RadMAP: The Radiological Multi-sensor Analysis Platform

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Abstract

The variability of gamma-ray and neutron background during the operation of a mobile detector system greatly limits the ability of the system to detect weak radiological and nuclear threats. The natural radiation background measured by a mobile detector system is the result of many factors, including the radioactivity of nearby materials, the geometric configuration of those materials and the system, the presence of absorbing materials, and atmospheric conditions. Background variations tend to be highly non-Poissonian, making it difficult to set robust detection thresholds using knowledge of the mean background rate alone. The Radiological Multi-sensor Analysis Platform (RadMAP) system is designed to allow the systematic study of natural radiological background variations and to serve as a development platform for emerging concepts in mobile radiation detection and imaging. To do this, RadMAP has been used to acquire extensive, systematic background measurements and correlated contextual data that can be used to test algorithms and detector modalities at low false alarm rates. By combining gamma-ray and neutron detector systems with data from contextual sensors, the system enables the fusion of data from multiple sensors

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into novel data products. The data are curated in a common format that allows for rapid querying across all sensors, creating detailed multi-sensor datasets that are used to study correlations between radiological and contextual data, and develop and test novel techniques in mobile detection and imaging. In this article we will describe the instruments that comprise the RadMAP system, the effort to curate and provide access to multi-sensor data, and some initial results on the fusion of contextual and radiological data.

Keywords: Gamma-ray detection, Gamma-ray imaging, Background radiation, Data fusion, Homeland security, Radiological search

1. Introduction

Searching for radioactive sources in urban environments is an important component of modern radiological and nuclear security. Toward this end, various vehicle-borne, large area detector systems have been designed and tested in recent years [1–4]. However, the problem of detecting illicit radioactive sources is confounded by the non-Poissonian background fluctuations commonly encountered in operational environments, which greatly limit the capabilities of these systems [5–8]. These fluctuations are caused by variations in the environment through which the vehicle is moving, but the exact radiological properties and geometric configuration of materials around the vehicle are seldom known well enough to predict or even understand these changes.

Many techniques have been brought to bear on the problem of background fluctuations in mobile detector systems. For systems using spectroscopic detectors, new finely tuned spectroscopic algorithms have been developed in recent years to account for background variations [9–17]. Some systems use some basic form of imaging, such as passive or active coded masking, whereby some source counts are sacrificed for improved knowledge of the background [2–4, 18, 19].

The Radiological Multi-sensor Analysis Platform (RadMAP) system has been developed to serve both as a unique experimental test bed for new concepts in mobile radiation detection and imaging, as well as a platform for the acquisi-

tion of the large, diverse multi-sensor datasets required for the systematic study of factors affecting detection performance in real-world environments. The data acquired with the RadMAP system may be used to facilitate, for example:

- The systematic study of natural radiological background variations across
25 diverse environments.
- The investigation of correlations between radiological background and contextual information.
- The development of novel algorithms for detection, imaging, and multi-sensor fusion.
- 30 • The characterization and performance assessment of algorithms at low false alarm rates.
- Trade studies of the factors influencing the design and implementation of mobile detection systems.

The broader scientific community has been given access, upon request, to the
35 RadMAP data to allow such studies to be performed. Access to the multi-sensor data is provided through the LBNL developed Gamma-Ray Data Cloud (GRDC). General access to the multi-sensor data is provided through the LBNL-developed Gamma-Ray Data Cloud (GRDC).

In this paper, we will describe the RadMAP system and its suite of radi-
40 ological and contextual sensors, and discuss several initial studies that have been performed using the data that it has collected. The possibilities for multi-sensor data fusion and the data service used to distribute the data will also be discussed.

2. RadMAP overview

45 The RadMAP vehicle was originally the Mobile Imaging and Spectroscopic Threat Identification (MISTI) vehicle built by the Naval Research Laboratory [2, 20] for the Domestic Nuclear Detection Office’s Standoff Radiation Detection System (SORDS) program. MISTI used a combination of high purity

germanium (HPGe) detectors for spectroscopic alarming and isotope identification, and an array of sodium iodide (NaI(Tl)) detectors with a lead coded mask for imaging. In addition, it had a side-facing camera, a multi-antenna Global Positioning System (GPS) receiver, and software for real-time gamma-ray source imaging and localization.

