Technology Independent Metrics that Bound the SNM Detection Problem

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Executive Summary

This analysis seeks to derive very simple boundary conditions to the problem of detecting special nuclear material (SNM) in a real world environment, with the expectation that such boundary conditions will serve as guides to investment. A basic investment guide chart is developed from this analysis. The approach is to baseline the current state-of-the-art via publicly available information, then use the technology independent disciplines of geometry and statistics to find the boundaries of the possible. Several issues are highlighted by this analysis, but detectability as a function stand-off distance between SNM and detector stands out as the key limiting factor. Qualitatively this message is technology independent, true for passive, background suppression and active interrogation systems. Stand-off distances on the order of a hundred meters will have useful but limited applications, while extreme distances hold no reasonable promise. The overriding message is clear: detection of SNM is a local problem. The radical breakthrough allowable within this analysis is the concept of massively distributed systems. The key to achieving such systems is a breakthrough in materials research that results in a material with which inexpensive detectors can be made that have both high sensitivity for detecting SNM and high selectivity for identifying SNM in the presence of background sources of radiation.

Basic Considerations

This white paper intends to lay out simple metrics as boundary conditions for the stand-off detection of special nuclear material (SNM). SNM is defined by Title I of the Atomic Energy Act[1] of 1954 as plutonium, uranium-233, or uranium enriched in the isotopes uranium-233 or uranium-235. The definition includes any other material that the Nuclear Regulatory Commission (NRC) determines to be special nuclear material, but does not include source material. The NRC has not declared any other material as SNM. Special nuclear material is only mildly radioactive, but it includes some fissile material─uranium-233, uranium-235, and plutonium-239─that, in concentrated form, can be the primary ingredients of nuclear explosives. Gamma-rays and neutrons are the only readily measurable radiations that travel any useful distance (defined as any distance beyond a meter) from SNM in a realistic field environment. Other radiations and measurement techniques are useful in specific situations, but are not readily adapted to stand-off detection and will not be specifically considered in this discussion; however, the basic arguments that will be made are universal and therefore applicable to such alternate approaches.

In order to bring forward the dramatic importance that standoff distance (distance from the SNM source to the radiation detector) plays in such measurements, this discussion will consider only the basic statistics and geometry of radiation measurements, and not the specifics of gamma and neutron transport and detection. This is not to discount the importance of such phenomena, but only to say that the basics of statistics and geometry apply universally and set certain basic boundary conditions. Using only these simple metrics also yields results that are independent of specific detection technologies. These results are only boundary conditions, but have the advantage that all possible technologies are contained within these limits.

When measuring any gamma or neutron radiation source in a field environment, the measurement will be made in the presence of an ambient background of those same radiations. Therefore, define the radiation measured during a given time interval as $\boldsymbol{T}$, consisting of a contribution $\boldsymbol{B}$ from the background and a contribution $\boldsymbol{S}$ from the source of interest.

$$(1) \quad \boxed{\boldsymbol{T} = \boldsymbol{S} + \boldsymbol{B}}$$

Note that this is true for both gamma and neutron measurements, and for both gross counting and spectral detection methods. The specifics of ***T***, ***S*** and ***B*** are very different depending on what is being measured and by what method the measurement is made.

As an example, some detectors measure gammas from any specific source considering only gross counts across a broad energy range, and have a corresponding ***S*** and ***B.*** More sophisticated spectral detectors are capable of measuring an energy spectrum from the same specific source. Given that nuclear isotopes have characteristic spectral signatures, such detectors allow the measurement to focus in on only those regions of the energy spectrum characteristic of the specific source being measured. ***S*** and ***B*** in that case will include only counts from this relevant subset of the energy spectrum, therefore signal to noise will be improved since the ratio ***S*/*B*** will be increased. Such spectral detectors have the ability to identify specific isotopes in the presence of competing sources of radiation. This ability to identify isotopes is referred to as selectivity. In general, the degree of selectivity of spectral detectors depends on the energy resolution of the particular detector; higher energy resolution detectors have higher selectivity. The other key measure of a detector is sensitivity, which is the efficiency with which a detector can transform radiation incident on the detector into measured counts. For example, if two different detectors have one-hundred identical gammas incident upon them, and one measures fifty counts while the other measures only ten, then the former is five times more sensitive than the latter. Together sensitivity and selectivity are key metrics for detectors measuring radiation from SNM.

Technology Independent Arguments

It is instructive for the purpose of bringing out general principals to ignore the sensitivity and selectivity of specific detection methods for the time being and consider only the source term ***S*** and background term ***B*** independent of what detection method was used to arrive at them, or even what specific radiation is being measured. Independent of any specific technology it is always possible to define the basics as laid out in equation (1).

Also, the assumption is made here that the actual measurements are such that simple Gaussian (ideally) or Poisson statistics apply. This simplification will suffice given that we are looking only for boundary conditions. A more accurate understanding[2] would be required to model the results for a specific radiation detection system.

In actual field detection it is not possible to measure ***S*** in isolation, but it is possible to measure ***T*** and ***B***. The source strength will actually be determined by measuring ***B*** while the source is not present and then subtracting this from the measurement of ***T*** (taking into account equal measurement times), so:

$$(2)\quad \boxed{\boldsymbol{S} = \boldsymbol{T} - \boldsymbol{B}}$$

The error on this measurement will be:

$$(3)\quad \boxed{\boldsymbol{\sigma_S} = \sqrt{\boldsymbol{\sigma_T^2} + \boldsymbol{\sigma_B^2}}}$$

where $\boldsymbol{\sigma_T} = \sqrt{\boldsymbol{T}}$ and $\boldsymbol{\sigma_B} = \sqrt{\boldsymbol{B}}$, so from equation (3) $\boldsymbol{\sigma_S} = \sqrt{\boldsymbol{T} + \boldsymbol{B}}$, therefore from equation (1):

$$(4)\quad \boxed{\boldsymbol{\sigma_S} = \sqrt{\boldsymbol{S} + 2\boldsymbol{B}}}$$

This error represents a lower bound, as any correlation will result in a larger error, which corresponds to a more difficult measurement. This is consistent with the intent to use this analysis to set boundary conditions on the possible.

The object of such a measurement is to measure a statistically significant value of ***S*** in the presence of a background. In cases where ***S*** gets small relative to ***B***, then $\boldsymbol{\sigma_S}$ gets large and it is impossible to assume a simple Gaussian distribution to which we can easily assign confidence intervals. Therefore confidence intervals will not be addressed and a statistically significant value of ***S*** will be simply defined as being non-zero at the 3-sigma level (i.e. $\boldsymbol{S} \pm 3\boldsymbol{\sigma_S}$). As a measure of statistical significance, a factor ***D*** is defined such that $\boldsymbol{D} \equiv \boldsymbol{S} / \boldsymbol{\sigma_S}$, therefore from equation (4):

$$(5) \quad \boxed{\boldsymbol{D} = \frac{\boldsymbol{S}}{\sqrt{\boldsymbol{S} + 2\boldsymbol{B}}}}$$

A statistical significance factor of $\boldsymbol{D} \geq 3$ will be used from here forward to represent a positive detection of the source of interest, while $\boldsymbol{D} < 3$ will be called a non-detection. Clearly the choice of a minimum value of $\boldsymbol{D}$ is subjective. A higher value would be equivalent to stating that a higher level of statistical certainty was required to declare a detection of SNM. This would also result in lower detectability for weak sources, where detectability refers to a systems ability to detect a source (in real systems, detectability is a function of the sensitivity and selectivity of the detection material being employed, as well as the total amount of useful detector material being employed by the system). For example, setting the minimum acceptable $\boldsymbol{D}$ at 3 for a specific system would result in a higher probability of detecting a weak source than if the minimum acceptable $\boldsymbol{D}$ were set at 5; however, setting the minimum acceptable $\boldsymbol{D}$ to 3 would result in more false alarms than setting it to 5. So in the end the choice of a minimum acceptable $\boldsymbol{D}$ is a political one. As will be seen, this analysis will focus on the qualitative behavior of detection systems so that small variations in the choice of a minimum acceptable $\boldsymbol{D}$ will not impact conclusions.

The discussion so far has considered only statistics and not geometry. The simplifying geometric assumptions will be made that the radiation background is uniform throughout the measurement area and that the SNM source of interest is a point source. This also fits in with the idea of setting boundary conditions, as real-world divergence from these simplifications will make detection more difficult, and therefore within the boundary conditions of these simplifying assumptions.

