into the signal “Current Pulse”.) providing a current (im)pulse, $\int I dt = Q$, to be presented to the Pulse Height Analyzer (PHA).

1.4 Signal Properties and Timing

Using an oscilloscope we can observe the photomultiplier’s output signal. The current pulse is analyzed as a voltage pulse in the PHA.

The pulse height is proportional to the amount of charge deposited on the last dynode of the PMT. Ohm’s law, $V = IZ$, suggest the PMT output is a voltage pulse.

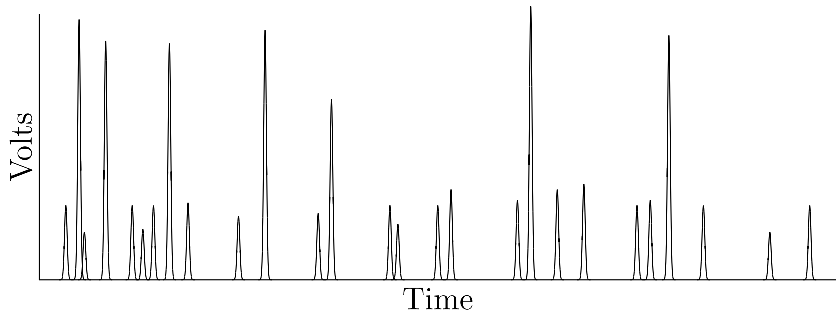

Figure 3: Oscilloscope Trace (slow sweep)

If you select a fast sweep speed you can see details of the individual pulses.

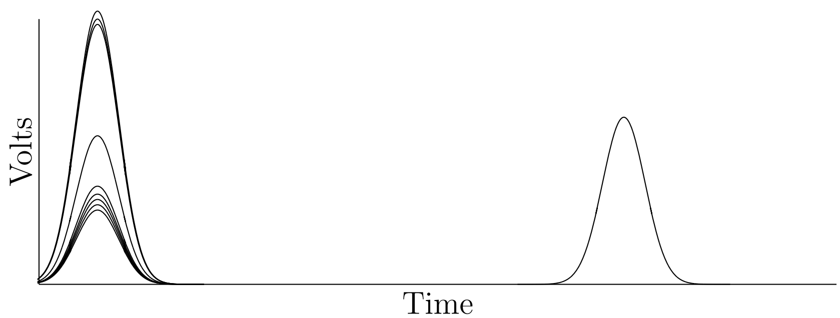

Figure 4: Oscilloscope Trace (fast sweep)

Often you will be able to "see" the distribution of pulse heights by the "band" structure in the oscilloscope trace. If the detection rate is too fast additional pulses will be seen "out there".

1.5 Pulse Height Analyzer

The voltage pulse charges a capacitor in the PHA. The capacitor is discharged linearly as a "clock" counts. The count or "channel number" is strobed to the data handler. This process requires at least the amount of time required for the largest processable pulse. This process defines the PHA's dead time. If pulses arrive too quickly, *id est* during the PHA's "dead time", they will not be "seen" and the information they contain will be lost.

The data handler stores and forwards the channel number and sometimes a timing signal to the data storage unit.

The readout consists of **counts**(per channel) versus **channel number** and is usually displayed as a histogram.

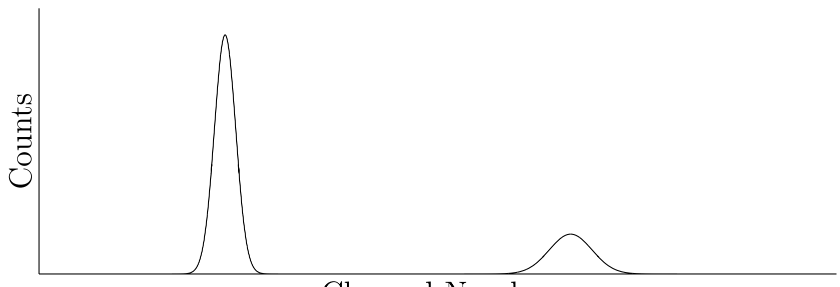

Figure 5: Energy Spectrum

Switching the scaler knob to DET1 sets the discriminator circuit to 100 milliVolts. The "counts" reported are from α-tracks only.

Switching the scaler knob to DET2 sets the discriminator circuit to 10 milliVolts. The "counts" reported are from α-tracks and β-tracks.

