Recently measured radiation levels inside the Rocky Flats National Wildlife Refuge

D. M. Wood, May 2019

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This document

- Presents direct measurements of the 'ambient dose equivalent [radiation] rate' (ADER) on trails inside the Refuge as 0.14 micro Sieverts per hour (μSv/h);
- Estimates the *variation* of the ADER from place to place in this sample of 4654 points as not more than 2%.
- U.S. Geological Survey data shows background radiation (due to soil radioactivity and cosmic rays) along the Front Range in the range 0.12 to 0.19 μSv/h; a 1999 Front Range survey found an average over 40 communities of 0.135 μSv/h. Thus there is *no evidence* of any excess radiation exposure to Refuge users, for the simple reason that plutonium (Pu) and americium (Am) isotopes constitute not more than 3% (in total) of natural soil radioactivity, and fluctuations in soil concentrations of natural radioisotopes around the Front Range are much larger.

Note: Clicking on a blue link takes you to a somewhere in this document; green links will take you to a Web site or remote document.

Introduction

A great deal of attention has been focused on plutonium (^{239,240}Pu) isotopes and americium (^{241}Am) released by the Rocky Flats plant during its operations. While very thorough documentation of soil levels of these (and useful contour maps) is available through the Department of Energy, most of this information pertains to the site before the cleanup, completed in 2005.

While there is also much post-cleanup sampling data (for example, here), no contour maps are available and visitors may not have a clear idea of radiation levels in the Refuge. This document presents and analyzes ambient radiation levels recently measured on all of the paths currently (as of May 2019) open to visitors. A less technical, two-page summary is available here.

It is important to note that past focus by some on Pu and Am around Rocky Flats has been out of all proportion to its actual importance, for several reasons:

1. National Institute of Standards and Technology (NIST) data shows that not less than 97% of total soil radioactivity is due to *naturally* occurring radioisotopes; see Appendix A. There are many more natural radioisotopes not tested for, but likely to be much more abundant in Rocky Flats soil than Pu or Am. Thus it is very likely that if more natural radioisotopes were measured, the importance of Pu and Am would shrink still more. (The same is presumably true of inhaled dust.)

2. From a radiological perspective, Pu and Am are no different from hundreds of other naturally-occurring radioisotopes. A human body does not care if an α particle or γ ray came from a plutonium nucleus or a (naturally occurring) thorium nucleus. α particles can be stopped by a sheet of paper or the outermost layer of dead skin; their range in air is less than 4 or 5 inches in any case.

3. There is nothing disturbingly toxic about plutonium either[1],[2]; "No humans have ever died from acute toxicity due to plutonium uptake" [1]. 'Hot particles' which lodge in the lungs have been dismissed as a special health concern since the 1970s.

The SAFECAST project and the bGeigie Nano

Recently developed geo-tagging programmable Geiger-Müller counters are now providing in Europe, Japan, and the U.S. a nongovernmental source of reliable radiation information in locales where radiation contamination is present or suspected. The SAFECAST project is the best developed among these. It relies on a large network of volunteers (originally in Japan after the Fukushima Daiichi accident) using well-calibrated hardware and a sophisticated application programming interface (API) for uploading, vetting, querying, and displaying such data in a uniform way. More than 3300 kit-built bGeigie Nano (bGN) monitors (see Appendix B for details) have been deployed for such radiation monitoring around the world. Such 'pancake' Geiger-Müller counters (by design) are capable of detecting common forms of terrestrial radiation (α and β particles and γ rays). The principal risks from environmental radiation are γ rays (like X rays but far more penetrating) and β particles (high-energy electrons).

As is common, the bGN is calibrated for the radioisotope ^{137}Cs, a common fission product relevant to reactor accidents. This does *not* mean that it is 'tuned' for this isotope, but that in the presence of this source by itself the measured dose rates would be reliable. Because Geiger-Müller tubes respond to a broad range of particle energies, they remain a semiquantitative tool in many environments. It is important to remember that Geiger-Müller counters cannot tell you *which* radioisotopes are present, however.

Although the bGN can be used for soil radiation measurements, for use by the SAFECAST project the intent is to assess *ambient* radiation—resulting from the general level of contamination and background radiation nearby. For this reason, data is acquired with the axis of the Geiger-Müller tube horizontal, so as not to be dominated by cosmic radiation (mostly incident from above) or very nearby surface contamination (mostly incident from below, from soil radioisotopes, for example). The bGN reports the ADER (ambient dose equivalent rate) in units of microSievert per hour (μSv/h). The ADER is very widely used in radiation monitoring. It is generally measured at a reference height of 1 meter above the soil. For this reason, α radiation *is not detected* in the measurements described below.

The ADER is an 'operational quantity' directly relevant to radiation protection, used for area monitoring. Technically, this is $dH^*(10)/dt$.

A recent journal article by some of the SAFECAST founders remarked "SAFECAST point measurements accurately reflect the ADER of the area surrounding the measurement point with a precision of a few square meters" [3]. The bGN calibration has also been recently confirmed [4]. At present more than 90 million readings are available on the free access SAFECAST database. The bGeigie Nano has already been incorporated into routine measurements by the Czech National Radiation Protection Institute (SÚRO), members of the Natural Resources Defense Council, and is under consideration for use by international radiation protection organizations. It was used by SAFECAST volunteers in December 2018 [5] in the first TEPCO-authorized visit to the Fukushima reactors by an external measurement team.

This document presents direct measurements of 'ambient dose equivalent [radiation] rates' (ADER) at locations around and inside the Refuge. They are quoted in a common unit (micro Sieverts per hour, μSv/h. Values are entirely consistent with separately measured background (soil+ cosmic ray) radiation for much of Colorado.

Rocky Flats National Wildlife Refuge data

Data capabilities

Sample screen grabs of mapping results from some of the northernmost trails taken with a bGeigie Nano and exported from the from the SAFECAST API are shown in Fig. 1.