Therefore there will be no geometric considerations for $\boldsymbol{B}$, while the radiation from a point source will disperse with distance across the surface of an expanding sphere centered on that source. Thus, if $\boldsymbol{r}$ is the radius of the sphere, then the surface of the sphere is $\boldsymbol{4\pi r^2}$, so if $\boldsymbol{S}_0$ is defined as the intrinsic strength of the radiation source, then:

$$(6)\quad \boxed{\boldsymbol{S} = \frac{\boldsymbol{S}_0}{4\pi \boldsymbol{r}^2}}$$

So from equation (5):

$$(7)\quad \boxed{\boldsymbol{D} = \frac{\boldsymbol{S}_0}{4\pi \boldsymbol{r}^2 \sqrt{\frac{\boldsymbol{S}_0}{4\pi \boldsymbol{r}^2} + 2\boldsymbol{B}}}}$$

At this point it will be instructive to use information about real world radiation detection systems to evaluate the ramifications of equation (7) for the detection of SNM. Instead of considering the particulars of any one specific system, consider what DNDO Director Vayl Oxford had to say in recent congressional testimony[3] about DNDO's research efforts into standoff detection. "Proof-of-concept efforts on several standoff technologies have demonstrated that very small amounts of material can be detected at 20 miles per hour from a distance of over 65 meters ─ again, a tremendous improvement over previous and current capabilities." It will be useful for the purposes of this discussion to frame this capability as a generic system. In the interest of round numbers set the maximum distance at 100 meters, then make the simplifying assumption that this is the maximum standoff distance currently achievable with any realistic CONOPS (concept of operations), and finally name this capability the "MAX System" (current state-of-the-art maximum standoff detection system). Within the parameters of this discussion, this is equivalent to setting $\boldsymbol{D} = 3$ at 100 meters for the MAX System.

The other piece of data necessary to exercise equation (7) is a value for the background $\boldsymbol{B}$. Ambient gamma and neutron backgrounds can vary widely due to natural and anthropogenic sources, and the ability to detect these radiations is highly dependent on the size and type of detection system employed. These discussions will choose to consider a natural background source[4] and will assume a detection system that results in a detection rate of 10 background events per second. While these rates are reasonable for this discussion, many other detection situations could have been chosen. Different choices will change the quantitative results, but will not qualitatively change the conclusions that will be drawn by this discussion.

While such choices are equivalent to baselining the discussion to the specifics of an unknown real world system, it will not qualitatively affect the comparisons that will be made. Also, having such a real world baseline will ensure that the conclusions drawn at the end of the analysis will be applicable to real technologies. Finally, since this baseline is based on a statement assumed to define the current limits of the state-of-the-art, all other technologies will presumably have lesser capabilities. Therefore, the concept of a technology independent boundary condition is preserved.

It is important to note at this point that ***S*** and ***B*** will represent counts in the detector attributable to source and background independent of how the were collected. In other words, it is assumed that the unknown system used to define the MAX System optimized collection time, relative speed of encounter between source and detector, and all other variables of the real world operational environment (in other words the CONOPS). So any other CONOPS would presumably be less effective, and therefore within the boundaries defined by this baseline. Therefore specific CONOPS need be discussed no further, and only the behaviors derived from this baseline ***S*** and ***B*** need be considered to define boundary condition behaviors.

The detectability of a MAX System defined in such a manner is displayed graphically as a function of distance to the source of SNM in Figure 1.

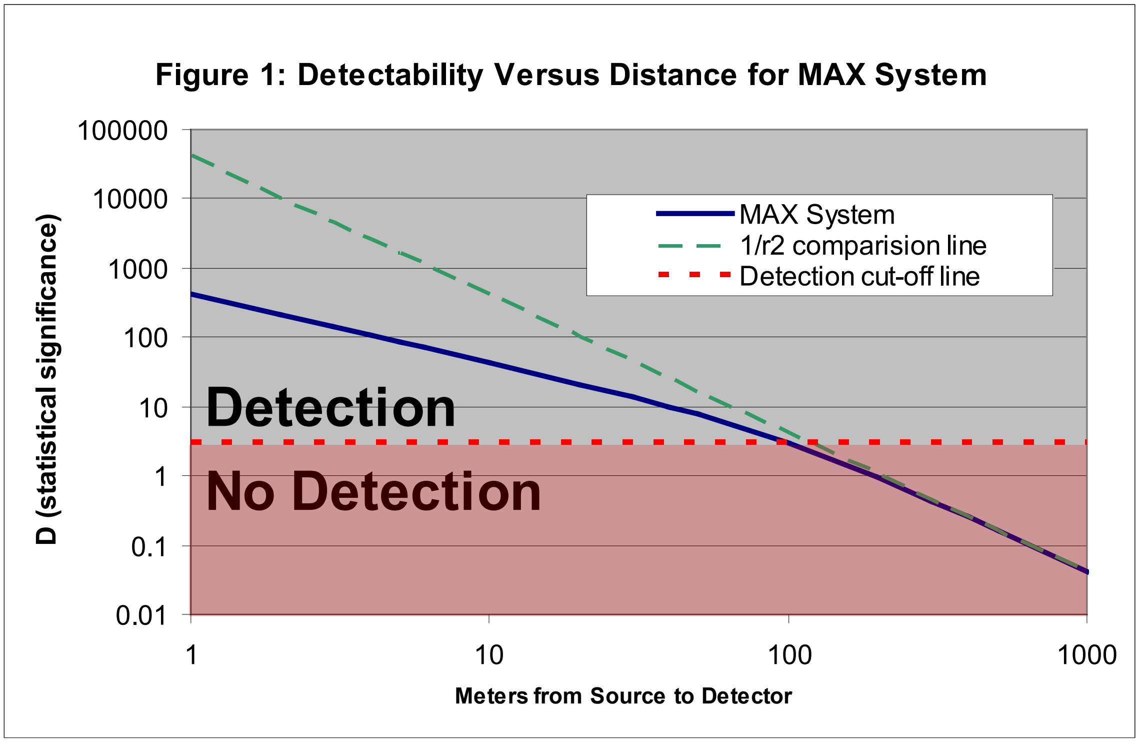
This figure shows a comparison line to simple inverse square behavior that matches up well with the MAX System line beyond 100 meters. This can be seen by inspection of equation (7). As ***r*** gets large, equation (7) reduces to:

$$(8)\quad \boxed{\boldsymbol{D} = \frac{\boldsymbol{S}_0}{4\pi \boldsymbol{r}^2\sqrt{2\boldsymbol{B}}}}$$

Conversely, when r gets small, equation (7) reduces to:

$$(9)\quad \boxed{\boldsymbol{D} = \frac{\boldsymbol{S}_0}{\boldsymbol{r}\sqrt{4\pi \boldsymbol{S}_0}}}$$

This results in simple inverse linear behavior as seen for small distances in Figure 1.

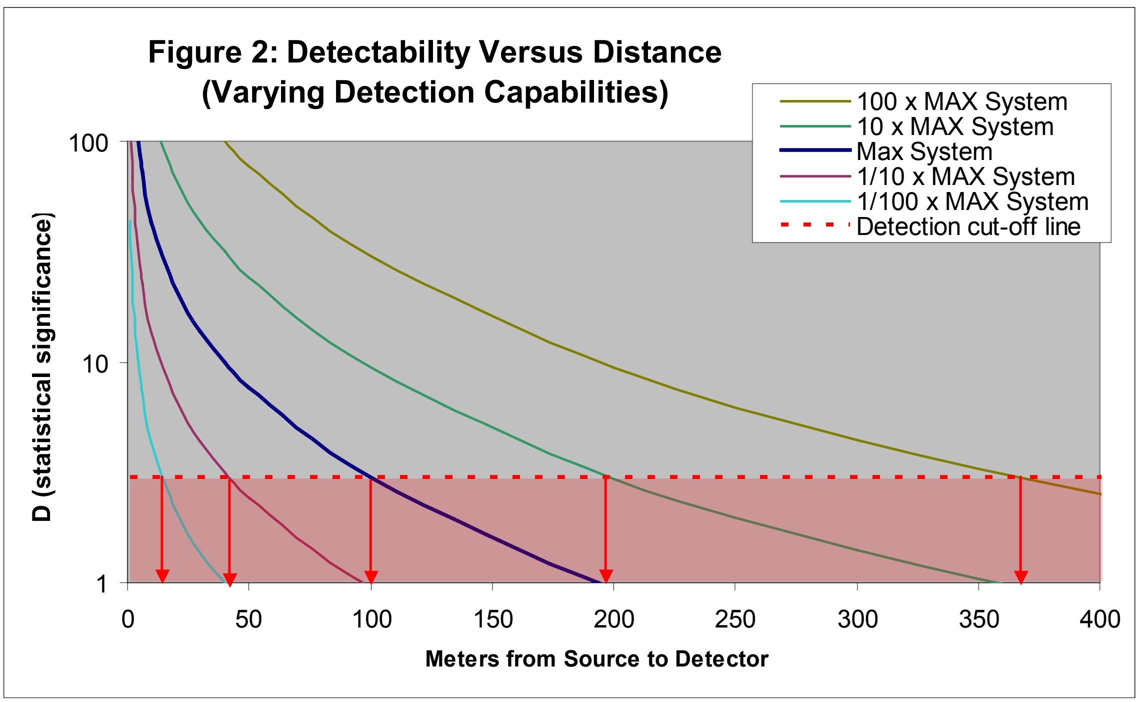


The question now becomes one of how will the performance of this passive detection system vary if the detection capability is increased or decreased (detection capability refers to the overall amount of useful detector material in a system—usually means more or larger detectors). It is important not to confuse detectability with detection capability. Detectability was defined earlier as a system's ability to detect a source, and it is a function of the systems overall detection capability, the sensitivity and selectivity of the detection material being used, and the choice made for the minimum acceptable statistical significance factor ***D***.