RadMAP represents a further development of MISTI's gamma-ray detectors and environmental sensors to include panoramic video, Light Detection And Ranging (LiDAR), weather, hyperspectral, and other sensors in order to provide a context for the radiation measurements that is as complete as possible (see Section 3). The HPGe detectors have been upgraded from liquid-nitrogen cooling to mechanical cooling to make longer measurement campaigns possible, and liquid-scintillator detectors have been added to enable the same explorations in the fast neutron domain.

As of 2016, RadMAP has traveled approximately 4000 miles in the San Francisco Bay Area, including through many urban areas such as Berkeley, Oakland, and San Francisco, in addition to some suburban and rural areas. The areas surveyed by the system to date are shown in Figure 1.

3. RadMAP instruments

3.1. Radiation detectors

The core sensors of the RadMAP vehicle consist of three types of radiation detectors: a 10×10 array of NaI(Tl) detectors with a coded lead mask for imaging, an array of between 14 and 24 HPGe detectors, and an array of 16 liquid scintillators for fast neutron detection. All of these detector systems report events in list mode; i.e., individual events are stored with timestamps. A cutaway view of the vehicle with the placements of these sensors is shown in Figure 2.

3.1.1. NaI(Tl) array

The gamma-ray imager aboard RadMAP consists of 100 $4 \times 4 \times 2$ inch NaI(Tl) detectors arranged in a 10×10 configuration, totaling approximately 1 m^2 of

Figure 1: A map of RadMAP’s surveys in the San Francisco Bay Area.

detector area and facing the right (“starboard”) side of the vehicle. In between neighboring detectors is a gap of approximately 1.5 cm. The detectors are read
80 out by electronics described in Section 3.1.3. The typical energy resolution of the NaI detectors is 8.1% full width at half maximum (FWHM) at 662 keV. In front of the detectors is a coded mask that is 12 pixels high by 18 pixels wide. The mask has the same pitch as the detector array and is comprised of lead pixels measuring approximately 4 inch $\times$ 4 inch $\times$ 2 cm, which is the same length and
85 width as the NaI detectors (Figure 3). The mask is positioned approximately 40 cm in front of the NaI array, yielding a pixel size of approximately 14 $^\circ$ square, a horizontal fully coded field of view of 90 $^\circ$, and a vertical fully coded field of view of 27 $^\circ$. The detector array is shielded around the sides and on the top by 2.5 cm of lead.

90 Two mask patterns have been used during RadMAP data collection thus far:

Figure 2: A cutaway view of the RadMAP truck showing the position of various radiation sensors. When there were between 18 and 24 liquid-nitrogen cooled HPGe detectors, additional detectors were mounted in a column to the left of the coded aperture.

the original coded mask pattern that the Naval Research Lab designed for the MISTI vehicle (the “NRL mask”) and an improved random mask pattern (the “2015 mask”). Additionally, some data in 2013 were collected with no lead mask pieces in place, and some with a 10×18 version of the 2015 mask, in order to

95 measure the effect of the amount of lead shielding on background variations [8]. Diagrams of both mask patterns are shown in Figure 3. The 2015 mask pattern was found by attempting to suppress the image artifacts of the NRL mask, as well as by enforcing a condition that every 10×10 sub-array of the mask is nearly 50% transparent for a more uniform flat field image (Figure 4). Using balanced

100 correlation to decode the masks also yields an improved system point spread function (SPSF), shown in Figure 5 [21, 22].

3.1.2. HPGe array

From 2011 to 2014, RadMAP fielded between 18 and 24 coaxial high purity germanium (HPGe) detectors manufactured by ORTEC. Each 100% relative ef-

Figure 3: Original 18×12 coded mask design (“NRL mask,” top) and the improved coded mask design (“2015 mask,” bottom). The relative position of the 10×10 NaI detector array is outlined in red. The perspective is from the image plane looking back toward the vehicle.