Raw data downloaded from the bGN can be visualized and labeled using the open source GIS (geographical information system) QGIS (Quantum GIS), as shown in panel (a) (with ‘Bing Aerial with labels’ imagery). The bGN writes sample data every 5 seconds; at a walking speed of 3 mph (4.4 feet per second), on average data points are about 22 feet apart. The GPS resolution is high enough that the displacement between paths when doubling back over a trail is obvious. The results on the SAFECAST worldwide map are shown in panel (b) with Google Maps imagery and the standard SAFECAST logarithmic color-coded radiation dose rate legend. Individual data points can be directly queried for a time and date stamps, heading, counts per minute (CPM) averaged over the current and previous 11 data points, counts for the previous 5 second interval, and the radiation dose rate (from the CPM). In this particular instance the data points are sufficiently close together that the API has displayed the measured data as a thick ribbon which attempts to display spatial variations of radiation dose rate—resolution *along* the path is sacrificed to provide a smoothed estimate of reality. Finally, the SAFECAST API can export data as a KML file, used to display geographic data using, for example, Google Earth. This data too can be queried point-by-point. A sample of the same region as in panels (a) and (b) is shown in panel (c) using Google imagery. Clicking on a displayed point on the SAFECAST map gives you full information about the data: the ADER, the counts averaged over the previous minute or previous 5 seconds, the heading, altitude, and date and time. The SAFECAST map provides a ‘temperature’ logarithmic map of radiation levels for each data point along the path.

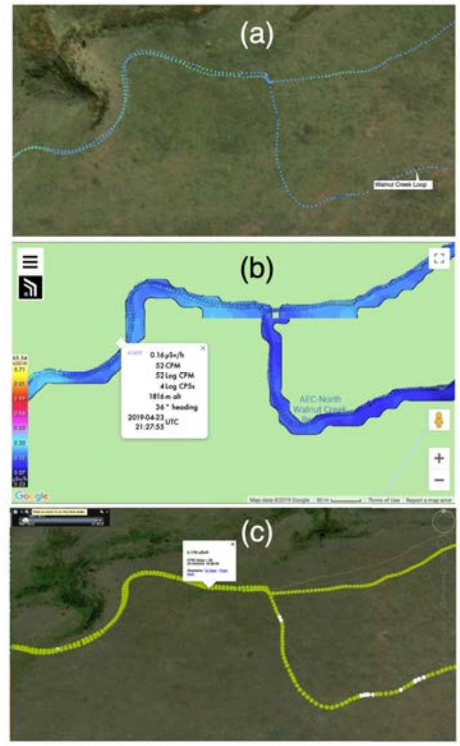


Figure 1: Data available for geographical points from SAFECAST exports, taken from the northern trails in the Refuge. Panel (a) from QGIS (top), native SAFECAST export with underlying points (middle, panel (b)), KML export to Google Earth, panel (c). The SAFECAST export includes counts per 5 sec and counts per minute (averaged over the previous 12 5-sec intervals). Here UTC indicates coordinated universal time, formerly known as Greenwich Mean Time (actually a time *zone*).

This is effectively the technique known as *dithering* in image processing. It is important to note that radioactive decay is a *random* process, so that the radiation dose rate is the result of statistical analysis. See Appendix C.

Sample data and understanding it

A screen grab from the SAFECAST data for the entire Refuge is shown in Fig. 2. [Chains of dots and blobs are existing data from 2013 and 2014 by other SAFECAST volunteers: thank you KB, Arthur, and Sean.] The most noticeable feature is that radiation levels along the trail are about the same as *outside* the Refuge, on roads or other external paths. (The bGN used outside its case a couple of centimeters above the ground would show higher radiation levels due to vertically incident cosmic rays and α and low-energy β particles from radioisotopes in the soil. This would hold true anywhere in Colorado.)

Using the temperature legend, we provisionally assume that ADER radiation levels are in the range of 0.12-0.23 μSv/h.

These measurements must be wrong! Where's the plutonium?!

1. As you can read in Appendix A, contributions from Pu and Am isotopes (which we refer to as 'Rocky Flats isotopes' below) amount in total to less than 3% of total soil radioactivity. The remainder is due to naturally-occurring radioisotopes (including plenty of α and β emitters) present all around the Rocky Mountains.

2. The fluctuations in radiation rates to the mineral content of the soil—see the section on background radiation below—are much larger than the 3%, so if there is a contribution from Pu and Am (and of *course* there is—it is just swamped by natural radioisotopes) it would be hard to detect without Pu-specific measurements.

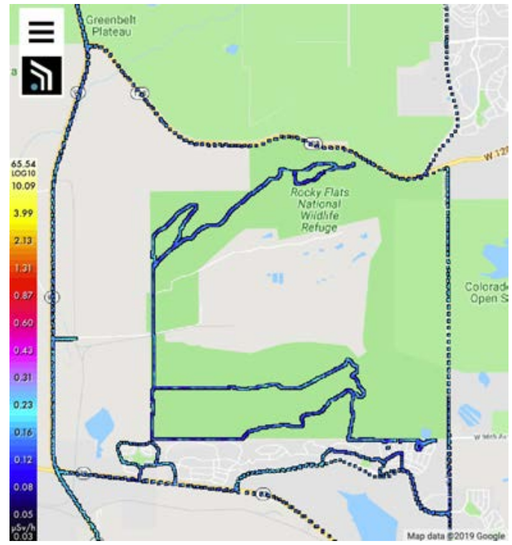


Figure 2: All trails currently open in the Rocky Flats National Wildlife Refuge.

Global perspective

Samples from the global SAFECAST map are shown in Fig. 3 using the same logarithmic radiation scale used previously.

Radiation levels throughout much of the rest of the world seem much lower (bluer) than around Rocky Flats. Should I be worried? No:

- The color coding was selected so that it can include at its upper (red-yellow) end the levels that *are* risky for human health (and this is a *log* scale!). The area around Chernobyl exhibits much, much higher radiation levels: the blue, red, and black exclusion zones included levels of 30-50 μSv/h, 50-200 μSv/h, and above 200 μSv/h in late 1986 Wikipedia. By 2009 levels in Pripyat had generally dropped to under 1 μSv/h.

- In some locations around the Fukushima Daiichi nuclear reactors the SAFECAST map shows levels of over 4 μSv/h. In Fukushima Prefecture dose rates decreased from 2.74 μSv/h in April 2011 to about 0.14 μSv/h in November 2018. Whoa! Some Colorado levels are above 0.14 μSv/h! Yes, but our *background* levels of radiation—due to soil radioactivity and altitude (the thinner atmosphere above us lets in many more cosmic rays) account for this (see the maps discussed later). Similar effects are seen around the world. In Europe, for example (see a recent radiation map) there