1.6 Detector Efficiency

The number of events detected with the RadNet equipment is just the number of "flashes" occurring in the sensitive volume (ZnS coating) of the detector. To determine the amount of activity in the dust sample, the EPA protocol is to multiply the results of a one minute "Count" by the appropriate "Detector Efficiency". The simple calculation produces the activity in pCi units. The number provided is labeled "Detector Efficiency". This is a misnomer. The number should be labeled "Detection Coefficient".

The number of particles detected is (the detector efficiency) times (the ratio of the [detector-sample] geometry to 4π) times (the number of particles ejected from the sample). [See equations (4) and (9)]

1.6.1 α Detection Coefficient $= 1.68$

Taking the Det1 count and multiplying by 1.68 to get the α activity is equivalent to multiplying the Det1 count by

$$\mathrm{C}_\alpha = 1.68\ \frac{\mathrm{pCi}}{\mathrm{Count/Min}} = 1.68\ [(10^{-12})(3.7 \times 10^{10}) \times (60)] = 1.68 \times 2.22 \tag{1}$$

A "Count" describes an event in which a "flash" is generated in the sensitive volume (ZnS) of the detector. A pCi of α activity describes $(10^{-12})(3.7 \times 10^{10})$ α-particles being produced each second. Therefore

$$\mathrm{C}_\alpha = 1.68 \times 2.22 \left(\frac{\alpha\text{-particles}}{\text{“flash”}}\right) = 3.7296\ \left(\frac{\alpha\text{-particles}}{\text{“flash”}}\right) \tag{2}$$

$$\mathrm{C}_\alpha \times \frac{\alpha\ \text{-“flashes”}}{\text{second}} = \frac{\alpha\text{-particles}}{\text{second}} \tag{3}$$

$$\frac{\alpha\ \text{-“flashes”}}{\text{second}} = (\mathrm{D_{eff}})_\alpha \left(\frac{\mathrm{GF}}{4\pi}\right) \times \frac{\alpha\text{-particles}}{\text{second}} \tag{4}$$

$$\therefore (\mathrm{D_{eff}})_\alpha \left(\frac{\mathrm{GF}}{4\pi}\right) = \frac{1}{3.7296} \left(\frac{\text{“flashes”}}{\alpha\text{-particle}}\right) \tag{5}$$

The geometric factor (GF) is $< 2\pi$ therefore,
the detector α -"efficiency" is $(\mathrm{D_{eff}})_\alpha > 53.63\%$.

1.6.2 β Detection Coefficient $= 1.07$

Taking the one minute β-particle count and multiplying by 1.07 to get the β activity is equivalent to multiplying the β-particle count by

$$\mathrm{C}_\beta = 1.07\ \frac{\mathrm{pCi}}{\mathrm{Count/Min}} = 1.07\ [(10^{-12})(3.7 \times 10^{10}) \times (60)] = 1.07 \times 2.22 \tag{6}$$

A "Count" describes an event in which a "flash" is generated in the sensitive volume (ZnS) of the detector. A pCi of β activity describes $(10^{-12})(3.7 \times 10^{10})$ β-particles being produced each second. Therefore

$$\mathrm{C}_\beta = 1.07 \times 2.22 \left(\frac{\beta\text{-particles}}{\text{“flash”}}\right) = 2.3754 \left(\frac{\beta\text{-particles}}{\text{“flash”}}\right) \tag{7}$$

$$\mathrm{C}_\beta \times \frac{\beta\text{ -``flashes''}}{\text{second}} = \frac{\beta\text{-particles}}{\text{second}} \tag{8}$$

$$\frac{\beta\text{ -``flashes''}}{\text{second}} = (\mathrm{D}_{\text{eff}})_\beta \left(\frac{\mathrm{GF}}{4\pi}\right) \times \frac{\beta\text{-particles}}{\text{second}} \tag{9}$$

$$\therefore (\mathrm{D}_{\text{eff}})_\beta \left(\frac{\mathrm{GF}}{4\pi}\right) = \frac{1}{2.3754} \left(\frac{\text{``flashes''}}{\beta\text{-particle}}\right) \tag{10}$$

The geometric factor (GF) is $< 2\pi$ therefore,
the detector β -"efficiency" is $(\mathrm{D}_{\text{eff}})_\beta > 84.20\%$.