105 efficiency detector was comprised of an approximately 88 mm diameter by 63 mm long germanium crystal and was cooled by an individual liquid-nitrogen dewar. The readout of the HPGe detectors was performed using the same electronics as the NaI array, although with different shaping times and higher analog-to-digital converter (ADC) bit depth [20]. The typical energy resolution was

Figure 4: The open fraction of each mask in the half-coded field of view of the original and improved RadMAP coded masks. The 2015 mask shows a much more uniform flat field, especially in the fully coded field of view (outlined).

110 1.7 keV FWHM at 662 keV.

In the summer of 2015, the original liquid-nitrogen-cooled germanium detectors on RadMAP were replaced with 14 mechanically cooled IDM-200-V detector modules from ORTEC [23]. Each module contains a single 85 mm diameter by 30 mm long crystal cooled by a Stirling-cycle cooler. A custom BNC output
 115 was added to each IDM for ease of integration with the existing readout system

3.1.3. *NaI(Tl) and HPGe readout*

From 2011–2014, the NaI(Tl) and HPGe detectors were read out by nine 16 channel Mesytec MSCF-16 shaping amplifier boards, which performed analog
120 shaping of the detector signals, while five 32 channel Mesytec MADC-32 boards performed analog to digital conversion of the shaped signals [24, 25]. More details on the original readout system can be found in [20].

In 2015, in order to eliminate the dependency on the older analog hardware and eliminate a spurious noise signal that was observed in the HPGe detector
125 data, the data acquisition system was upgraded to a fully digital system using eight Struck Innovative Systeme SIS3316 16-channel 14-bit 250 MHz digitizers [26]. These digitizers are individually read out over Ethernet by a dedicated Linux server.

The first SIS3316 board is synchronized using a 10 MHz external NIM clock
130 derived from the 10 MHz sine output of the rubidium frequency standard (see Section 3.7 for details), and the remaining seven boards are synchronized to the first board using the LVDS cable bus on the front panel of the boards. In this way the boards are synchronized to the nanosecond level. The time synchronization of the boards was confirmed by searching the data for events
135 where several detectors have events with timestamps within 10 ns of each other, and many muon events were identified as a result (Figure 6). Muon events could not be observed in the original analog readout system due to its lower dynamic range and timing resolution. Section 3.7 contains more information on the timing synchronization with other systems.

140 3.1.4. *Liquid scintillators*

Fast neutron signatures are valuable for the detection of special nuclear material (SNM). To explore the fast neutron domain with RadMAP, an array of liquid scintillators was installed. The scintillator array consists of 16 Eljen Technology EJ-309 organic liquid scintillators [27]. Each detector is oriented
145 horizontally and stacked vertically in two columns of eight detectors each. Each cell is a 5 inch diameter by 5 inch long aluminum cylinder coupled to a 5 inch

Figure 6: Two examples of muons detected by the NaI(Tl) array on board RadMAP. Muon events are found by searching for multi-detector events within 10 nanoseconds of each other, demonstrating the synchronization of the latest readout system.

Hamamatsu photomultiplier tube (PMT). The PMTs are powered by a VME high voltage power supply module controlled by iseg VHS 4030n (4 channels) and VHS C030n (12 channels) HV modules [28], which provide between -1500 V and -2000 V to each PMT. The total active detection volume of the system is approximately 25 liters. EJ-309 was selected for its pulse shape discrimination (PSD) characteristics, enabling neutron-induced signals to be distinguished from gamma-ray interactions [29], as well as for its low toxicity and high flash point.

The PMTs are read out by two Struck SIS3320 250 MHz 12-bit digitizers, each with eight channels. Each digitizer reads out one vertical column of eight detectors. The Struck-provided data acquisition software is used to control the digitizers and collect and save raw trace data. Once raw signal pulses with associated timing information are recorded, the data are then parsed into a usable format for data processing, PSD, and analysis. The data for the neutron detectors are saved on a dedicated laptop running Windows.