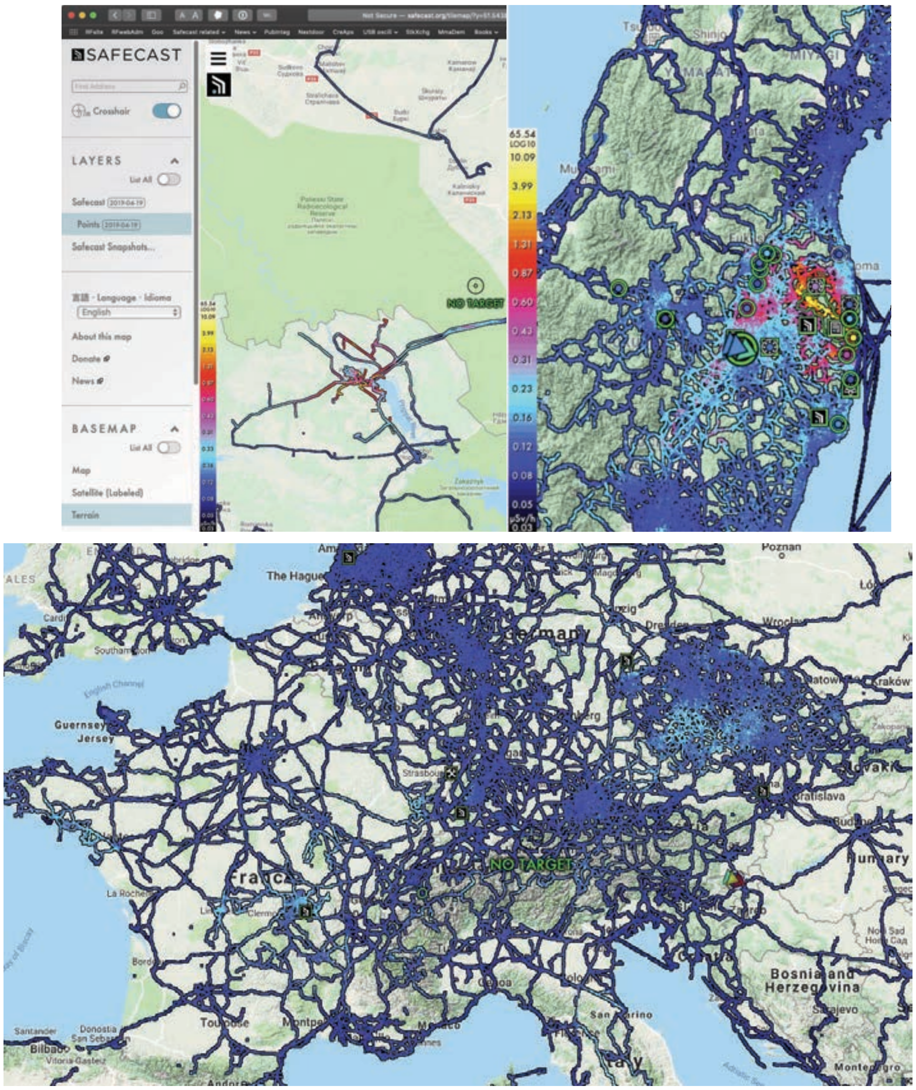


Figure 3: SAFECAST data for the region around the Chernobyl and Fukushima Daiichi reactors (top left and right, respectively), and for western Europe. The logarithmic radiation dose rate color scheme is identical in all images.

are background levels of radiation comparable to ours around the Alps (altitude) or minerals (the Massif Central in France), or radon (Czechia). Colorado gets a double whammy because of both minerals (and the radon they produce) *and* altitude.

A sample path (in slate blue) along the southern and western parts of the Refuge is shown in Fig. 4. At the top of the figure is shown in orange the measured ambient dose equivalent rate (ADER) converted from the measured running average number of counts per minute (using 334 CPM = 1 μSv/h). Both curves have been smoothed using a ‘moving average’ (boxcar filter) over the previous 59 points. Points in red along the altitude curve are labeled with locations from a fairly current Fish and Wildlife map.

It is very tempting to assume that the orange curve encodes variations in the radiation level along the path. However, at these dose rates (under 1 count per second on average) the Poisson statistics describing radioactive decay mean that count values fluctuate considerably. In fact, as we will see below, this curve demonstrates that the smoothing of noisy data may (depending on the ‘signal to noise’ ratio) enhance non-existent features which reflect *only* statistical noise. This does not mean we cannot estimate the non-uniformity of the radiation rate from place to place, however.

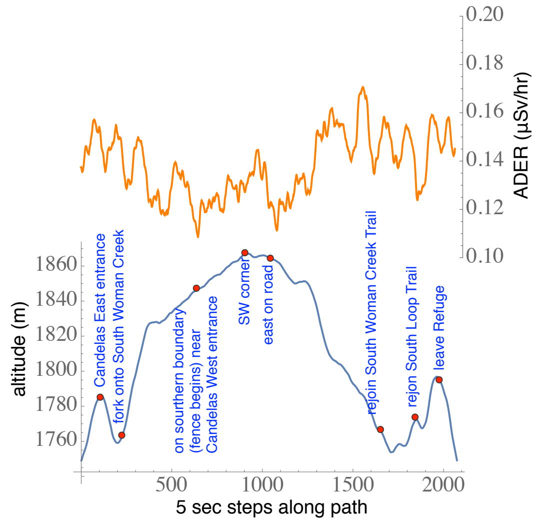


Figure 4: Altitude and radiation rates along path with locations marked.
GPS altitudes are not as reliable as map coordinates, so the altitudes for entering and leaving via the ‘Candelas East’ entrance do not coincide.

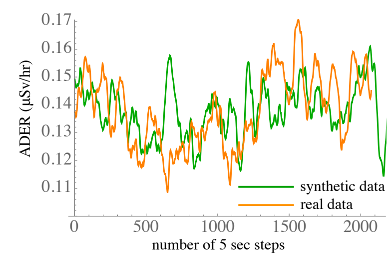


Figure 5: In orange: variation of measured dose rate along the path shown in Fig. 4. In green: *synthesized* data from pure Poisson statistics with the same mean count (or radiation) rate. Both real and synthetic data have been smoothed in the same way. Overall similarity of the two means that the measured variations along Refuge trails are entirely consistent with statistical fluctuations, not ground truth; see the text.
This does *not* mean that such measurements could not detect serious changes in radiation levels, only that the changes along the trails in the Rocky Flats National Wildlife Refuge are quite small.

Variation of radiation levels along paths

We can fairly easily decide whether the variation in count rate along the path is due to physical variations in the radiation level or statistical fluctuations by comparing with synthetic data. If we generate a large number of random numbers picked according to a Poisson distribution with the same mean as the *real* data (in dark orange) and smooth it in the same way, we see results like the green curve in Fig. 5. The two curves are quite similar overall, indicating that the *real* data is entirely consistent with a strictly Poisson distribution (that is, with fluctuations due to the randomness of the count rate, not due to changes in the actual radiation rate along the path). Can we use the measured changes to identify ‘hot spots’ on the trails? Almost definitely not. The upshot of careful analysis in Appendix C (with more synthesized data representing differences in radiation rates) is that 10% differences in radiation rates along a path are easily identified, 2% differences can probably be identified, but 1% probably cannot.

