LESSONS LEARNED: DETECTING AND IDENTIFYING RADIATION SOURCES IN MODERN URBAN ENVIRONMENTS.

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INTRODUCTION: It is a difficult and demanding proposition to search urban areas for potential terrorist radiological threats, whether the threat is a nuclear device (superpower-manufactured or improvised), a dispersal device ("RDD"), or simply a lost commercial or medical source. Many of the concepts of modern radiation detection need to be adapted to the dynamic nature of the modern city. Advances in technology mean that there are more radiation detection instruments, with greater sensitivity, in use on a daily basis for antiterrorism purposes in major cities around the world. In the last decade, isotope identification has migrated from the laboratory to the street. The combined effect of increased perceived threat, improved awareness, and increased availability of cheaper and more sophisticated detection equipment is that searches for radiation threats are no longer the province of specialized teams from scientific institutions. The average searcher is no longer likely to have an academic background. Therefore, work must be done to make the job of searching for radiological threats easier, particularly in dense urban areas which pose the likeliest targets for radiological terrorism.

The author of this paper was heavily engaged in several large search operations in several US cities over the course of several years, in support of development of technology and operating concepts for radiological antiterrorism. This paper is intended to capture some of the important lessons learned in the course of two years of development of an urban search capability in North America in 2006-2007.

URBAN SEARCH POSES UNIQUE PROBLEMS

Successful application of radiation detection in an antiterrorist mode relies heavily on three factors: high probability of detection; high probability of identification; and operationally sound procedures. Mobile threat detection requires both a detector and a spectroscope, whether used separately or combined in the same instrument. Threat detection requires answers to several questions, the most important of which are: How much ionizing radiation is present, what isotope is present, and what is the exact location of the source? In urban search operations, in order to detect threat sources while disregarding anomalies or innocuous radiation sources, both detection probability and identification probability must be maximized. The complexities of the urban environment make it more difficult to successfully search for threat radiation sources.

Much of the extant expertise in this area is derived from static monitoring (i.e. health physics and safety measurements) or interdiction operations, such as customs inspections at ports and border crossings. In both static monitoring and interdiction operations, there is a high degree of control over the environment. For example, customs personnel can control the speed at which vehicles transit through checkpoints or the speed at which they scan cargo containers. Mobile search operations in a city are much more complicated due to speed. In various permutations of the search scenario, the detector is in motion, the radiation sources (both benign and threatening) is in motion, or both. In nearly all circumstances, the speed of the source relative to detector adversely affects the "dwell time" (the time period in which the source's photons can be effectively intercepted by the detector material) and thus reduces probability of detection.

UNDERSTANDING URBAN BACKGROUND RADIATION IS VITAL: Background radiation in the urban environment varies tremendously, even within a small area. Count rates, particularly in the low energy end of the spectrum (<100 KeV), will fluctuate wildly. This is due to variations in cosmic, terrestrial (geologic), and artificial radiation sources used for legitimate purposes. Construction materials will contribute to this variance. The author's direct experience was that background routinely fluctuated by a factor of 10 in three different urban areas in the USA, with some notable regions with fluctuations of up to a factor of 20. Therefore, using an arbitrary alarm threshold, based on a background collected when the detector is turned on, while an adequate procedure for a fixed sensor, is clearly not an optimal approach for mobile detection.

Significant anomalies will exist in every urban environment. Medical, industrial, and scientific radiation sources are fairly ubiquitous in modern cities. Search teams should have an awareness of the types and quantities of regulated and unregulated radiation sources in their search area so that search operations are not impeded by false alarms. It is also important to note that some types of anomalies will be transient in nature. The most common anomalies noted in the author's field work were people with temporary uptake of medical isotopes. Industrial radiography, usually undertaken as part of construction work, was a distant second. A useful guide to these sources is Technical Guide 238. (US Army, 1999) Because of the transitory nature of these situations, the search team must understand that there will be some fraction of anomalies that will be so transitory that they will not be able to be fully investigated. The user will have to adopt a risk management approach to anomalies consistent with local policies.

ALERT THRESHOLDS AND THE DYNAMIC BACKGROUND PROBLEM: Because background gamma levels will fluctuate in a city environment, arbitrary count rate alert thresholds are not very useful as they will permit many false alerts and allow for the possibility of valid threats being lost in the background radiation. In many monitoring and detection operations, the common approach is to use a reading of twice background as an alarm point. (One example, see Iowa, 2005) However, this is clearly insufficient for a complex urban area, where the range of readings will normally exceed this threshold. One approach that is commonly used is an average background. Instead of an arbitrary background set at the beginning of operations, a rolling average over a period of time is utilized. Many detection systems use an average count rate over a previous period in time, (60 seconds, for example, or 5 minutes) to provide background information, either for the purposes of threat detection, or for isotope identification. This approach may be well suited for a static or low-speed situation.