3.2. RadMAP position and aspect

Position information is provided by two systems. The first is a Magellan ADU5 GPS receiver with a 5 Hz data rate [30]. This unit provides a coarse GPS location and the primary pulse-per-second (PPS) for the global clock. As this

165 unit relies solely on a GPS signal, its accuracy is degraded in many situations, such as urban areas, where the GPS signal is attenuated or can be impacted by multipath effects (e.g., [31, 32]). Typical uncertainties range from ~ 3 meters in open areas to ~ 10 meters or more in urban areas. Because of these limitations, the use of the Magellan ADU5 on RadMAP was discontinued in 2015.

170 Starting in 2013, more accurate positioning was provided by a NovAtel SPAN-CPT GPS/INS receiver [33]. Because it uses inertial information as well as GPS information, its accuracy is greatly improved over the Magellan system, especially in urban areas. Typical accuracy is 3 cm after post-processing with public base station data as well as precise satellite orbit and clock information. 175 Its data includes orientation (pitch, roll, and yaw) for the vehicle at up to 0.05° accuracy. The NovAtel data is acquired over USB by the main Windows server. A comparison between the Magellan ADU5 and the NovAtel SPAN-CPT for RadMAP data is shown in Figure 7.

3.3. LiDAR

180 Two Velodyne HDL-32E LiDAR units [34] are installed on the left and right front corners of the truck (shown in Figure 2). Each LiDAR unit uses 32 infrared lasers to measure a three dimensional point cloud around the truck. The beam directions range from $+10.67^\circ$ to -30.67° in elevation, for an angular spacing of 1.33° . In azimuth, measurements are taken at an angular spacing of 0.12° to 185 0.15° as the LiDAR head rotates. The average rotation rate is approximately 10 Hz, and the maximum range is 80–100 m. In order to increase the vertical coverage of the LiDAR point clouds, each unit is tilted forward 10.67° to cover 0° to -41.34° in the forward direction and $+21.34^\circ$ to -20° in the rear direction. Custom acquisition code records the LiDAR data on RadMAP’s main Windows 190 server.

3.4. Visual imagery

For wide field of view, high rate imagery, two Point Grey Ladybug 3 spherical video cameras [35] are installed at the top left and right corners of the truck cab,

Figure 7: GPS locations from RadMAP in downtown Oakland using the Magellan ADU5 (left) and the NovAtel SPAN-CPT (right). The SPAN-CPT is able to remain highly accurate even when the view of the sky is blocked by tall buildings. (Google Maps imagery from DigitalGlobe, U.S. Geological Survey, and USDA Farm Service Agency.)

directly above the LiDAR sensors (Figure 2). Each camera uses six 2 megapixel
 195 sensors arranged to cover more than 80% of a full spherical field of view. Images
 are recorded at a rate of 15 frames per second. Custom acquisition code records
 data from both Ladybug cameras on the main Windows server.

In addition, a simple visual camera system covers the imaging field of view
 of the NaI(Tl) array. RadMAP currently uses a Raspberry Pi with a visual
 200 CCD camera and a fisheye lens, covering a field of view of approximately 100°
 horizontal and 77° vertical. This field of view subsumes the fully coded field of
 view of the gamma-ray imager. Images from this camera are recorded at a rate
 of 1 Hz. In 2015, this camera replaced an older visual/infrared camera.

3.5. Weather

205 In May 2012, RadMAP was equipped with its first weather station. The New Mountain 100 recorded wind speed and direction, temperature, barometric pressure and relative humidity [36]. Soon after, a standalone digital rain gauge was added to allow the study of correlations between rainfall and background level from radon. In December 2012, the weather station was upgraded to the
210 Vantage Vue 6250 by Davis which includes rain measurements along with all of the features of the previous system [37]. The position of the Davis weather station on the top of the truck is shown in Figure 2.