Thus we conclude that the bGeigie Nano data show that the average ambient dose equivalent (radiation) rate along the available trails in the Refuge is 0.14 μSv/h and does not vary more than 2% along the paths measured so far.

Background radiation in Colorado

As mentioned above, Colorado experiences the highest levels of background radiation in the U.S. due to its relatively high altitude (so that fewer cosmic rays are absorbed by the atmosphere) and the large fraction of hard rock minerals (containing radioisotopes of thorium and uranium and their decay products) in our soil, especially near the Front Range. The USGS provides maps for the coterminous U.S; replotted data for Colorado are shown in Fig. 6. Soil mineral radioactivity is deduced from aerial γ-ray measurements of ^{40}K and decay daughters of ^{232}Th and ^{238}U.

It is very clear that high soil radioactivity is found east of the Continental Divide and is very non-uniform throughout the state, varying by a factor of 20 or so. From the legends above each panel I estimate a dose rate around Rocky Flats of 69-134 nanoGray per hour (nGy/h) from terrestrial (soil) radiation and 51.9 to 60.0 nGy/h from cosmic rays.

We convert doses in Gray directly into Sievert, finding
Terrestrial: 69-134 nSv/h *Cosmic ray:* 51.9-60.0 nSv/h
for a total of 0.12-0.19 μSv/h.

The (paywall accessible only) article "Spatial variations in natural background radiation: absorbed dose rates in air in Colorado" [6] measured natural ambient background radiation dose rates at 1150 locations, including 40 more populated communities along the Front Range. Terrestrial dose rates varied by 22%. The authors noted

> ... Total dose rates (including cosmic and terrestrial components) in Front Range communities below 2000 m [6600 feet] elevation averaged 135 nGy/h.
>
> ... West of the Continental Divide, the terrestrial component accounted for roughly 60% of total measured dose rates, while east of the Continental Divide, where enriched granitic source rocks and associated soils are prevalent, the terrestrial component generally accounted for two-thirds or more of total dose rates.

I replotted a well-known figure from this article in Fig. 7. (It can be found as Fig. 2 on p. 8 of a freely available document.) It shows the dose rate along the I-70 corridor from Grand Junction to Denver. In accord with their findings generally in Colorado, the dose rate peaks well *east* of the Continental Divide. At any location, add the dose rate (in red) from soil ('terrestrial') radiation to that from cosmic rays (in blue and closely following the altitude, shown in green) to find the total background radiation. It is very clear that Colorado background radiation rates change by large amounts from place to place.

We conclude that radiation rates within the Rocky Flats National Wildlife Refuge are completely consistent with Front Range background radiation values.

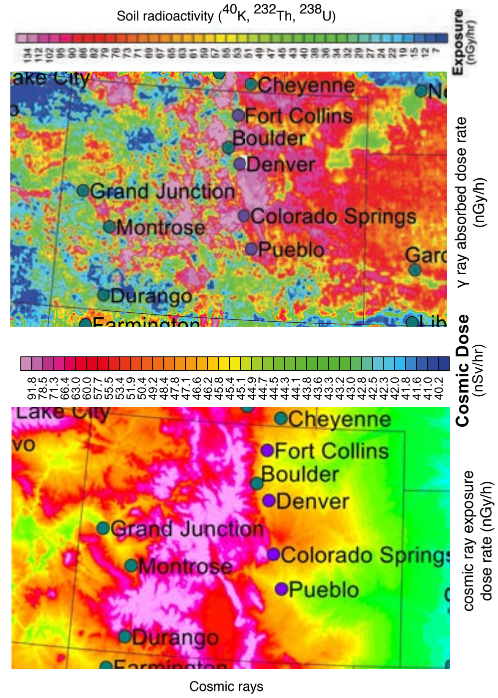


Figure 6: USGS data for radiation exposure rates due to soil minerals (upper panel) and to cosmic rays (lower panel). These were replotted from original data by DMW using a different color legend scheme than those online.

As you can read here, γ rays and β particles have the same 'biological effectiveness'. Charged cosmic rays are primarily muons (like electrons, only heavier), with some protons and neutrons, electrons and positrons, and plenty more γ rays. Conventionally units of Sievert are used for the biological impact of low levels of radiation (*i.e.*, for 'stochastic' (dose equivalent) rather than 'deterministic' effects.). Energy deposited per unit mass is described using the units of Gray. We ignore these distinctions here.

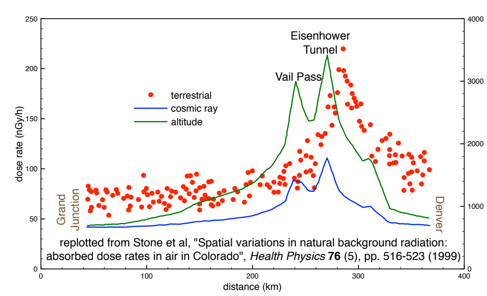


Figure 7: Redrawn from article indicated.

It is worth noting that although parts of Colorado experience among the highest *background* radiation rates in the world, the cancer rate is the lowest in the U.S.

Currently open trails in the Wildlife Refuge

See next page.