Figure 2 shows the results for varying the detection capability in two separate order-of-magnitude increases and two separate decreases. The figure (which has shifted to linear scales to highlight differences) shows some surprisingly dramatic limits to the gains that can be made by increasing the detection capability. A system with ten times the detection capability as the MAX System gains less than a factor of two in usable range, while a system with 100 times the detection capability has less than 4 times the range. The underlying reason is that while additional detection capability means an increase in source radiation detected, it also results in a corresponding increase in background radiation detected. Inspection of equation (7) will reveal that the statistical significance factor $\boldsymbol{D}$ increases only as the square root of the factor by which the detection capability is increased. This can be seen by defining a factor $\boldsymbol{Z}$ to represent the multiple by which detection capability is varied. Insert this in equation (7) where appropriate for both the source and background terms, and call the new statistical significance factor $\boldsymbol{D'}$.

$$\boldsymbol{D'} = \frac{\boldsymbol{Z S_0}}{4\pi r^2 \sqrt{\frac{\boldsymbol{Z S_0}}{4\pi r^2} + 2\boldsymbol{Z B}}}, \text{ therefore:}$$

$$(10) \quad \boxed{\boldsymbol{D'} = \frac{\boldsymbol{S_0}\sqrt{\boldsymbol{Z}}}{4\pi r^2 \sqrt{\frac{\boldsymbol{S_0}}{4\pi r^2} + 2\boldsymbol{B}}}}$$



By comparison with equation (7) it can be shown that $\boldsymbol{D'} = \boldsymbol{D}\sqrt{\boldsymbol{Z}}$. So increasing the detection capability 100 fold only increases $\boldsymbol{D}$ by 10; this increase is quickly lost with increasing distance from the source as the performance is dropping off by nearly the square of the distance at that point. Given that real world detection has more limiting factors that this simplified case, these ranges can truly be considered boundary conditions to what is possible.

A similar logic holds true in cases where the detection capability is decreasing. Dramatic decreases in detection capability are not nearly as penalizing as might be expected, for the same reasons just laid out for the increasing capability case. On the other hand, as the inverse linear behavior of equation (9) begins to dominate at smaller distances, the variations due to standoff distance are not as rapid as at greater standoff distances where the inverse square behavior of equation (8) is dominating. However, there are also many real world considerations that come into play to limit the performance as the detection capability is decreased. The most significant limitations have to do with certain minimum detector sizes needed to detect gamma and neutron radiations efficiently. Though a discussion of such factors is beyond the scope of this analysis, they essentially make the 1/100 line in Figure 2 unrealistic for most applications, and it is only included to show the full range of effects.

The two figures can also be viewed in terms of system costs. Costs for radiation detection systems of a given type scale roughly in direct proportion to the detection capability (i.e. ten detectors cost ten times more than one detector of the same type). As a baseline, a cost figure needs to be established for the MAX System in order to use it for comparisons. The DNDO ASP (Advanced Spectroscopic Portal) systems cost estimates range[5] from about \$300k to over \$500k depending on the gamma-ray detectors being employed. Since the MAX System being theorized here would be large enough to get to the limit of current state-of-the-art detectability as previously stated, it is reasonable to assume it would cost more. A round figure of \$1M will be assumed. This assumption isn't based on any reality, and is used only for the purpose of a rough comparison.

Applying these assumptions to the data from Figure 2, we have the \$1M MAX System able to detect SNM at a range of 100 meters, a \$10M system not quite able to reach 200 meters, and a \$100M system falling well short of 400 meters. On the other hand, we have a \$100k system that works out to a range of about 40 meters. The diminishing return on investing in larger passive detection systems is fairly obvious.

A more obvious way to get a metric on system size and cost as a function of capability is to plot system size as a function of the maximum distance at which SNM can be detected. System size is essentially the factor $\boldsymbol{Z}$ that was defined when deriving equation (10). So the desired plot is $\boldsymbol{Z}$ as a function of $\boldsymbol{r}$ after setting $\boldsymbol{D}' = 3$ (the minimum detection criterion set earlier) in equation (10). By so doing, $\boldsymbol{r}$ becomes the maximum range at which SNM can be detected by a system that has $\boldsymbol{Z}$ times the detection capability of the MAX System. So solving equation (10) for Z with $\boldsymbol{D}' = 3$ yields:

$$(11) \quad \boxed{\boldsymbol{Z} = \frac{144\pi^2}{\boldsymbol{S}_0^2}\left(\frac{\boldsymbol{S}_0}{4\pi}\boldsymbol{r}^2 + 2\boldsymbol{B}\boldsymbol{r}^4\right)}$$

Figure 3 plots this function with dotted lines showing the MAX System that can detect to 100 meters, and the size system it would take to detect the same SNM source at a kilometer.

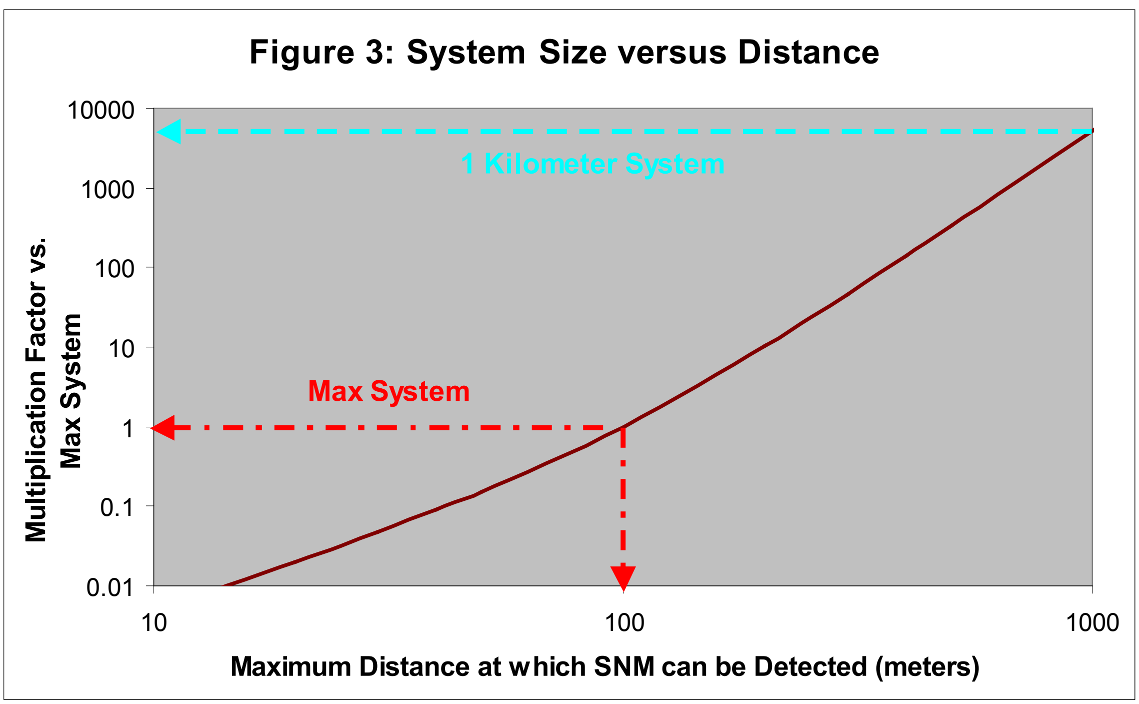


Figure 3 demonstrates the dramatic increase in system size that would be required to scale the MAX System capabilities up to the point where an SNM detection would be possible at a kilometer. If this is scaled by the previous assumption that a MAX System would cost $1M, then the price tag for a kilometer system turns out to be > $5B. An increase in cost from a million dollars to over 5 billion dollars for a factor of ten increase in effective range is a return on investment that would be hard to justify. And this is only a discussion of boundary conditions. When real world considerations such as air attenuation and the engineering and operational difficulties of such a large system are brought into account the situation will be even worse. These graphs argue strongly that attempting to extend the range of passive detection systems much beyond 100 meters is an unrealistic proposition.

This leads to the idea of using multiple smaller systems to survey an area, rather than a single large system. It won't be possible in most situations to blanket an area with a large number of sensors, but it will be instructive for this discussion to consider what the advantages of such a strategy would be where possible.

Figure 4 shows a square red-shaded area to be surveyed. A single system surveying this square area for SNM would have to be positioned at the center of the square and have an effective range as shown by the circle. The diameter of the circle is equal to the diagonal of the square. A system at the center would then have to have an effective range equal to the radius of the circle, which means the effective range of the system would have to be equal to half the diagonal of the square area to be surveyed.