3.6. Hyperspectral imagery

The RadMAP system employs two hyperspectral imagers (HSIs), both of
215 which are operated as “push-broom” imagers – i.e., they record one-dimensional images, and the second image dimension is obtained using the forward motion of the vehicle. The first of these cameras is the Resonon Pika II, with 640 spatial pixels and an effective field of view (FoV) of $43.5^\circ \times 0.14^\circ$ [38]. (The narrow horizontal FoV is due to the one-dimensional nature of the camera.) Each of
220 the spatial pixels records visual and near-infrared light in 240 12-bit spectral channels ranging from 400 – 900 nm. The second camera is the Resonon NIR, with 320 spatial pixels and an effective FoV of $90.0^\circ \times 0.36^\circ$ [39]. For each of its spatial pixels it records 145 14-bit spectral channels ranging from 900 – 1700 nm (i.e., near infrared). Both cameras are synchronized to a common trigger which
225 operates at a rate of 45 Hz, and both are read out by a dedicated Windows computer.

3.7. Sensor integration and synchronization

In order to register data from all of the sensors, each computer and sensor records time in seconds since the UNIX epoch (i.e., midnight UTC on January 1,
230 1970). The required time accuracy is dictated by the desired position accuracy of reconstructed spatial datasets, e.g., in order to achieve an accuracy of $\lesssim 10$ cm

at typical driving speeds of 25 mph (11 m/s), all data must be synchronized to $\lesssim 10$ ms.

In order to obtain the time accuracy required, the on-board computers are
235 synchronized using Network Time Protocol (NTP) [40], which is capable of syn-
chronizing the clocks to within a few milliseconds of the main clock. The com-
puters are synchronized to the clock on the main Linux server, which is in turn
synchronized to GPS time using the Magellan ADU5 and the utility GPSD [41].
The Magellan outputs National Marine Electronics Association (NMEA) data
240 messages and a pulse-per-second (PPS) signal, and together these are used to
obtain a $\sim 1\text{-}\mu\text{s}$ -accuracy NTP time source. In addition, the PPS is stabilized
by a Stanford Research Systems FS725 rubidium frequency standard [42] in case
of a GPS dropout.

For some sensors, hardware triggering is preferred over software triggering in
245 order to ensure that sufficient synchronization is maintained. For these sensors
— the Ladybug cameras, the LiDARs, and the hyperspectral cameras — a sys-
tem was developed to provide the required trigger pulse types and rates to each
one. The hardware synchronization is controlled by an Arduino Mega 2560 [43],
which receives both the NMEA string from the Magellan ADU5 as well as the
250 PPS from the rubidium frequency standard. The Arduino is programmed to
output the correct pulse frequency and shape to each of the sensors, e.g., a 5 V
square wave at a frequency of 15 Hz for the Ladybug cameras, and these triggers
are synchronized to the PPS pulse. The LiDARs require both a PPS trigger
pulse and an NMEA message after a set delay.

255 In 2015, the NovAtel SPAN-CPT unit replaced the Magellan ADU5 as the
source of both the NMEA messages and the PPS. Since the SPAN-CPT can be
configured to output different NMEA messages, it was straightforward to use
it as the main GPS time source for RadMAP. The new timing logic is shown
in Figure 8.

Figure 8: Diagram explaining how time is synchronized to high precision among the computer servers, SIS3316 boards, and contextual sensors on board RadMAP. Before 2015, the Magellan ADU5 was used instead of the NovAtel SPAN-CPT. The SPAN-CPT's high precision position and aspect information is logged over the USB connection to a Windows server.

3.8. Data rates

Data from all different sensors and detectors on board the RadMAP vehicle are stored on board on a redundant array of independent disks (RAID). Some of the sensors, e.g., the Ladybug cameras, have high data rates, while other sensors, such as the radiation detectors, typically have much lower data requirements.

Table 1 shows the typical total data rate of the RadMAP system as well as a breakdown into the typical rates of the individual components.