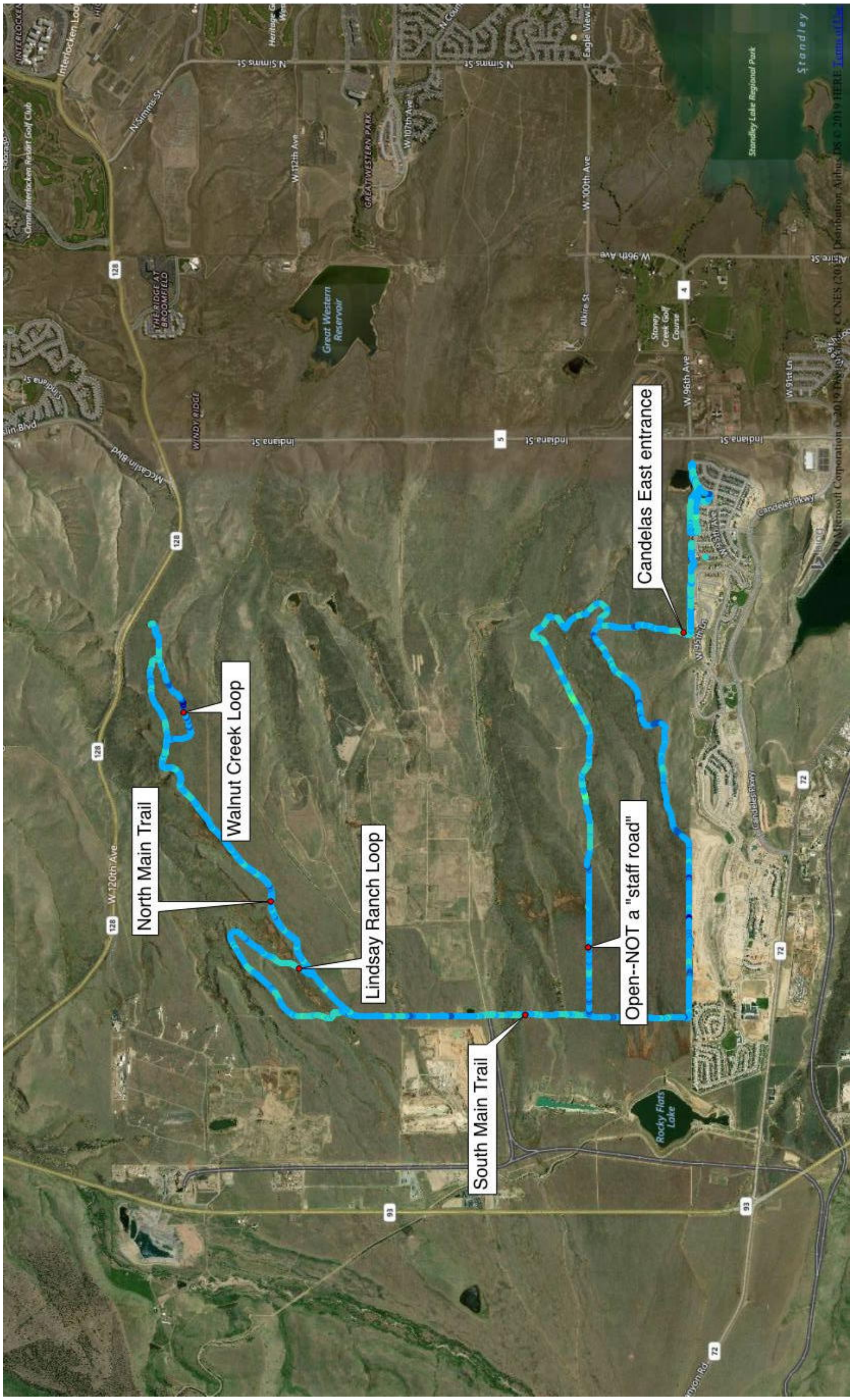
Takeaway points

- Plutonium and americium radioisotopes contribute not more than 3% (in total) of soil radioactivity in the Refuge, according to meticulous but often overlooked 'soil standards' from NIST (and earlier, from the National Bureau of Standards). Pu and Am are no different than hundreds of other naturally-occurring radioisotopes.
- Direct measurements of the ambient dose-equivalent radiation rate using a bGeigie Nano geo-tagging Geiger-Müller counter show an average dose rate of 0.14 μSv/h, on the basis of 4654 points sampled every 5 seconds.
- Using data available data from the USGS, the two sources of background radiation (cosmic rays and soil radiation) are expected to contribute to a background exposure rate throughout much of Colorado ranging from 0.12 to 0.19 μSv/h. A 1999 measurement of background radiation along the Front Range and along I70 [6] found an average among 40 Front Range communities of 0.135 μSv/h.
- Thus these recently measured Refuge radiation rates are *completely consistent* with background radiation levels.
- Total radiation levels along all available trails in the Refuge show no statistically meaningful dependence on location. (This would probably not be true of of soil radiation levels measured very close to the soil, since uranium deposits, for example, would vary with local geology.)

References

[1] George L Voelz and Ileana G Buican. *Plutonium and Health*. Tech. rep. 26. Department of Energy, Los Alamos National Laboratory, 2000. URL: http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-00-1613.

[2] Health Physics Society. *WHAT ABOUT "DEADLY PLUTONIUM"?* Tech. rep. Health Physics Society, 1993. URL: http://hps.org/documents/plutonium2.pdf.


North Main Trail
Walnut Creek Loop
Lindsay Ranch Loop
South Main Trail
Open--NOT a "staff road"
Candelas East entrance

[3] Azby Brown et al. "Comments regarding "Calibration of Safecast dose rate measurements" by Cervone and Hultquist". In: *Journal of Environmental Radioactivity* 197 (2019), pp. 127–128. issn: 18791700. doi: 10.1016/j.jenvrad.2018.11.001.

[4] Joshua Walsh, Kevin Kelleher, and Lorraine Currivan. "Assessment of Safecast bGeigie Nano Monitor". In: *Radiation Environment and Medicine* 8.1 (2019), pp. 1–8.

[5] Naomi Schanen. *Radiation monitoring group formed during Fukushima nuclear disaster now a source of global data | The Japan Times*. 2019. url: https://www.japantimes.co.jp/news/2018/03/09/national/radiation-monitoring-group-formed-fukushima-nuclear-disaster-now-source-global-data/{\#}.XNSM7tNKjok (visited on 05/09/2019).

[6] J Stone et al. "Spatial variations in natural background radiation: absorbed dose rates in air in Colorado". In: *Health Physics* 76.5 (1999), pp. 516–523.

[7] S. Nour, K. Inn, and J. Filliben. "Development of the NIST rocky flats soil standard". In: *Journal of Radioanalytical and Nuclear Chemistry* 277.1 (2008), pp. 161–168. issn: 02365731. doi: 10.1007/s10967-008-0725-4.