Figure 1 illustrates a simple detection scenario. In this scenario, typical of urban environments, the background count rate ranges between 1000 and 1800 counts per second (cps). Three different alert thresholds are depicted (1.5 x, 2 x, and 3x an average of the previous 30 seconds). The detector encounters three different situations. At point T1, there is an anomaly comparable to a count rate of four standard deviations above the natural background. At point T2, there is a benign medical radiation source (9500 cps), and at point T3 there is a threat radiation source (peak count rate 3800 cps.) The operators receive an alert when the count rate exceeds the alert threshold. Incidentally, at point T1, the detector may receive a false positive if the alert threshold were set to 150% of the average background. The anomalous background count rate was only 4 standard deviations from the mean, and therefore likely to occur at least occasionally in routine operation. Therefore, an alert threshold of 150% of average is likely to incur an unacceptable false positive rate. In practice, an alert threshold of twice the averaged background or higher is needed to suppress false positives from random fluctuations. Some users set an alert based on standard deviations (sigmas - σ) above an average. At least 4σ is required to avoid a punitive false alert rate. However, with a detector or a source in motion, it is altogether possible for these approaches to fail completely. In addition to nuisance alarms based on expected fluctuations, two types of false negative detection failures were discovered when using averaged background: "detector lag" and "ascending baseline."

DETECTOR LAG: Detector lag occurs when a detection event temporarily increases background, thus screening possible threats. This is also illustrated in Figure 1. The mobile detector drives past a large gamma source at point T2 (maximum count rate near 9500 counts/second (cps)), followed by another smaller source a few seconds later (count rate 3100 cps.) Since the detector is moving quickly, the source is only seen by the detector during a short period. The point T2 indicates successful detection, where the count rate exceeds the various alert thresholds. This is a successful detection of a potential threat. The detector then passes a second threat at point T3. However, the second threat is undetected, because the count rate never exceeds the alert threshold. The time period to the right of T2 has an artificially increased alert threshold that may act to screen hostile threats.

ASCENDING BASELINE: Figure 2 illustrates a different example. In this case, the search team is moving very slowly towards a threat source. The detector moves slowly towards the threat source (T1), which has a peak of around 5300 cps. In this example, the source is never detected. The slow increase of count rate gradually pushes up the alert threshold, and the count rate never exceeds the alert threshold. This is also a likely failure mode when the search team encounters a very large source at a significant distance. In such a situation, the count rates will initially be low and increase slowly.

FAILURE MODES IN ISOTOPIC IDENTIFICATION: Mobile isotope identification presents similar failure modes. For an adequate identification of an isotope, a threat spectrum is compared to a background spectrum. A relatively clean and accurate background, free of anomalous gamma spectra, is required for an accurate identification. In a static situation, background will be relatively stable and can be set once a day or so. However, the background will change as the detector is moved. While driving around a city, constantly re-acquiring a stable background for identification is difficult, and is likely to be impossible at road speeds. In other words, by the time a background spectrum has been saved, the detector is already in a different location. Under many mobile search situations, the background data used for identification is likely to be tainted. In both figures 1 and 2, isotope identifications would likely fail due to tainted background.

TECHNICAL SOLUTIONS

The problems identified above can be significantly mitigated by appropriate technical countermeasures.

DETECTOR DESIGN CONSIDERATIONS: Equipment that has been designed to both detect radiation and identify isotopes tends to suffer from engineering trade-offs in the design process. Some detector materials that work well for detection do not work well for identification, and vice versa. The author's technical approach was to use separate devices for detection and identification, allowing for optimal selection of technologies. The ideal detector has good energy response across the spectrum of potential threat isotopes, from low energy emitters such as U-235 to high energy threats such as Co-60. Good sensitivity is also important. Sensitivity is, in part, a function of the size of the detection material. Probability of detection will be increased by increasing the surface area and/or volume of scintillation material. This is particularly important in mobile detection operations, as larger detectors effectively increase the "dwell time". The practical effect of these planning considerations is that larger, cheaper, lower resolution detectors made from scintillating plastic (e.g. anthracene doped polyvinyltoluene - PVT) are actually better detectors than their more sophisticated and more expensive alternatives, such as sodium iodide, cadmium-zinc-telluride (CZT), lanthanum bromide ($LaBr_3$) or high purity germanium (HPGe).