4. Data applications and use cases

The large sets of synchronized, multi-sensor data acquired by RadMAP allow for the development and assessment of advanced detection and imaging algorithms, the investigation of novel data fusion approaches, and the exploration of

Datastream	Format	Typical data rate (GB/hour)
NaI and HPGe	list-mode	3
Liquid scintillators	list-mode with waveforms	5
Visual/IR camera	JPEG images	0.5
LiDARs (2)	libpcap format	16
Ladybug cameras (2)	PGR video format	360
Hyperspectral visual	ENVI files	47
Hyperspectral NIR	ENVI files	25
Other	Various	0.5
Total		457 GB/hr

Table 1: The approximate amount of data collected per hour by each of the sensors on the RadMAP truck.

new concepts in mobile radiation detection. Already, the multi-sensor data collected with the RadMAP system have been used in a number of studies including an examination of the trade-offs between detection through spectroscopy and imaging [8], the characterization of an advanced spectroscopic detection algorithm [44], and the development of techniques for the fusion of LiDAR, visual imagery, and radiation data (Section 4.3). Such studies are facilitated, in part, through the use of the Gamma-Ray Data Cloud (GRDC) data service for the curation, indexing, and querying of data (Section 4.6). In this section, we summarize several example use cases.

4.1. Routine surveys

Routine surveys of the San Francisco Bay Area have been performed with RadMAP since 2011 [7]. Gamma-ray detector count rates for an urban region of the Bay Area (in this case, downtown Berkeley and Oakland) are shown in Figure 9. Increases in count rate are mostly due to passing particular building facades or going through an underpass or tunnel, as well as encountering medical nuisance sources. These data demonstrate the non-Poissonian background distributions typically observed in an urban area.

In [7], the survey data were segmented into subsets based on environmental and geographic considerations. Individual datasets associated with urban, rural,

290 and industrial environments were generated along with a feature specific set capturing data recorded on bridges. Analysis revealed that the local background distributions differed significantly both from each other and from the background distribution of all locations combined. This study served to illustrate the strong correlation between local environment and radiological background
 295 while suggesting that from an operational perspective, the use of context and/or environment specific detection thresholds and background models could allow for improved detection sensitivity at a constant false alarm rate.

Figure 9: NaI(Tl) and HPGe gross count rates binned in 1-second intervals and normalized by number of detectors. The vehicle is stationary for the first 10 minutes and final 10 minutes of the survey, which is why count rates are flat there. The large increase in counts at 18:13 is due to an encounter with a medical source (^{131}I), and the maximum rate reaches 1800 counts per second per detector (truncated for display). There is also an encounter with a weak medical source (^{99m}Tc) at 18:20, which is not obvious in comparison to the other fluctuations in the gross count rate but is clearly visible in the spectrum.

4.2. Development and evaluation of gamma-ray detection algorithms

The RadMAP dataset has also been used as a standard for characterizing
 300 and assessing the performance of gamma-ray detection algorithms. The dataset has been used to directly compare spectral- and imaging-based detection algorithms [8], evaluate the effects of detector efficiency and resolution using realistic backgrounds [45], and evaluate state-of-the-art detection and identification algorithms [44].

305 In [8], data from RadMAP’s NaI(Tl) array were analyzed using source in-
jection. Different spectral and imaging algorithms were applied to the data and
compared against ideal cases. Even a simple linear region-of-interest spectral
estimation was shown to offer a drastic improvement in false alarm rate over
simple energy windowing. Likewise, the power of using imaging as a means to re-
310 duce systematic background fluctuations was also quantified. For the RadMAP
imager, even simple spectroscopic approaches outperformed imaging approaches
due to the higher number of source photons that would be detected without a
mask.

In [45], RadMAP data were further applied to the study of the trade-offs
315 between detector size and energy resolution. One of the key findings was that
spectroscopic detection algorithms performed better than imaging methods for
the RadMAP NaI(Tl), but for a larger array or worse resolution detectors, imag-
ing might eventually outperform spectroscopy. In addition, the HPGe detectors
on RadMAP were compared to the NaI(Tl) array. It was found that when
320 trained spectral algorithms are used, the equivalent of about seven 100% rel-
ative efficiency germanium detectors would yield the same performance as the
1 m² NaI(Tl) array, however these results are strongly dependent on the algo-
rithm applied to the NaI data.