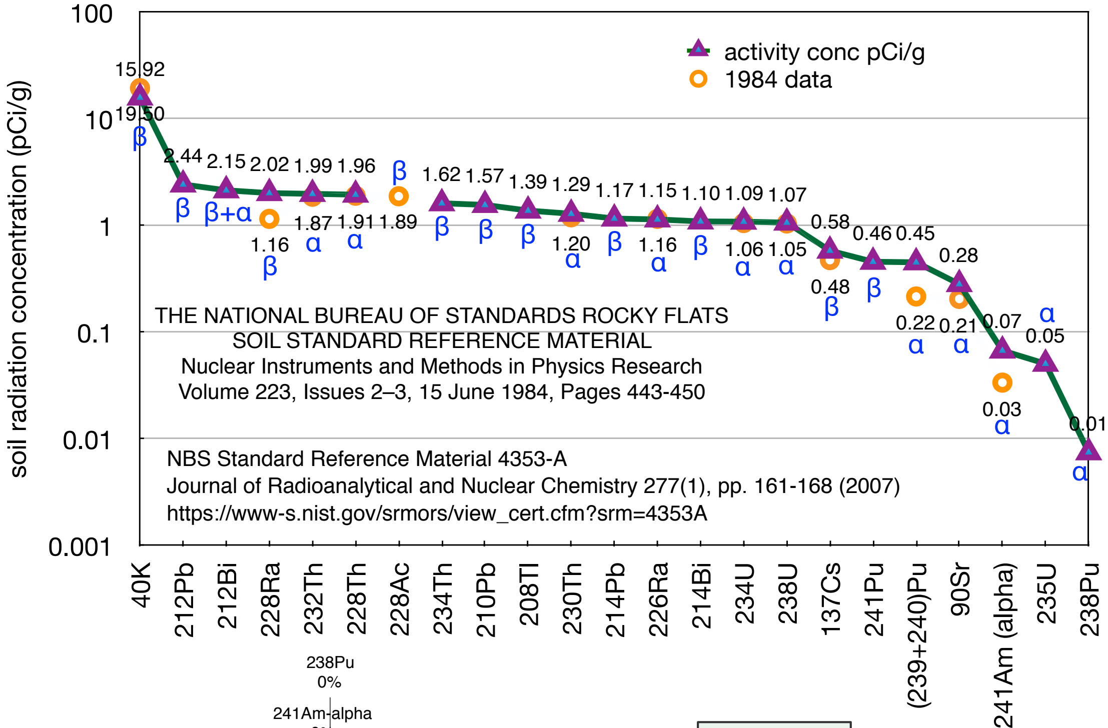
[8] *About Safecast | Safecast*. url: https://blog.safecast.org/about/ (visited on 03/04/2018).

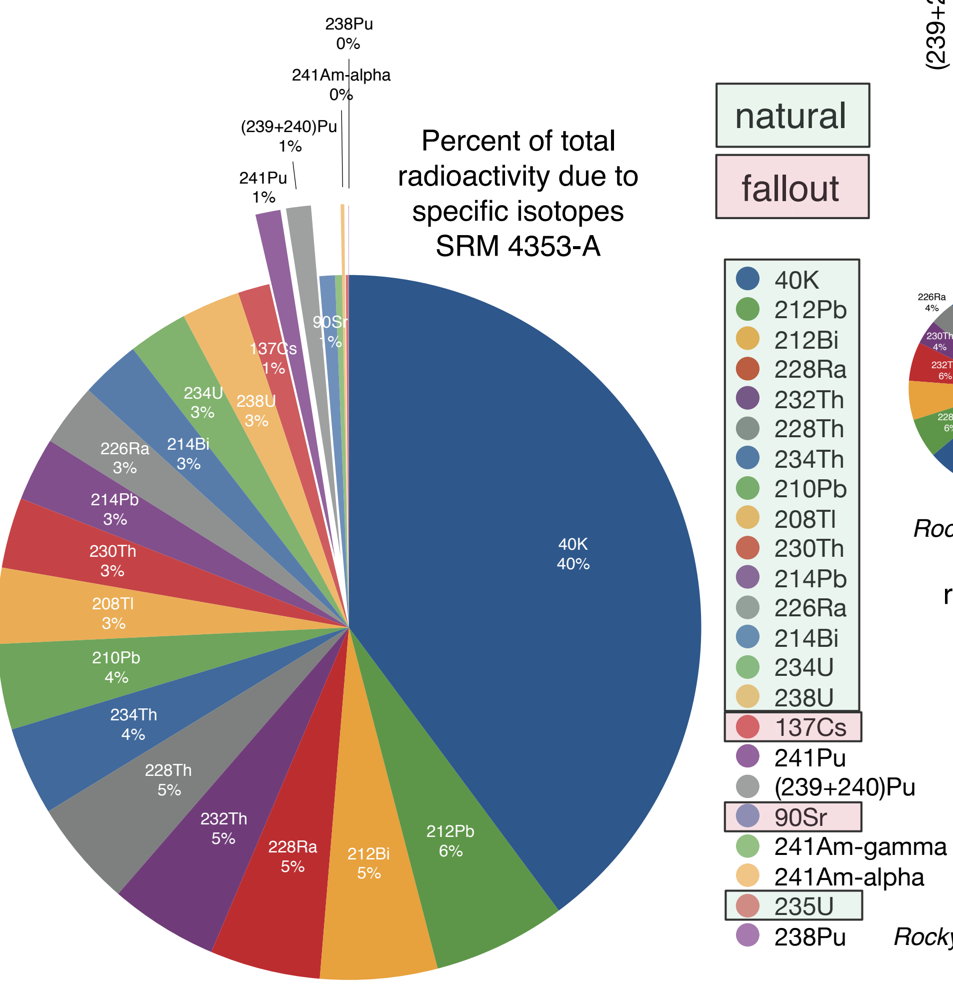
Appendix A: NIST soil standards from Rocky Flats

Two extremely well-characterized National Bureau of Standards (and later the National Institute of Standards and Technology) 'soil standards', meant to serve government and commercial laboratories in the United States and abroad and measured independently by multiple labs here and in Europe, were prepared in 1986 and 2007 [7]. They were collected from two sites (on east and west sides of Rocky Flats, within what is now the Refuge) in 1978, well before plant closure or cleanup. The authors also estimated the incidence of 'hot particles' as 1.8 per 90 grams of soil; you would need to ingest an amount of soil equal in weight to a golf ball to encounter one, on average.

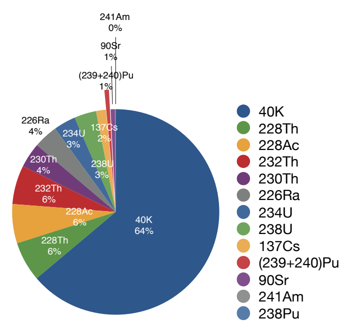
Inhalation of hot particles as a health risk was discarded by the early 1980s.

Results for Pu and Am are consistent with soil levels measured and reported by the Department of Energy. Because these standards were comprehensive, they also make clear that Pu and Am contributions to total soil radioactivity are at the level of 1%. To the extent that these soil samples are representative, the same would hold true of windblown dust around the Refuge.