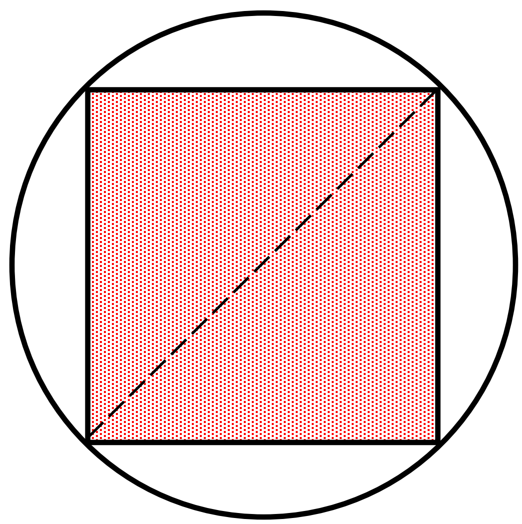


Figure 4: diameter = diagonal

Figure 5 shows a situation where the area to be surveyed is the same red-shaded square, but now it is being surveyed by a radiation detection system consisting of four detection sub-systems─a "system of systems" approach. Each of the four sub-systems would sit at the center of its own circle with an effective range outlined by its circle. In this case the effective range of each of the four sub-systems would be equal to the radii of each of the four circles. Each circle has a diameter equal to half the diagonal of the square

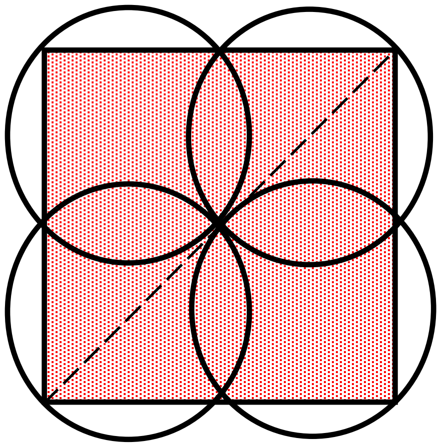


Figure 5:
2 x diameter = diagonal

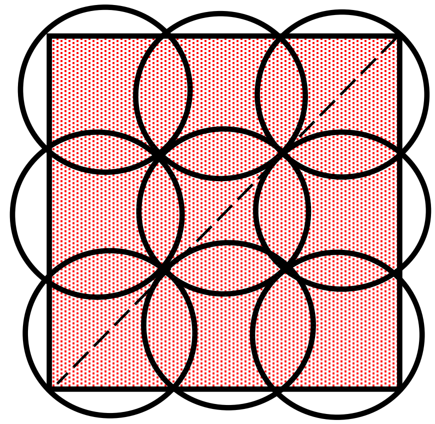


Figure 6:
3 x diameter = diagonal

being surveyed, so the effective range of each sub-system is equal to one quarter of the diagonal of the square area to be surveyed. Figure 6 extends this paradigm to nine sub-systems. Following the same logic, the effective range of each of the nine sub-systems equals one sixth of the diagonal of the square area to be surveyed.

This can extrapolated to a general rule. Define a square area to be surveyed with a diagonal ***d***, a total number of radiation survey sub-systems ***N***, and call the necessary effective range of each of the ***N*** sub-systems ***r***. Then ***r*** will be determined by:

$$\boxed{\boldsymbol{r} = \frac{\boldsymbol{d}}{2\sqrt{\boldsymbol{N}}}} \tag{12}$$

Figure 7 shows cost comparisons for this system of systems approach to surveying an area with differing numbers of sub-systems. The same cost baseline assumptions were made here as for the single system approach. Only detection equipment costs are considered, not the costs of integrating and operating multiple systems.

The graph shows how dramatically less expensive it is to use many smaller sub-systems rather than fewer large sub-systems. This comparison doesn’t take into account technical or operational complexities associated with a system of systems, but the associated costs would have to be unrealistically substantial to overcome such dramatic differences in equipment costs. Consider the case of the two square-kilometer survey area from Figure 7. This can be evaluated by first referring to Figure 4, a square with this area would require a circle with a one kilometer radius to survey it. This corresponds to the system discussed before that would cost > $5B to achieve an effective detection range of one kilometer. Table 1 evaluates this 2 square-kilometer survey area by pulling the necessary data out of Figure 7.

Figure 7: Total Cost to Survey a Large Area
[Fixed System Detection Probability]

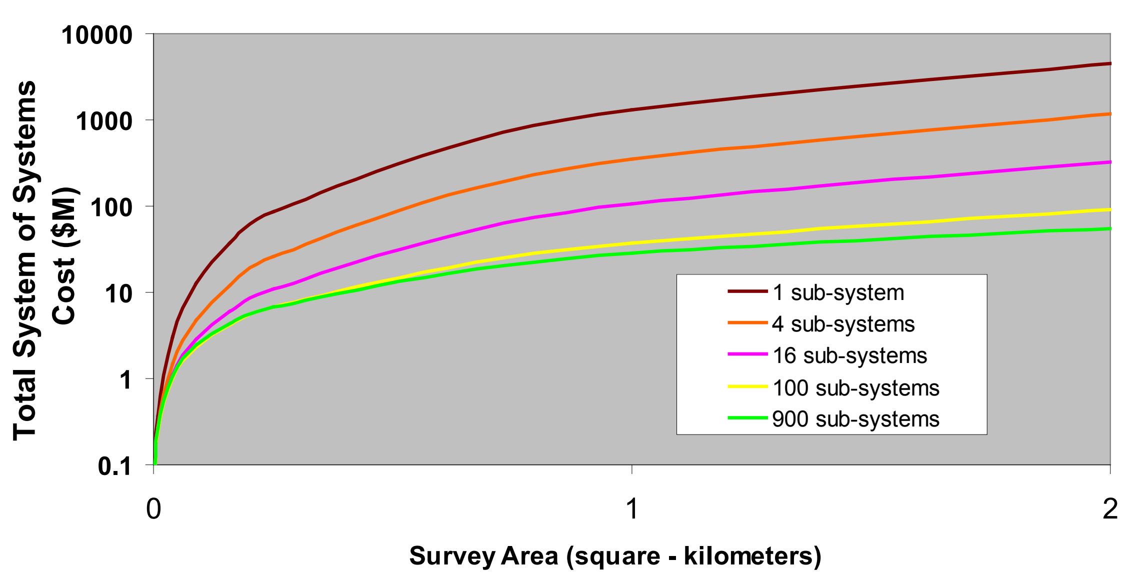


Table 1: Cost Breackout from Fig. 7 for 2 square-kilometer Survey Area			
Total System of Systems Cost	**Number of sub-systems**	**Maximum sub-system detection range**	**Cost of each sub-system**
$5.2B	**1**	**1 kilometer**	**$5.2B**
$1.3B	**4**	**500 meters**	**$325M**
$372M	**16**	**250 meters**	**$23M**
$100M	**100**	**100 meters**	**$1M**
$60M	**900**	**33 meters**	**$67k**

The numbers are telling. It would cost nearly one-hundred times more to survey this area with one detection system than to do so with a system consisting of nine-hundred smaller sub-systems. Since this simple analysis is only meant to establish boundary conditions, we expect that reality would be even more severe in both the upper and lower bounds. The system of many sub-systems would certainly cost more when the many physical, technical and operational realities of real world deployment are considered. The same is true for the single system solution; it would certainly cost more to achieve such functionality if it were actually developed.

As mentioned, it isn't practical to blanket every area that requires monitoring with an extensive system of detectors. However, this analysis makes it clear that solutions requiring passive detection must be designed to encounter targets at as close a range as possible. This could take many forms: inspection portals, natural or economic choke-point monitoring, deployment with all forms of law enforcement and intelligence or special forces assets, unattended covert sensors, special search teams, networks of moving sensors, and even placement in business and personal spaces when it makes sense and is socially and politically acceptable. Targeting sensor deployment with information leveraged from non-detectors sources should be standard practice.

This analysis demonstrates some general boundary conditions from simple mathematical constraints. Regardless of the technical details, geometry and statistics apply universally. The take-away message is clear: passive detection of SNM is a local problem.