ADVANTAGES OF PVT AS A DETECTOR: While it is often disregarded as an antiquated or inadequate technology, PVT scintillators have several advantages. Per unit of volume, PVT is roughly one thirtieth the cost of NaI. It is also much easier to manufacture and to use PVT in the fabrication of large detectors. The largest commercially NaI crystals routinely available commercially are a bit larger than 4000 cm^3, whereas PVT can easily be made in much larger configurations. The other alternatives, $LaBr_3$, CZT, and HPGe are even more expensive and are available in only much smaller configurations. PVT is also significantly less dense than its competitors. PVT is approximately 1.03 grams/cm^3, whereas NaI is about 3.67 g/cm^3. LaBr3 and HPGe are denser, at over 5 g/cm^3. Effectively, NaI is a rock. This means that some lower energy photons, which may be of interest to a search team, will penetrate a shorter distance into the detector material and elicit less of a response from the detector. Therefore, some radiation threats may actually be missed if you are using a detector constructed from one of the denser materials.

CLASSIFICATION: While PVT does not have the energy resolution to be able to identify isotopes, PVT detectors have sufficient capability to provide a general classification of the radiation detected. PVT detectors can be used to discriminate between low energy natural background and higher energy artificial sources. In addition to theoretical work in this area (Kwak, et.al. 2009), at least one manufacturer has fielded detector hardware that takes advantage of this capability. (Philliou/Craft, 2004) Effective use of this ability allows many false alerts to be rapidly screened out without having to use a sophisticated identifier, thus increasing the net effective speed of a search operation.

BACKGROUND LATCHING: One solution to the isotope identification problem is to use a suite of detectors rather than a single, sophisticated instrument. The detector should be separate from the identifier. The detector can be utilized as a trigger. Once an anomaly is detected, the isotope identifier can "latch" its background, nearly instantaneously. This would preserve a relatively clean background for use in isotopic identification. Operator discipline is required to "unlatch" the alert and resume background collection.

BACKGROUND MAPPING: The most important lesson learned was that it is very important to develop and maintain good baseline information. This is only practical if a reasonable operating area is defined and assessed. A full methodology for doing this may be the scope for an additional paper. The most important tool for handling baseline is a background map. Detection equipment should be combined with a GPS system and a sufficiently detailed map. Commercially available software can provide the framework for excellent mapping capability. Geographic information systems (GIS) are invaluable in storing background information. Background radiation measurements can be collected and related geographically to specific geographic coordinates.

SITUATIONAL AWARENESS: By properly storing background radiation readings as a background map in a GIS platform, a skilled user can have a much higher degree of situational awareness of the normal radiological environment. Known anomalies can be catalogued, annotated, and analyzed. Zones of particular concern can be subjected to additional background collection to allow for a more accurate understanding of the area. Search teams can use detection data to conduct trend analysis.

USING BASELINE DATA FOR ALERT THRESHOLDS: Once a GIS-based baseline is developed for an operating area, different alert thresholds can be developed, utilizing background radiation baselines for a specific location. This technique, during the author's trials, was vastly superior to the time-based averaging methods discussed above. Net sensitivity is greatly increased, since alert thresholds can be set much lower without risking spurious false positives. False positive rates are decreased as well, as varying levels of background radiation from geological and architectural sources are adequately surveyed and built into the baseline.

ADVANCED DATA PLOTTING: Once a user has an adequate data set for use a baseline, it is important to consider what techniques may be useful for processing this data into a useful map. Simple plotting techniques, such as plotting collected count rates onto a map in a grid, are useful only at an elementary level. A much more useful approach is to use the baseline data to create a Voronoi diagram of the operating area. In effect, this technique builds a baseline map around the background radiation data, rather than forcing data into arbitrary squares on the map. Voronoi diagrams provide a much more useful basis for analyzing the data. (See Gold/Remmele/Roos.) Mathematical techniques such as Delaunay triangulation can be used to transform a set of data points into a highly accurate smooth contour map. These diagrams and techniques are routinely used in other disciplines, such as meteorology, to map data. Voronoi diagrams are often used to map rainfall data. Their utility has been studied for use in radiation measurement. (See Cortez et.al.)

Figure 3 is an example of advanced data plotting. It shows a basic background survey turned into a Voronoi diagram. The Voronoi diagram is transformed, through triangulation, into smooth contours, which are a better representation of background than a square grid. These techniques will provide several advantages. First, it is easy to combine multiple data collection sessions into one baseline dataset. Second, the background data more closely matches the actual phenomena being measured, rather than being forced into arbitrary grid squares. Third, there are simple mathematical techniques that can be applied to determine the state of completion ("done-ness") of the background collection effort.

CONCLUSION

Searching for hostile radiation sources in an urban area is a very complex operation, fraught potential for false positives and false negatives. Some existing techniques are clearly unsatisfactory for operational use. A clearer understanding of the urban radiation environment allows for proper use of detection hardware, improved operating procedures, higher probability of successful detection and identification, and lower rates of false positives.

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