Rocky Flats Soil Number 2



Rocky Flats Soil Number 1

Percent of total radioactivity due to specific isotopes SRM 4353

Appendix B: The bGeigie Nano Geiger-Müller counter

The data discussed in the text were taken using a bGeigie Nano (henceforth bGN), a Geiger-Müller counter carefully designed for environmental radiation monitoring; see Fig. 8.

While the LND 7317 Geiger-Müller tube is a 'pancake' design, making it especially good for detecting α and β particles (in addition to γ rays), its most important feature is that can geo-tag, time stamp, and log the data it takes every 5 seconds. This means that while or after driving, biking, or walking you can view radiation levels along your path, on a map if you wish. Bluetooth and smart phone apps for iOS and Android permit starting and stopping logging and real-time monitoring. As part of the SAFECAST project [8], data from a bGeigie Nano can be uploaded to a worldwide database. After it is vetted it is made part of a world-wide map displaying radiation data in a uniform way.

As noted on their web site, "From the outset, SAFECAST has not sided with either the pro- or anti-nuclear camps, and has striven to demonstrate the advantages to science and to the public of having an independent organization devoted solely to providing the most accurate and credible data possible. SAFECAST is "pro-data." Independence, transparency, and openness are essential for us and the key to our credibility. SAFECAST was quickly recognized in Japan and abroad as a reliable and unbiased source of environmental information which citizens can use when making decisions."

Figure 8: bGeigie Nano, case open. This is an Arduino-based GPS- and Bluetooth- enabled logging and geotagging Geiger-Müller counter. It is battery powered and USB rechargeable, with upgradeable firmware.

The bGN project uses open source hardware and open source software; each bGN is built from a kit and is calibrated 'in software'.

The International Atomic Energy Agency hosted the *International Symposium on Communicating Nuclear and Radiological Emergencies to the Public* in October 2018. The SAFECAST blog notes that

> The response to Azby's presentation at CNREP2018 was a clear indication that experts at national and international agencies increasingly "get it." The expert community as a whole recognizes that since the Fukushima accident in particular, a crisis of trust exists which is amplified by misinformation circulating within social media, and that this has clear safety implications. In the event of a future accident or incident, people are likely to be inundated with conflicting messages, some of them malicious, and will have difficulty knowing who to believe.

Appendix C: Statistics of bGeigie Nano data

Because of the very minor spatial variations of measured ADER values throughout the available trails within the Refuge, I merged all data into 4654 counts per 5-second intervals (CP 5s) and 4654 running average counts per minute (CPM).

The CPM is identical to the sum of the counts per 5-sec intervals over the previous 12 intervals (1 minute). This average effectively smooths the large statistical fluctuations present in Geiger-Müller counts.

Unlike a number of more familiar probability distributions (*e.g.*, a gaussian), for the Poisson distribution the breadth of the distribution is directly determined by the mean or average. In other words, the count rate itself determines how uncertain its value is. For Poisson statistics,

$$\overline{n} = \mu, \qquad \sigma = \sqrt{\mu} \tag{1}$$

$$\Rightarrow \sigma/\overline{n} = 1/\sqrt{\mu} = 1/\sqrt{\overline{n}} \tag{2}$$

where we have used the traditional notation σ for the standard deviation and μ for the average value of the count rate. The quantity $\sigma/\overline{n}$ is the relative uncertainty (sometimes called the 'coefficient of variation') of the average count rate. In signal processing terms, its inverse

$\overline{n}/\sigma = \sqrt{\overline{n}}$ is the 'signal to noise ratio', determining how difficult it will be to analyze the signal.

Before discussing fits, we examine the 'autocorrelation function' of our lists—one of 5-second samples and one of 60-second (1 minute) samples. Each list is of the same length, 4654. Crudely speaking, the autocorrelation function measures the extent to which the count rate in a particular interval can be predicted from ('is correlated with') preceding ones. The autocorrelation function is another list of numbers, but we choose to examine its values only over the first half of the entries. Its definition is

$$C(j) \equiv \frac{\langle x_{i+j}\, x_i\rangle - \langle x_i\rangle^2}{\langle x_i^2\rangle - \langle x_i\rangle^2} \tag{3}$$

$C(j)$ measures how correlated a number in the list is with another number in the list j steps away. From the definition the zeroth ($j = 0$) element of the array is 1: given a particular number in our original list, we are 100% able to predict the number 0 steps away—the *same* number. A particular list member is *perfectly* correlated with itself. For more steps away the correlation generally falls quickly with j in a way that reflects the randomness of the list itself. The autocorrelation function is a *statistical* property because its entries are averaged over *all* members of the list, not only one.

If each sample is absolutely statistically independent of the next and is drawn from the same distribution, then

$$\langle x_{i+j} x_i\rangle \rightarrow \langle x_{i+j}\rangle\langle x_i\rangle \tag{4}$$
$$= \langle x_i\rangle\langle x_i\rangle = \langle x_i^2\rangle, \tag{5}$$

so that $C(j \neq 0) = 0$ (there is no autocorrelation). Thus the autocorrelation function $C(j)$ measures the 'decay' of statistical correlation between different members (on average) of the sample and the extent to which the sample members are genuinely independent. Why would they *not* be independent? (i) No finite set of samples will fail to be correlated to some small extent since the averages converge fluctuate for finite sample size; (ii) In reality, the location of the Geiger-Müller counter changes from point to point, meaning that count rates *can* reflect different radiation levels from place to place.

In Fig. 9 we show the autocorrelation function for the set of 5-second samples in the left column and for the list of 60-second samples; in the top row is the autocorrelation function for the first 2327 list entries and in the lower row the short-time (small j) values. It is clear that the 5-second samples are very weakly correlated with themselves after 3 steps or so for the 5-second list whereas the 60-second samples (counts per minute) are quite strongly correlated over hundreds of steps.

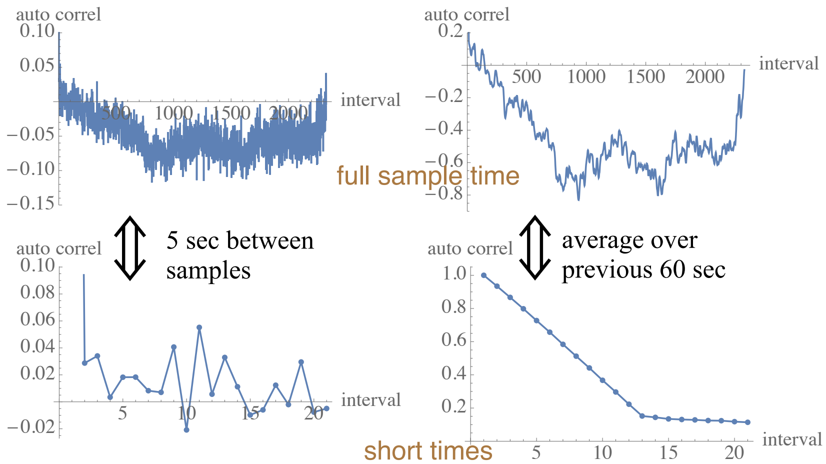


Figure 9: Autocorrelation function for 5 second samples and for running average 60 second samples. Top panels show long term behavior, lower panels show short term behavior. Note the linear decline for the first 12 steps for the 60 sec running average data.