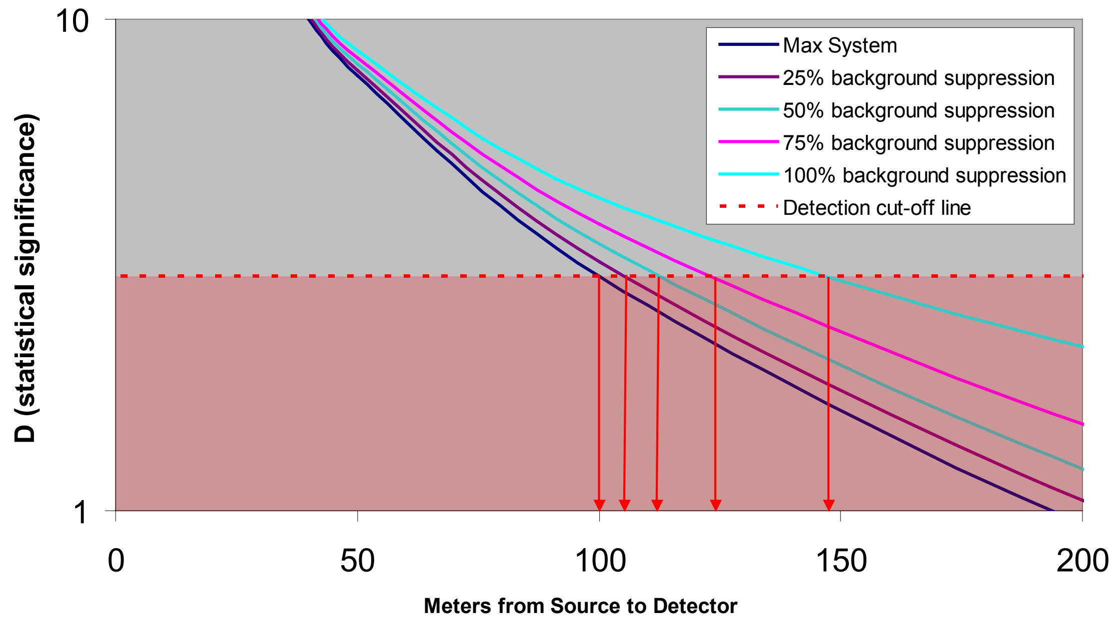
Background Suppression

So far this discussion has considered only passive detection systems. Sensitivity and selectivity were defined upfront as key detector performance metrics for the detection of SNM in an environment of competing sources of radiation. The analysis then showed that SNM source detectability versus distance is a metric that sets boundary conditions on the possible. However, beyond just standoff distance, the statistical significance factor $\boldsymbol{D}$ defined by equation (7) has a background term $\boldsymbol{B}$ and a source term $\boldsymbol{S}_0$ whose variability need to be considered.

The most straight-forward of these is the background term. Passive background suppression systems, like lead collimators for gamma detectors, can reduce background inexpensively without losing significant flux from the SNM source. More exotic methods, like Compton imaging,[6] can provide dramatic background reductions by essentially only looking at events that were generated in the immediate area of the source.

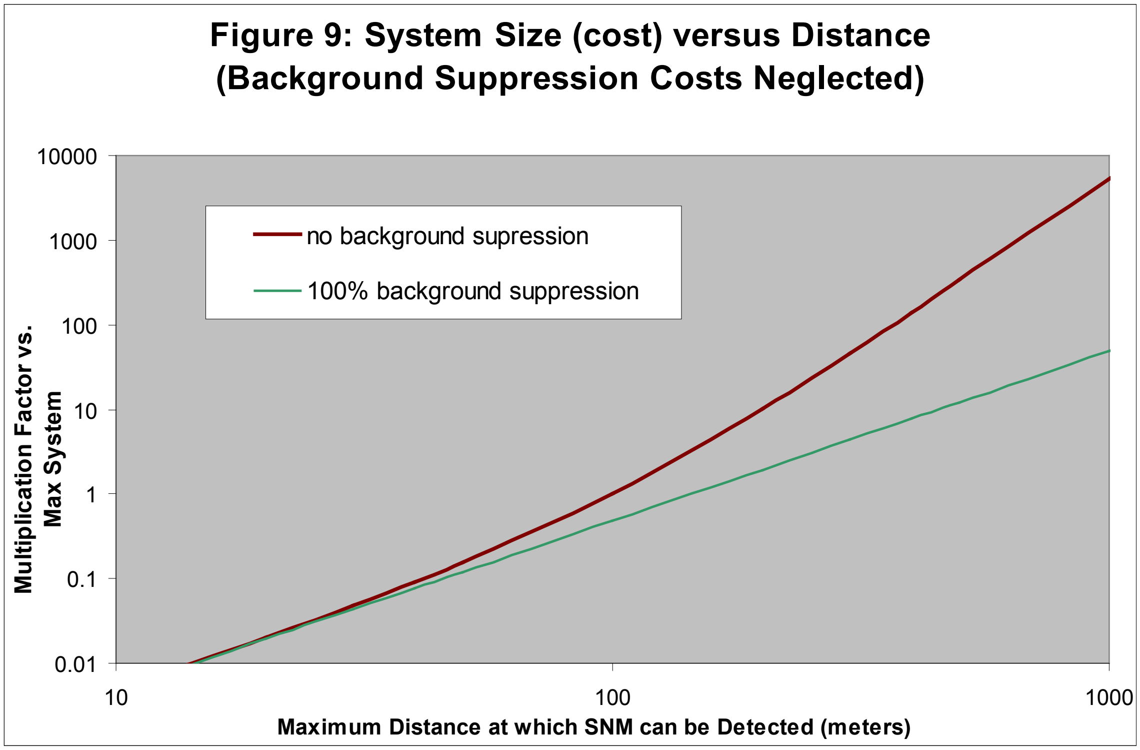
Figure 8 shows the MAX System with varying levels of background suppression considered. The figure shows only modest gains over the MAX System. Gains from passive collimation are likely worthwhile even if they are only modest, since it is a cheap and simple strategy. The gains from background suppression alone would not justify a costly and complex system like a Compton imager, however such systems have other advantages (like spatial location of SNM in a complex environment) which could well make them worthwhile.

Figure 8: Detectability Versus Distance (MAX System with background suppression)



An appreciation of what the effects of background suppression would be in conjunction with increasing overall detection capability to reach greater effective system ranges can be gained by going back to equation (11). This was used to measure necessary system capability increases as a function of system effective range as shown in Figure 3. Setting $\boldsymbol{B} = 0$ in equation (11) demonstrates the same metric in the case of 100% background suppression. This, along with the original case with no background suppression, is shown in Figure 9. While this graph shows the same modest gains as Figure 8 for ranges on the order of 100 meters, the gains at longer ranges are substantial.

Without background suppression, a detection capability increase of over five-thousand is required to be effective out to a kilometer. With complete background suppression, an increase in detection capability of about fifty achieves the same kilometer effective range.



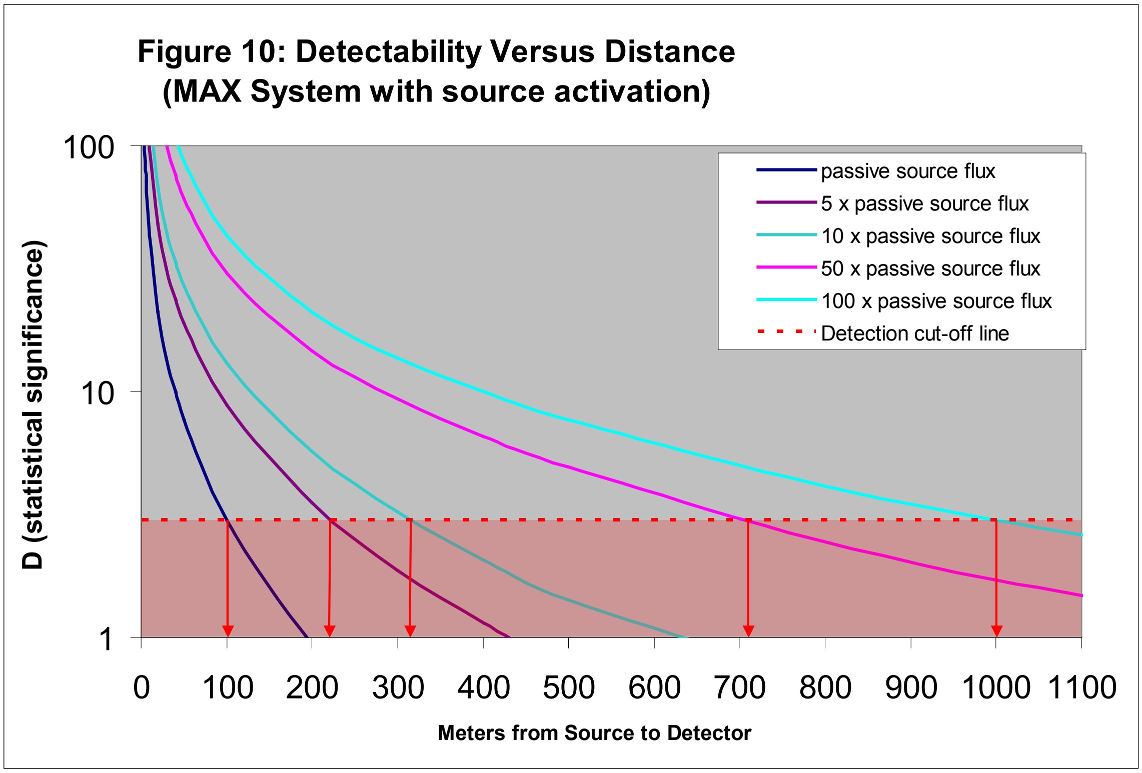
Complete background suppression saves a factor of one-hundred in system detection capability increases. Systems with less than complete background suppression would fall between the two extremes as seen in Figure 9. This factor of one-hundred for the complete suppression system would also correspond to an equal factor in cost savings, but considers only the cost of increased detection capability and not the cost of whatever system might be used to suppress the background. The costs for background suppression depend on the system used, but are certainly high for any system capable of suppressing a high percentage of the background. Combining such costs with the costs of increased detection capability to develop a system capable of detection at ranges approaching a kilometer is likely to be exceedingly high. Whether they are as high as the > $5B cost of an entirely passive system is beyond the scope of this analysis.