4.3. Fusion of gamma-ray images, video, and 3D point clouds

325 The use of real time LiDAR and video to augment the analysis of radia-
tion data holds the potential to improve detection and localization performance
while also providing contextually complete data products to aid in the inter-
pretation of the radiation measurement. Potential concepts include the use of
contextual cues present in visual imagery to inform detection algorithms of the
330 local environment, the use of ranging information from LiDAR to improve lo-
calization performance, as well as complete fusion of a gamma-ray image with
a three-dimensional scene reconstruction [46, 47].

In one example from RadMAP data, panoramic imagery, LiDAR, and coded-
mask images have been fused into a video showing the location of a medical

335 nuisance source (^{99m}Tc) encountered in an urban area (Figure 10). In this
video, the coded-mask image was projected onto the LiDAR point cloud, which
was in turn overlaid onto Ladybug imagery. The combined data product reveals
that the source is in the front compartment of a nearby car. Fused data products
such as this one could help rapidly identify and adjudicate sources in complex
340 environments. A software pipeline for automatically producing data products
like Figure 10 does not yet exist but is possible using existing data.

Figure 10: The fusion of a gamma-ray image of a medical isotope (^{99m}Tc) using RadMAP's NaI array with a point cloud from a LiDAR, overlaid on visual imagery from RadMAP's Ladybug cameras. The source clearly appears in the driver's side of the SUV near the center of the image.

4.4. *Characterization of fast neutron background variability and correlations with contextual data*

Neutron backgrounds are primarily cosmogenic and are generally lower and
345 less variable than gammas, but for weak SNM source detection, systematic variability still limits detection sensitivity. The largest known influence on neutron background variability is atmospheric pressure, which affects the development and attenuation of cosmic ray showers [48]. Analysis of the RadMAP liquid scintillator data has confirmed that pressure is indeed the dominant factor in

background variability, and a correction to the observed neutron rates using the on-board weather station has been developed [49, 50].

After atmospheric pressure, the largest effect on the fast neutron background rate in urban areas has been found to be the “sky-view factor” [51]. The sky-view factor is the fraction of the sky that is not blocked by nearby buildings, which attenuate the cosmogenic neutrons. The resulting analysis of RadMAP fast neutron background data shows that, for sky-view factors >0.15 , the shielding effect of buildings in urban environments is dominant over any additional production in building materials from spallation processes (Figure 11). Details and further discussion are in [49, 50].

Figure 11: Pressure-adjusted count rates for sky-view factors from all runs that travel through select portions of Berkeley, Downtown Oakland, or Downtown San Francisco. A quadratic fit describes the data well for sky-view factors of 0.15 to 1.0. Low sky-view factors require further investigation and are excluded from the fit. From [49, 50].

4.5. Hyperspectral image classification

Hyperspectral imagers provide visual or infrared images with dozens to hundreds of channels. The additional spectral information can be used to identify

the materials in a scene through identifying features in their reflectance spectra that are impossible to find using RGB imagery. Hyperspectral imagery has
365 been used to distinguish different types of minerals, vegetation, soil, and man-made materials (e.g., [52, 53]). Since different types of materials often have very different radiological signatures, being able to easily distinguish different materials in a scene is a potentially powerful type of contextual data for radiation measurements that has been little examined to date.

370 An example of a largely unsupervised classification of HSI data into different materials is shown in Figure 12. The particular workflow used here was performed on data from RadMAP’s NIR camera using the Environment for Visualizing Images (ENVI) software by Excelis [54]. The first step was to reduce the dimensionality of the data from 145 channels using the forward Minimum
375 Noise Fraction (MNF) rotation [55]. The MNF transform separates noise from data and orders the new MNF bands from low to high noise. The next step was to segment the scene; the first 30 MNF bands were fed into a K-Means iterative spatial cluster classification method [56]. This segmentation further reduces the dimensionality of the data before the final image classification step.
380 In order to maintain adequate separation among spectrally dissimilar materials, 50 classes were chosen. The resulting image acts as an unsupervised Region of Interest (ROI) map. The final step is to convert the ROI map into a more relevant classified image. To do this we apply the Spectral Angle Mapper [57] method to the original 145 channel image using the ROI classes produced in the
385 previous step. In this final step, spectrally similar ROI classes can be combined to form material classes. The end result is several material classes to represent the scene. This method resulted in the six readily interpreted classes for an urban scene in Figure 12.