The 'raw data' from the bGN are the 5-sec samples. During the 5 sec interval the actual number of counts ranges from 0 counts up to 13 counts. These values may be histogrammed, placed on a grid centered at $\{0.5, 1.5, \ldots 13.5\}$, and fit to an unnormalized Poisson distribution. By the same token, the counts per minute (12 5-sec intervals) can be similarly histogrammed and fit.

It is crucial to use a Poisson distribution because the average number of counts per 5 sec is a small integer. By contrast, the average number of counts per minute is 12 times larger, now a *large* integer. It is well known that the Poisson distribution becomes gaussian in this limit.

Because the spatial position of the Geiger-Müller counter is changing, this function for this situation will display some effects from the simple time fluctuations of the Poisson process of random radioactive decay and some, presumably much smaller, effects of changes in actual radiation levels along the path traversed. We can confirm that they *are* small by examining careful fits to the 4654 data points discussed earlier. A fit of the 5-second samples to a Poisson distribution is shown in the top panel of Fig. 10 in the margin. The average count rate is 4.36 ± 0.04 counts per 5 seconds, meaning that a radioactive particle is detected *on average* about every 1.15 seconds. [Here the $\pm$ indicate the range defining the '95% confidence interval' ($\pm$ two standard deviations, as measured by the 'standard error').] If we use the running average counts per minute data we find an average of 46.64 (or 46.89) using an unconstrained gaussian fit [green] (or Poisson fit [red]). As remarked above, for a Poisson distribution the width is entirely determined by the average, so comparing a gaussian fit to a Poisson fit gives some insight into how important spatial variations of the radiation rate along the path might be. In the CPM case [panel (c)] the gaussian fit is slightly better than the Poisson fit [red in panel (d)] presumably because there is small contribution to the width of the distribution curve due to actual, physical variations of the radiation dose rate. The bottom panel of Fig. 10 shows exactly this.

The gaussian fit (green curve) is slightly broader than the Pois-

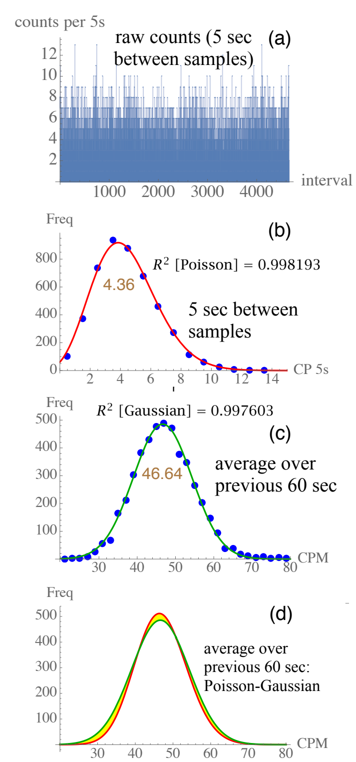


Figure 10: Curve fits to 5-sec data (red, top panel), to counts per minute from the running average, (blue, middle panel), and difference between best Poisson and best gaussian fit to CPM data, bottom panel.

son fit (red curve), but the gaussian curve reaches a slightly higher maximum. The yellow shaded area shows the *difference* between the two fits. The smallness of this difference indicates just how small the spatial variations (encoded in the different values of the curve peaks and the spacing between the curves) must be.

Simple model to identify minimum detectable radiation 'contrast'

How small a difference in radiation rates *could* we detect using the methods above, that is, using a 'moving average' to remove the Poisson noise in our data?

We consider a change in count rate along a path of the form

$$n(x) = n_0 + \Delta \times \quad 2\left(\frac{1}{1+e^{\beta(x-x_2)}} - \frac{1}{1+e^{\beta(x-x_1)}}\right) \tag{6}$$

where x is the location (in terms of time steps) along our path. Here n_0 is the original (background) count rate and Δ is the difference at the peak of the 'envelope' function (which multiplies Δ). The envelope function is picked to go smoothly to zero to the left of x_1 and to the right of x_2; the parameter β determines how abruptly the envelope approaches zero. Then we generate a large number of random numbers from a Poisson distribution of mean $n(x)$, smooth this list using a moving average, and compare with the envelope function to decide if we can see the difference or not. We expect the relevant quantity to be the ratio Δ/n_0, which we call the *contrast* of the spatial change in count rate.

In Fig. 11 in the margin we show the rationale for the belief we can detect a 2% contrast but probably not a 1% one. The profile of the higher radiation rate region is shown in red and the moving average smoothed count rate is shown in blue. Our criterion for distinguishing the high-count region is that peaks in the red region be discernibly larger than those outside. A 10% contrast is readily detected in the smoothed count rate (in blue, top panel), a 2% rate appears to have a clear 'hump' in the higher-rate region (second panel), but for 1% (with either an abrupt or a gradual onset of the higher rate, bottom two panels) peaks outside the region are comparable in size and thus not clearly detectable.

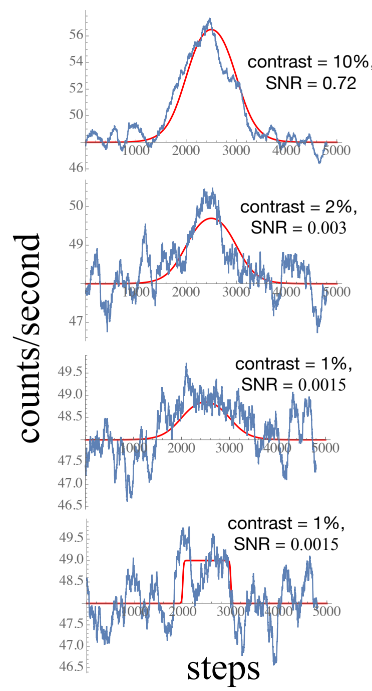


Figure 11: Marginal detection of spatial variation of radiation rate with 'contrast' of higher-rate region (shown in red) for a nominal (background) 50 counts per minute rate.