Active Systems

As mentioned earlier, the source term $\boldsymbol{S}_0$ is the other variable to be considered when analyzing the statistical significance factor $\boldsymbol{D}$ (defined by equation (7)). We have no control over this directly, as this is the radiation generated by the SNM being sought. However, it is possible to stimulate the SNM, usually by bombardment with externally generated gamma-rays or neutrons, to radiate at a higher flux. This process can take many different forms and is generally referred to as active interrogation.[7,8,9,10,11] The stimulated radiation of concern is usually gamma or neutron radiation (though others are possible), and so for this analysis the previously defined MAX System will continue as the baseline detection system for discussion. The spectral details of the radiation being detected differ from the passive detection case, but for the purposes of this discussion all that matters are that there is a source $\boldsymbol{S}_0$ in the presence of a background $\boldsymbol{B}$. The differences in radiation transport are also not being considered here, beyond the fact that the radiation from the stimulated SNM is considered to remain isotropic as in the passive case. Systems that exploit non-isotropic radiation distributions are beyond the scope of this analysis. Real world considerations will limit the performance of actual deployed systems, but as before this analysis is merely looking for boundary conditions.

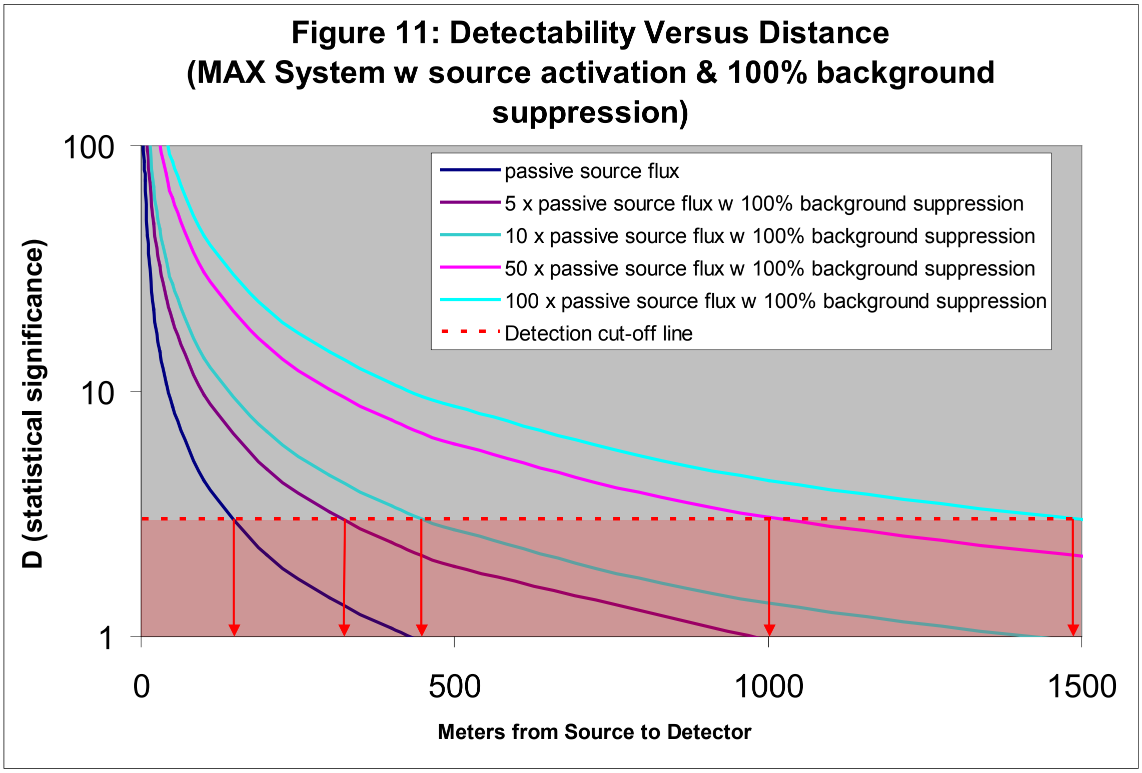
It is beyond the limits of this discussion to the consider the means by which the activating radiation will reach the SNM, though it is clear that if the detection is being made at a specific standoff distance that the flux generated needs to be delivered from the same distance to maintain the concept of standoff. This analysis will be limited to the degree to which the activation process increases the term $\boldsymbol{S}_0$ versus the passive case.

Active interrogation systems also offer hope of penetrating shielding to detect an SNM source hidden behind shielding. While the specifics are not within the scope of this analysis, the overall net effect is intrinsically included. This analysis does not distinguish between increases in the term $\boldsymbol{S}_0$ that occur from activation of a bare source, and those that are the net result after the shielding has been penetrated by first the activating radiation and then the returning radiation from the activated source. Obviously, the activation radiation would have to have a higher flux in the shielded case, but such specifics are not part of this analysis. Figure 10 shows such cases.



Since only the source term $\boldsymbol{S}_0$ is increasing, and not the background term $\boldsymbol{B}$, the effective range is increasing in proportion to the square root of the source term; this can be seen by inspection of equation (8), which was shown earlier to be relevant for longer ranges. So a factor of one-hundred increase in source intensity yields a factor of ten in effective range.

Active systems that return higher energy neutrons or gammas than passive systems will automatically have lower ambient backgrounds, because natural backgrounds are lower at higher energies. Also, if the system that delivers the activating radiation is pulsed in time, the background can be further lowered because time-of-flight techniques[12] can be used to only make measurements during those times when radiations from the inspected object are impinging on the detection system. Therefore, it is natural to consider background suppression as an intrinsic part of active detection systems. Figure 11 demonstrates how complete background suppression would improve the performance of an active system.



This system can reach a kilometer in effective range with an increase in source flux of fifty over the passive case, a factor of two improvement over the active case with no background suppression.

These active scenarios show that it may be possible to detect SNM without increasing the detection system size beyond what has been defined as the MAX System for this analysis. However, all these active cases have neglected the cost and technical challenges of getting the appropriate activating flux of neutrons, gammas or other radiations onto the SNM in order to activate it by the necessary factor of fifty or one-hundred to be detected by the MAX System at one kilometer (a kilometer over which the activating flux must travel and over which the activation radiation must return). The challenges include beam attenuation through air and any other intervening materials, focusing such a flux so that it activates the desired (possibly moving) target and not just a broad area, safety and political issues concerned with any living organisms that may come in contact with this flux of neutrons or gammas, the technical challenges of deploying a device to deliver this flux (likely an accelerator), and the challenges associated with coordinating the detection system with the activation system.

Some of the challenges, like beam focusing of the delivered flux over large distances, have outcomes predictable from this type of analysis. Even the most tightly focused beam will be diverging, and so will be subjected to the same geometric considerations raised throughout this analysis. Others, like attenuation of the delivered flux through air, are well understood and easily calculated.[13,14] In even the most optimistic scenarios these two considerations will attenuate a flux being delivered to a target at a kilometer standoff by many orders of magnitude. Even if these challenges can be overcome, the cost is likely to be substantial. An estimation of those costs is beyond the scope of this analysis. However, considering all of these complicating factors in even the most basic sense make kilometer standoff active systems so unlikely that even in the long term there is no reasonable expectation that they are possible.