Reporting Data

The radioactivity measured in the laboratory is used to generate a report specifying the rate radiation arrived at the EPA's RadNet Monitoring Station.

Rate of change of Activity proportional to Activity

$$A \equiv -\frac{dN}{dt} = \lambda N \implies \frac{dA}{dt} = -\lambda A \tag{11}$$

$$A = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + \cdots + a_n t^n + \cdots \tag{12}$$

$$\frac{dA}{dt} = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + \cdots + n a_n t^{n-1} + (n+1)a_{n+1} t^n + \cdots \tag{13}$$

$$(n+1)a_{n+1} t^n = -\lambda a_n t^n \Rightarrow a_{n+1} = -\frac{\lambda}{n+1} a_n \tag{14}$$

$$A = A_0 \left[1 - \lambda t + \frac{1}{2}(\lambda t)^2 - \frac{1}{2 \cdot 3}(\lambda t)^3 + \cdots + \frac{(-1)^n}{n!}(\lambda t)^n + \cdots \right] = A_0 e^{-\lambda t} \tag{15}$$

This is a two step process.

1. Measuring the radioactivity on the filter in the laboratory allows us to determine the amounts and lifetimes of the radioisotopes lodged in the filter at the time the air flow was turned off at the EPA's RadNet Monitoring Station.
2. The amounts and lifetimes are then used to infer the rate of radiation deposited on the air filter during the collection cycle.

2.1 Counting "Decays"

The number of counts occurring during the one minute window is approximately proportional to the activity of the sample at the beginning of the time window.

$$N(t) = N_0 e^{-\lambda t} \tag{16}$$

$$\text{Count}_{t_0} \equiv \mathcal{E}\mathcal{G} \int_{t_0}^{t_0+\delta t} dt \quad \left\{A_0 e^{-\lambda t}\right\} \implies \text{Count}_{t_0} = \mathcal{E}\mathcal{G} \int_{t_0}^{t_0+\delta t} dt \quad \left\{-\frac{dN}{dt}\right\} \tag{17}$$

$$\text{Count}_{t_0} = \mathcal{E}\mathcal{G}\left\{N_{t_0} - N_{t_0+\delta t}\right\} = \mathcal{E}\mathcal{G}N_0 e^{-\lambda t_0}\left\{1 - e^{-\lambda\delta t}\right\} = \mathcal{E}\mathcal{G}N_{t_0}\left\{1 - e^{-\lambda\delta t}\right\} \tag{18}$$

$$\text{Count}_{t_0} = \mathcal{E}\mathcal{G}N_{t_0}\left[\lambda\delta t - \frac{1}{2}(\lambda\delta t)^2 + \cdots - \frac{(-1)^n}{n!}(\lambda\delta t)^n + \cdots\right] \tag{19}$$

For $\lambda\delta t$ small :

$$\text{Count}_{t_0} \approx \left[\mathcal{E}\mathcal{G}\lambda N_{t_0}\right]\delta t \tag{20}$$

$$\text{Count}_{t_0} \approx \left[\mathcal{E}\mathcal{G}A_{t_0}\right]\delta t \implies A_{t_0} \approx \left[\frac{1}{\mathcal{E}\mathcal{G}}\right]\frac{\text{Count}_{t_0}}{\delta t} \tag{21}$$

Activity added at rate $\mathcal{R}$

$$\frac{dA}{dt} = \mathcal{R} - \lambda A \tag{22}$$

$$a_1 = \mathcal{R} - \lambda a_0 \text{ , and for } n \geq 1,\ a_{n+1} = -\frac{\lambda}{n+1} a_n \tag{23}$$

Set $a_0 = A_0$

$$A(t) = A_0 + \left(\frac{\mathcal{R}}{\lambda} - A_0\right)\lambda t - \frac{1}{2}\left(\frac{\mathcal{R}}{\lambda} - A_0\right)(\lambda t)^2 + \cdots - \frac{(-1)^n}{n!}\left(\frac{\mathcal{R}}{\lambda} - A_0\right)(\lambda t)^n \tag{24}$$

