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A Bayesian Approach to Aerial Localization of Radioactive Sources

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To the Graduate Council:

I am submitting herewith a thesis written by Robert Blake Wilkerson entitled "A Bayesian Approach to Aerial Localization of Radioactive Sources." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.

Howard L. Hall, Major Professor

We have read this thesis and recommend its acceptance:

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(Original signatures are on file with official student records.)

A Bayesian Approach to Aerial Localization of Radioactive Sources

A Thesis Presented for the
Master of Science
Degree
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Robert Blake Wilkerson
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I would like to dedicate this paper to my wife, Bethany.

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Abstract

Securing nuclear material has become an important area for the safety of the U.S. and other countries. Within nuclear security, there is a potential to use orphaned or stolen radioactive sources to cause harm. As the amount of radioisotopes used by government and commercial businesses increases, the need to secure these sources becomes exponentially more difficult. It is well known that there have been several cases of lost, orphaned or stolen nuclear sources across the globe. There is a need for state-of-the-art radiation search methods to search for these potentially dangerous radioactive sources that could be misplaced. While there are several well established methods for ground-based source search, the options for using air-based detection systems are not as effective. This thesis describes the development and implementation of the Broad-Area Search Bayesian Processor (BASBP) algorithm. This program was created to effectively search for lost sources from an unmanned aerial detection system. This approach utilizes Bayes' theory coupled to a MCNP weighting method to quickly estimate the location of possible radioactive sources. This Bayesian algorithm shows improvements in source localization for low-level source isotopes. BASBP has been shown to locate radioactive sources that are weaker than standard minimum detectable activities. It also shows promise for using other data to more effectively locate lost radioactive sources.

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Chapter 1

Introduction

In 1997, an international exercise took place in Finland which looked at certain methods for radiological search and localization of radioactive materials over a specified search area. There were teams comprised of both aerial gamma spectroscopy (AGS) and car gamma spectroscopy (CGS). The teams were tasked with finding any and all radioactive sources in the area of interest. Of the thirteen sources placed within the search perimeter, three sources were found by each group [2]. A similar exercise took place in 1999 using CGS to measure two radioactive nuclides as groups drove by the sources. Of the teams that ran the exercise, only one found a source as they were searching. During post-processing nearly all teams found significant source signals [2]. This level of detection capability is far below expectations needed for a system that plays such a vital security role. The outcome from these exercises showed a need for a detector system that was capable of real-time detection and localization. These field tests also used relatively strong sources. If the sources were well shielded, the results could have been worse. Low signal-to-noise ratio (SNR) environments will typically increase false positive results or lower true positive results depending on the thresholds needed for detection decisions. The concern for finding sources like these is continually increasing as potential for utilizing radioactive material increases.

The potential of illicit actions involving nuclear and other radioactive materials has grown significantly in recent decades. With adversaries improving their capabilities and resources, the threat is continually evolving. In regard to general nuclear security, the International Atomic Energy Agency (IAEA) states that there are four main areas of concern for nuclear material security:[1]

- Nuclear explosive devices,
- nuclear material to build an improvised nuclear explosive device,
- radioactive material to construct a radiological dispersal device (RDD), and
- dispersal of radioactive material through sabotage of installations where nuclear material can be found or in transport

For this project, the focus points toward locating lost or orphaned radioactive sources. These same sources could potentially be used in RDDs or other attacks. There is a justified need to locate these type of sources to prevent any nuclear threat that they might incur. Many strong isotopes are used every day that have a potential to be stolen or orphaned. Medical and commercial food irradiation devices can carry extremely strong radioactive nuclides which pose a serious concern with their potential use in an improvised device. According to the IAEA Incident and Trafficking Database (ITDB), between 1995 and 2015, 2889 confirmed incidents were reported by participating States. Of these radioactive source incidents, 454 incidents involved unauthorized possession and related criminal activities [9]. This data solidifies the need to improve security measures for such radioactive sources.

This research focuses on common isotopes that will decay via gamma emission. Several common gamma-emitting isotopes are shown in table 1.1 with some of their general purposes in commercial use. Because gamma rays can be highly penetrating, these sources would need to be quickly located to prevent harm to the public and others who come in close proximity to them.

Table 1.1: Common Gamma Ray Emitting Radioactive Sources [18]

Isotope	Use	Minimum Activity (Ci)
Cs-137	Industrial Sterilization	5000
	Medical Sterilization	1500
	Nuclear Medicine	5
Co-60	Industrial Sterilization	5000
	Medical Sterilization	1500
	Industrial Radiography	11
Ir-192	Industrial Radiography	5
	Nuclear Medicine	0.02

These strong sources can be located based on their high source activity and the strong signal-to-noise ratios (SNR), which do not require advanced search methods to locate. There are well established search methods that do not require specialized detection algorithms. But a more recent area of interest is an educated adversary who is familiar with radioactive sources. If an individual shields a radiation source well, it could pose an issue in a high background environment to locate. Furthermore, the relative intensity of these sources falls off as the distance between the detector and source increases. This is of special concern for aerial search methods. Inherently or equivalently shielded low-strength sources are becoming a growing concern for radiation detection search methods.