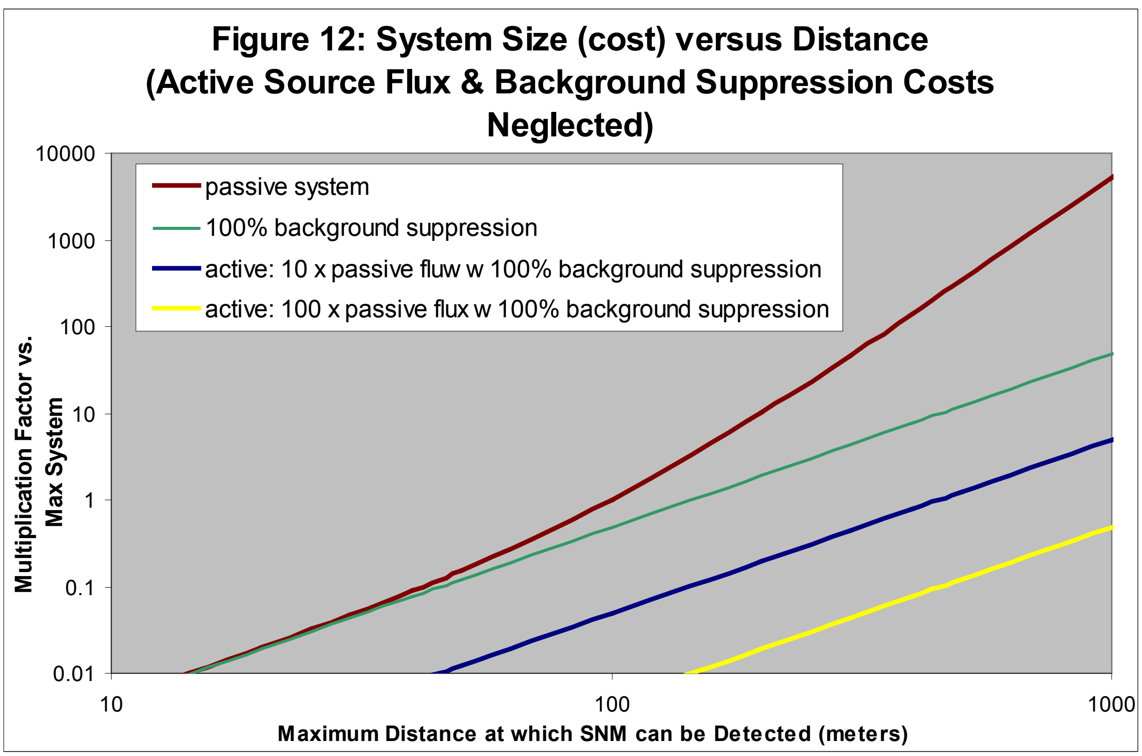


Figure 12 plots the active scenarios against the passive and passive plus background suppression scenarios. This figure considers only the detection system capability costs, and not those associated with background suppression or active flux delivery systems. When looked at from this detector only point of view, the advantages of active interrogation to reach a kilometer standoff distance seem obvious. However, as mentioned above, even simple geometry and air attenuation considerations will complicate the situation by orders of magnitude. If such considerations were added to the simple calculations that generated figure 12, then the active interrogation lines would certainly lose their advantage.

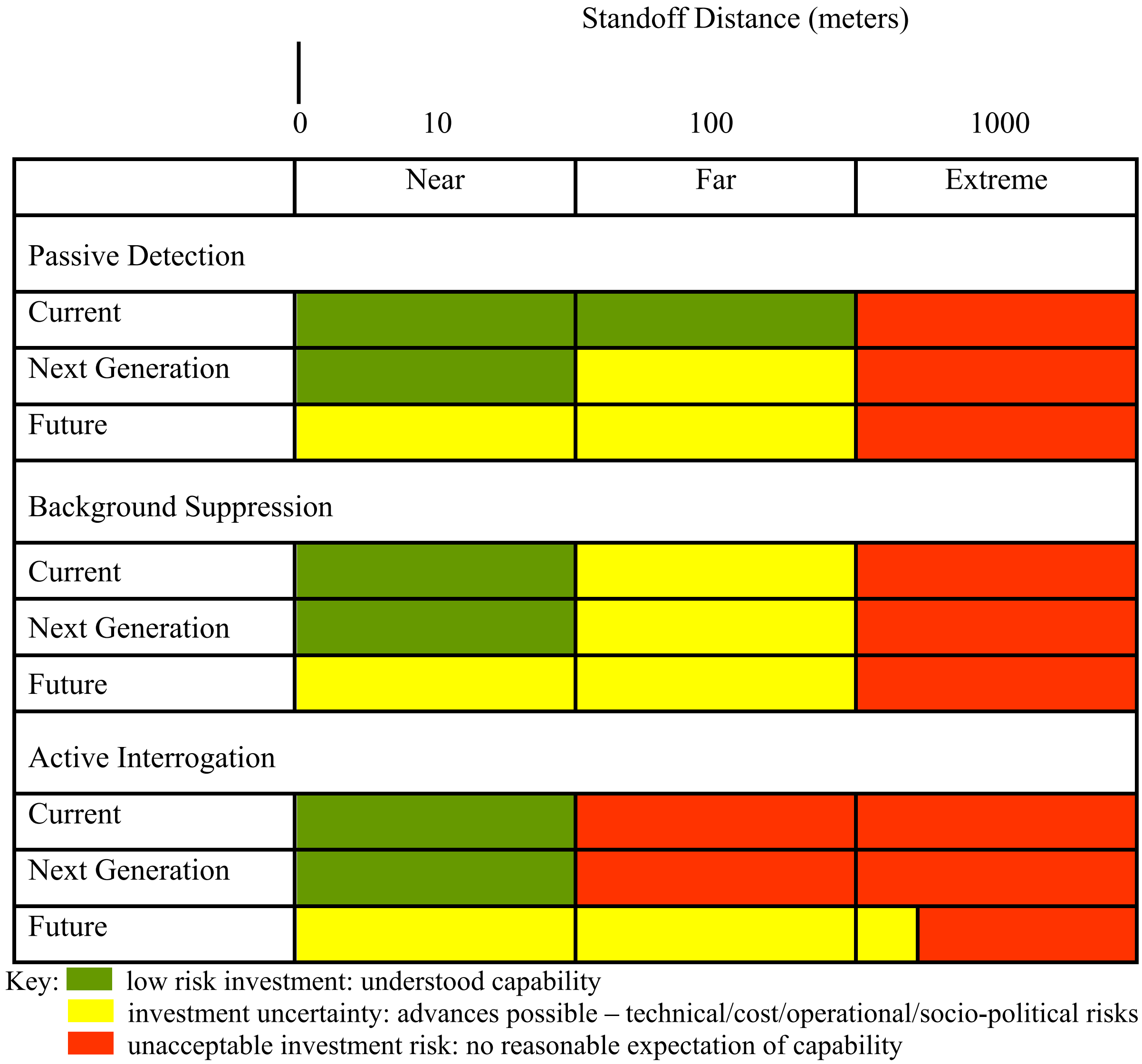
Overall Evaluation

Pulling all of this analysis together in a simple fashion will help illuminate overall trends that bound the issue of standoff detection of SNM. Table 2 is expressed as an investment guide that shows the categories of passive detection, background suppression and active interrogation that have been considered in this analysis. It subdivides each into currently understood capabilities, those capabilities foreseeable as the next generation (< 5 years), and those capabilities that are only notional and will require significant research to determine if they are viable.

These categories are then cross-referenced with three broad categories of standoff distance between SNM target and detection system. The "near" category represents distances from the source of SNM out to a few tens of meters. The far category is focused at around one-hundred meters or so. The extreme category represents distances from just short of a kilometer on out to infinity. There is obvious room for discussion about where one category ends and another begins, but such distinctions aren't necessary in this discussion. The three categories are meant to convey only a broad-stroke understanding of possibilities.

The key to Table 2 shows a simple stoplight chart system to indicate the outlook for investing in systems in those categories. Green represents capabilities that are already sufficiently understood to understand what can be gained by deployment, and are therefore a safe investment. A capability does not have to be currently deployed or even understood in great detail to get a green rating. A green rating means only that deployment of such a system has a low risk of technological surprise. Since this analysis has focused only on boundary conditions, more detailed analysis would be required to determine if investment in a specific system is really low risk. Yellow means that there is reason to believe a capability may be possible, or at least that there is no currently know

Table 2: Investment guide to SNM Detection Solutions vs Standoff Distance



reason to rule it out. Possibilities with this rating have significant uncertainties from a technical, cost, operational or socio-political point of view. Even if a technology with this rating turns out to be technically feasible, it may unacceptable for any number of other reasons. A red rating means that there is no reasonable expectation that a capability is viable in this category. It doesn't mean that all possibilities in this category have been proven impossible, only that the possibilities as they are currently understood are so remote that significant investment is unwise. Given that this rating has been derived from this boundary condition analysis, any further analysis would be expected to show even further reasons why investment would be unwise.

It is worthwhile to break Table 2 down category by category before considering the overall message.

<u>Passive Detection / Current Technology / Near Distance</u>

Passive detection has a wide variety of applications at near distances. The key is choosing a detector with both the appropriate detection efficiency (sensitivity) to detect SNM, and in most applications this also means a detector capable of spectrally identifying SNM, which will require spectral energy resolution (selectivity) appropriate to the specific detection scenario. Detectors with appropriate sensitivity and selectivity can be costly, and such costs can prohibit distributed detector system deployments. It will always be possible to shield SNM against passive detection.

<u>Passive Detection / Current Technology / Far Distance</u>

Such a system was assumed as the current technology limit as the basis for this argument. The issues are the same as for the near distance with cost being a key issue, as these will have to have high sensitivity and selectivity to be effective at these distances. Operational considerations will be key to choosing scenarios where such detection systems might be effective. These scenarios will also require advances in associated technologies like ranging systems. A system like this can only be effective if it is able to continuously monitor the range and offset between the detection system and the target. Software issues will also be a key to success, as these systems must have advanced data reduction and decision making capabilities to be most effective in field operations.

<u>Passive Detection / Current Technology / Extreme Distance</u>

As demonstrated in Figures 2 and 3, this is only technically feasible if unreasonable system sizes and costs are assumed. This will never be a reasonable scenario.

<u>Passive Detection / Next Generation Technology / Near Distance</u>

Many foreseeable advances can affect detector sensitivity and selectivity, system costs, effectiveness, ruggedness, software capabilities and operational uses. It is very probable advances will occur in these areas. None of this will alter the fact that it will always be possible to shield SNM against passive detection. Carefully matching the technology to the operational environment and employing well designed CONOPS and associated non-detector technologies can reduce false alarms and increase overall detection probability.