$$\begin{aligned} A(t) = A_0 &\left[1 - \lambda t + \frac{1}{2}(\lambda t)^2 - \frac{1}{2 \cdot 3}(\lambda t)^3 + \cdots + \frac{(-1)^n}{n!}(\lambda t)^n + \cdots\right] \\ &+ \left(\frac{\mathcal{R}}{\lambda}\right)\left[\lambda t - \frac{1}{2}(\lambda t)^2 + \cdots - \frac{(-1)^n}{n!}(\lambda t)^n + \cdots\right] \end{aligned}$$

$$A(t) = A_0 e^{-\lambda t} + \frac{\mathcal{R}}{\lambda}\left(1 - e^{-\lambda t}\right) \Rightarrow A(t) = \frac{\mathcal{R}}{\lambda}\left(1 - e^{-\lambda t}\right) \tag{25}$$

$$\mathcal{R} = \frac{\lambda A(t)}{1 - e^{-\lambda t}} \implies \lim_{\lambda t \to \infty} \mathcal{R} = \lambda A(t) \text{ , and , } \lim_{\lambda t \to 0} \mathcal{R} = \frac{A(t)}{t} \tag{26}$$

$$\text{Events} = -\int \frac{d\mathcal{N}}{dt} dt \tag{27}$$

$$\int \frac{d\mathcal{N}}{dt} dt = \int_{t_1}^{t_2} dt \ \left[-\lambda \mathcal{N}_0 e^{-\lambda t} \right] = -\lambda \mathcal{N}_0 \int_{t_1}^{t_2} dt \ e^{-\lambda t} \tag{28}$$

$$\text{Events} = -\mathcal{N}_0 \left(e^{-\lambda t_2} - e^{-\lambda t_1} \right) \tag{29}$$

$$\text{Events} = -\mathcal{N}_0 e^{-\lambda t_1} \left(e^{-\lambda (t_2 - t_1)} - 1 \right) \approx \mathcal{N}_0 e^{-\lambda t_1} \left[\lambda (t_2 - t_1) \right] \tag{30}$$

$$\frac{\text{Events}}{(t_2 - t_1)} \approx \lambda \mathcal{N}_0 e^{-\lambda t_1} \iff \mathcal{A}(t_1) = - \left. \frac{d\mathcal{N}}{dt} \right|_{t_1} \tag{31}$$

2.1.1 Determine Activity and Lifetime

$$\frac{d\mathcal{N}}{dt} \propto \mathcal{N} \implies \frac{d\mathcal{A}}{dt} = -\lambda \mathcal{A} \tag{32}$$

$$e^{-\lambda t} = 1 - \frac{(\lambda t)}{1!} + \frac{(\lambda t)^2}{2!} - \frac{(\lambda t)^3}{3!} + \cdots + (-1)^N \frac{(\lambda t)^N}{N!} + \cdots \tag{33}$$

$$\mathcal{A}(t) = \mathcal{A}_0 e^{-\lambda t} \implies \frac{d\mathcal{A}}{dt} = -\lambda \mathcal{A}_0 e^{-\lambda t} \tag{34}$$

$$\mathcal{A} = \frac{1}{2} \mathcal{A}_0 \text{ , when , } t = t_{1/2} \iff e^{-\lambda t_{1/2}} = \frac{1}{2} \implies \lambda t_{1/2} \approx 0.693 \tag{35}$$

$$< t >= \frac{\int_0^\infty dt \ \ t e^{-\lambda t}}{\int_0^\infty dt \ \ e^{-\lambda t}} = \frac{\int_0^\infty d(\lambda t) \ \ (\lambda t) e^{-\lambda t}}{\lambda \int_0^\infty d(\lambda t) \ \ e^{-\lambda t}} = \frac{\int_0^\infty dx \ \ x e^{-x}}{\lambda \int_0^\infty dx \ \ e^{-x}} \tag{36}$$

$$d(x e^{-x}) = e^{-x} dx - x e^{-x} dx \implies x e^{-x} dx = -d(x e^{-x}) + e^{-x} dx \tag{37}$$

$$\int_0^\infty dx \ \ x e^{-x} = -x e^{-x} \Big|_0^\infty + \int_0^\infty dx \ \ e^{-x} = \int_0^\infty dx \ \ e^{-x} \tag{38}$$

$$< t >= \lambda^{-1} = \tau \text{ , where , } \lambda = \frac{\ln 2}{t_{1/2}} \therefore t_{1/2} = \ln 2 < t > \approx 0.693 < t > \tag{39}$$