4.6. *Gamma-Ray Data Cloud*

390 The unique nature of the datasets produced by RadMAP are likely to be valuable to many research communities, including those engaged in detection algorithm development and computer vision research. To facilitate access to and

Figure 12: Demonstration of hyperspectral data being used to classify materials in an urban scene using data taken with the NIR camera on board RadMAP. At the top, a false color RGB image is generated using three Short-wave Infrared (SWIR) bands (1550, 1300, and 1050 nm). The bottom image shows the six major classes that could be easily distinguished by a largely unsupervised classification pipeline (black pixels are unclassified). This material information could provide useful contextual information to associate with gamma-ray measurements.

analysis of RadMAP’s synchronized datasets by collaborators, a data service has been developed called the Gamma-Ray Data Cloud (GRDC) [58, 59].

395 The data service contains datasets from the RadMAP detectors that are registered by timestamp and provides a web frontend for the browsing of available datasets and the formation of queries of the data (Figure 13). Front-end visualization tools include colorizing one-dimensional RadMAP paths by any available one-dimensional dataset (GPS-measured altitude is shown in Figure 13),
 400 creating histograms of one-dimensional datasets, and creating two-dimensional histograms of any time-synchronized list-mode dataset.

Queries consist of the desired datasets as well as any selections by time, latitude and longitude, or any other one-dimensional dataset (the latter selections are generated using the histogram tool). Web requests for data result in
 405 automated generation of requested data into an HDF5 file [60], which is made available for download. The data service provides an API for querying and downloading sequential portions of the datasets. The API also supports the creation of new, user-defined datasets that are registered back into the data service and can be made available to other users of the system for comparison

410 studies and to enable additional multidisciplinary analyses based on these user-created datasets. This functionality provides the potential for the entirety of the RadMAP data to grow in overall value as more analyses are performed. For example, as new spectral detection algorithms are developed, their registered outputs could be directly compared to the results of other algorithms that have
415 also been registered. As another example, user-created datasets containing features derived from the contextual sensors could be registered and correlations with features in the radiological data could be explored.

Any users interested in accessing RadMAP data on can request `GRDC.nersc.gov` access through the website `bdc.lbl.gov`. The RadMAP group is actively
420 adding more data to the website after data validation activities. For example, much of the LiDAR and Ladybug imagery data was found to have poorly controlled time offsets prior to the implementation of the time synchronization methods outlined in Figure 8. As such, this data has not been deployed online, however work to synchronize and distribute those data are ongoing. Conversely,
425 over 250 hours of NaI, HPGe, GPS and weather data are available online. Prior to publication, quality spot checks are performed and gamma-ray detector energy calibrations are accomplished using prominent ambient background lines.

5. Summary

The RadMAP platform is a novel testbed for exploring the fusion of radio-
430 logical and contextual data, enabling a new era for detection algorithm development and multi-sensor fusion. A large dataset has been taken in the San Francisco Bay Area containing synchronized multi-sensor data, which has already begun facilitating the systematic study of radiological background variations, the testing of gamma-ray detection algorithms, the comparison of different de-
435 tection modalities, and the fusion of gamma-ray images with video and LiDAR. RadMAP datasets are registered in the Gamma-Ray Data Cloud data service, allowing for broader access within the community and a common framework in which to register, share, and compare results. Such a large, shared dataset can

Figure 13: The GRDC web frontend, which allows for browsing, querying, and downloading different datasets from the RadMAP vehicle, as well as the creation of new, user-defined datasets.

enable new collaborative developments in detector modalities and algorithms
 440 for homeland security, new concepts in multi-sensor data fusion, and a more
 complete understanding of complex urban gamma-ray backgrounds.

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