Passive Detection / Next Generation Technology / Far Distance

Beyond the advances foreseeable in the near distance category outlined above, the primary need is for dramatic cost reductions in high selectivity (energy resolution) systems to allow widespread use. This requires major advances in detector materials and robust software identification and decision making capabilities. Such advances are not unreasonable, but cannot be guaranteed possible.

Passive Detection / Next Generation Technology / Extreme Distance

There are no foreseeable near term advances that would be dramatic enough to make such systems reasonable even at the nearer end of this distance category. In light of Figure 7, finding clever ways to exploit distributed systems to fill this gap will always be the preferred solution.

Passive Detection / Future Technology / Near Distance

The key advance here would be very inexpensive detectors with high enough sensitivity and selectivity to form the basis of a massively distributed system. A revolutionary capability would be worldwide systems of systems with millions of autonomous nodes capable of detecting SNM and self-reporting to a network(s) capable of handling such massive data flows. The sub-systems would have to be intelligently deployed in a large variety of different scenarios with such wide distribution that it would become probable that an encounter of the SNM would occur somewhere between the time that the material is initially acquired and the time it is delivered as a weapon to a target. The software, communications and systems coordination advances are foreseeable from current technologies, but the detector material would require a revolutionary advance. Such an advance is not unreasonable, but cannot be guaranteed possible. It will still be possible to shield SNM against even the most advanced passive detection.

Passive Detection / Future Technology / Far Distance

The advances required for the future technology in the near distance category would automatically yield benefits in this category.

Passive Detection / Future Technology / Extreme Distance

Even the most radical advances are unlikely to be dramatic enough to make such systems reasonable. Finding clever ways to exploit distributed systems to fill this gap will remain the preferred solution.

Background Suppression / Current Technology / Near Distance

Simple suppression technologies have long been in use at near distances, and so investing here has understood benefits. More complex techniques have been developed for a variety of applications; adapting these techniques for SNM detection has many possibilities, but will require advances that will need to wait for the next generation for development. It is still possible to shield SNM against these methods.

Background Suppression / Current Technology / Far Distance

There are clear application possibilities in this category for simple systems, with most issues having to do with a cost trade-off between adding more detection capability versus adding background suppression in a specific scenario. The higher levels of background suppression from more complex systems will require research to find cost effective ways of employing such techniques.

Background Suppression / Current Technology / Extreme Distance

Figure 9 showed a $50M size detection capability would be required even if complete background suppression were possible. As the percentage of background suppressed drops from 100%, the costs dramatically rise, and this doesn't even include the costs of the background suppression system. Real world considerations like air attenuation are also not considered here, and would have a dramatically limiting effect. This is clearly beyond current technology.

Background Suppression / Next Generation Technology / Near Distance

Advances, especially in cost, are foreseeable in this category. This will not overcome the shielding possibility.

Background Suppression / Next Generation Technology / Far Distance

Next generation developments foreseeable in the near distance category will also yield benefits in the far distance, but may not be enough to be cost effective compared to increasing detection capability. More dramatic advances may be required for effective systems here. It is still possible to shield SNM against these methods.

Background Suppression / Next Generation Technology / Extreme Distance

There are no advances in background suppression technology on the horizon that would overcome the extreme system size and cost limitations already mentioned.

Background Suppression / Future Technology / Near Distance

Advances that allow near complete background suppression at reasonable costs are possible. It is still possible to shield SNM against these methods.

Background Suppression / Future Technology / Far Distance

Advances that allow near-complete background suppression at reasonable costs will have to be scaled up and might lose effectiveness, but are not impossible. It is still possible to shield SNM against these methods.

Background Suppression / Future Technology / Extreme Distance

Even if advances in background suppression technology could reach near-complete suppression cost effectively, that would not overcome the extreme system size and cost limitations already mentioned. Such background suppression advances would have to be in conjunction with advances that reduced detector costs radically, and even then it is hard to imagine this being a better solution than the distributed system possibilities that would be enabled by the detector advances. This category requires too many dramatic advances to be considered a reasonable possibility

Active Interrogation / Current Technology / Near Distance

Active Interrogation systems are under development and do not require radical technology advances, though are not currently developed; it is reasonable to expect near term solutions. These systems begin to address the shielding problem. There are serious cost and safety concerns. This category is green because simple radiography systems, a subset of this category, already exist.

Active Interrogation / Current Technology / Far Distance

Such systems do not currently exist.

Active Interrogation / Current Technology / Extreme Distance

Such systems do not currently exist.

Active Interrogation / Next Generation Technology / Near Distance

There are good possibilities for significant advances in the next generation. These systems begin to address the shielding problem. There are serious cost and safety concerns.

Active Interrogation / Next Generation Technology / Far Distance

There is nothing on the horizon in the next few years that has a reasonable chance to overcome the technical, safety and political problems associated with getting a sufficient degree of activating radiation on target.

Active Interrogation / Next Generation Technology / Extreme Distance

The comments for the far distance apply even more so here.

Active Interrogation / Future Technology / Near Distance

Many possibilities exist to improve the effectiveness of these systems and some address safety concerns, possibly allowing more widespread use of such systems.

Active Interrogation / Future Technology / Far Distance

Possibilities for real advancement in this category, especially in safety issues, may lie along the lines of exotic schemes like muon accelerators. It is beyond this discussion to say if such potential systems are possible or reasonable, but the possibilities here are likely remote for the practical reasons listed in the discussion on active systems. Such feasibility questions need to be answered before significant investments are made in such concepts.

<u>Active Interrogation / Next Generation / Extreme Distance</u>

The comments for the far distance apply even more so here. This category is shown as mostly red because even the simplest calculations of practical considerations can show that possibilities are so remote as to be considered unfeasible. The category was left with some yellow only because these simple calculations are outside the scope of this analysis. Investment in this category should never proceed without simple feasibility calculations being levied against any proposals. Even should a proposal not be eliminated by simple considerations, great care should be taken to check the physics of a proposed solution before proceeding with significant investment.

<u>Overall Message</u>

Having considered the individual pieces of Table 2, it is worth considering the overall message that can be drawn from this table. The extreme distance possibilities are very grim as illustrated by the virtually complete red color, and for investment purposes this category is not worth considering; extreme ranges are not the solution to the SNM detection problem. There is a great deal of yellow in the far distance, and further research is required before it is known whether it becomes more green or more red. In any case, it is safe to say there will be scenario specific opportunities at these ranges. The key here will be discovering where the right places and scenarios are to effectively use assets at these ranges. The near distance is clearly the place where the most possibilities exist.

<u>Key Themes for Metrics</u>

Several key recurring themes are identified by this analysis around which metrics can be developed for measuring the success of programs to develop specific systems and technologies. When developing metrics it will always be necessary to consider the specific application of these themes to a technology being developed for a unique operational environment.

Passive Systems:

1) Overall system detectability as a function of standoff distance and cost.
2) Detector material sensitivity and selectivity as a function of cost.
3) Effectiveness of software for enabling and improving automated identification and decision making.
4) Associated technologies to leverage detection capabilities. An example would be a technology that could recognize indicators of suspicious activity to select targets for inspection.
5) Operational considerations to reduce false alarms, improve detection capability and target items for inspection.

Background Suppression:

All of the above plus a cost analysis of background suppression effectiveness versus a simple increase in detection capability.

Active Interrogation:

All of the above plus:

1) Safety concerns and technological or operational measures that enable the use of active systems.
2) Social and political considerations and measures that might decrease or eliminate such concerns.

Conclusions

Several messages can be derived from this analysis. There are a number of areas where advances in detector technology can significantly improve our ability to detect SNM; however, there are also sharp limitations to what technology can do. Any effective approach to detecting the movement of SNM will require a systems approach, where a multilayered system of systems is employed worldwide. This extended system must include not only detection technology, but must effectively leverage all other available assets, from exploiting law enforcement and intelligence operations to leveraging non-detector technologies. Active interrogation techniques hold the only promise for a direct solution to the shielding problem, but technical, cost, operational and safety concerns will relegate them to limited use. Where possible, systems that pair active and passive systems could prove effective.

There is one overriding message that comes through clearly from this analysis: detection of SNM is a local problem. Effectiveness drops off dramatically as a function of standoff distance. Qualitatively this message is technology independent, true for passive, background suppression and active interrogation systems. Its derivation depends on nothing more than the mathematics of geometry and statistics. Extreme ranges hold no reasonable promise and should be eliminated from serious funding considerations. Far ranges will have useful but limited applications. The radical breakthrough allowable within this analysis is the concept of massively distributed systems. The key to achieving such systems is a breakthrough in materials research that results in a material with which inexpensive detectors can be made that have both high sensitivity and high selectivity. As such materials are being sought, parallel research should proceed into the systems architecture, software, communications, data handling and alarm reporting advances that will be necessary to enable a worldwide massively distributed detection network.

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