Also over large search areas, the ability to detect radioactive sources becomes a extensive and time consuming. Logistics of moving a vehicle or team of personnel across several square miles of space will take considerable time. Teams are limited to the conditions of the ground being searched. This research project investigates the potential increases in detection from a gross measurement system in tandem with Bayesian updating algorithm to estimate the location of potential radioactive sources.

1.1 General Search Methods

Nuclear source search is not a new aspect of nuclear security. There are numerous research projects that look into the different methods of source search. These methods are generally limited to using gamma or neutron spectroscopy because their mean free paths are considerably longer in air than other radiation emissions. Again, this research will focus looks at gamma radiation methods. Future work could include neutron gross count rates as well.

Since those experiments in 1999, there have been different methods investigated for radiation search and localization. The techniques vary from swarm search to multi-detector network systems for source tracking [4, 14, 16, 17]. Most of these techniques reside on a ground-based system though. Analyzing considerably larger areas for radiation flux becomes a serious concern for passive detection. For ground-based mobile detection, projects are typically limited to well built roads or off-road capability of the vehicle. A detector's sensitivity to movement needs to also be accounted for in these situations. The restrictions inherent to land-based methods can cause impassable terrain to be overlooked. Air-based localization is not limited by these restrictions which shows clear benefits in varying terrains. Aerial platforms are physically restricted by objects at their flight level. The main concern for air-based search is, as discussed, the source signal that reaches the detector.

Aerial localization of radioactive sources is not a novel concept, but the application of newer techniques has not been adopted. The general practice of search from an aerial vehicle uses teams looking at source signal and self assessment of the flux from the measurements. The currently employed methods require a user-operated system with general detection thresholds based on the standard deviation from the background count rate of an area. This method looks impartially across the whole spectrum of radioactive isotopes. While this method can be effective at higher source strengths, the training necessary for these teams would prove extensive, and the teams would need to be on stand-by if a source is thought to be within a search area. Potentially dangerous sources that are well shielded or inherently low-source strength may not reach the threshold of detection if it is set too high. On the other hand, if the cut-off is set low based on the expected decreased count rate, the number of false positive results will increase.

1.1.1 MLEM Search

One major method used in the research is the use of maximum likelihood estimation method (MLEM) and its substrates. There is extensive research on this method with many search algorithms implementing a form of MLEM. In 2007, a team applied a comparison between the extended Kalman filter (EKF), unscented Kalman filter (UKF), and MLE. Their results showed that MLE performed the best in application but due to slower results a Bayesian framework is needed [7].

In a separate study, the MLE was able to achieve similar estimation errors for higher SNRs compared to a Bayesian estimator, the Bayesian estimator is able to provide accurate estimates for SNRs down to 5dB while the MLE failed for SNRs below 10dB [13]. This shows a possibly benefit to Bayesian implementation over a MLEM method.

1.2 Aerial Search Methods

Aerial search is a developing approach to locating lost or orphaned sources. But the implementation struggles due in part to the large-distance to ground or the speed at which an aerial platform covers an area. Along with distance complications comes the inherent varying background in a search area. Some man-made sources are introduced into the background especially in urban environments, making detection a difficult problem to solve. Because SNR is one of the most difficult problems in source search, Canberra researched the detection limit (L_D) and minimum detectable activity (MDA) of a source using several different algorithms [10]. This research showed promising results for implementation of smarter algorithms at low source strengths which could be useful in air-based monitoring.

Also, aerial detection methods are at present more rudimentary with simple gross count measurements or possibly with spectral identification [11]. With stolen sources, time has to be considered in a search environment as well. New aerial methods have been further developed with these hurdles in mind.

1.2.1 Nuisance-Rejecting Spectral Comparison Ratio Algorithm (NSCRAD)

A group at Pacific Northwest National Lab (PNNL) investigated the potential for using anomaly methods via aerial detection systems to localization a source [3]. They created the Nuisance-Rejecting Spectral Comparison Ratio algorithm (NSCRAD). The principle theory is the rejection of background to improve the signal-to-noise (SNR) for the detection at altitude and to combat the variance in measurements due to flight speed, field of view (FOV), and naturally occurring radioactive material (NORM) in the land sets. NSCRAD's methodology is generalized by the following. First, spectral windows are created to maximize the differences between these categories. This is completed by the optimization of the source and rejection of the background and nuisance sources (potassium, uranium, and thorium (KUT) or other medical and industrial sources). The spectral comparison ratios (SCRs) are calculated for each spectra or sample time. After creating spectral SCRs, new SCRs are created for naturally occurring radioactive material (NORM) and assumed nuisance spectra. Finally, the standardized distance metric is calculated, and a threshold is set for the distance and any value above threshold indicates a threat or anomalous source.

The NSCRAD system is used in tandem with a NaI(Tl) and CsI detectors. The background rejection described was completed with several aerial runs over a search space spanning 30-400 meters. The threshold was set using previous measurements to maximize detection and minimize false alarms. With the correct optimization and configuration of the NSCRAD, the aerial detection capabilities have improved detection of threat materials and rejection of background induced false alarms.

1.2.2 Adaptively Reevaluated Bayesian Localization (ARBL)

A second method created at Pacific Northwest National Lab looked at the aerial approach using a Leidos designed array of 92 CsI scintillating crystals designed for directional information or imaging. They use a maximum likelihood algorithm for near real-time detection and localization techniques. As discussed earlier, maximum likelihood estimation method (MLEM) has been used in many search applications. For real-time mapping of the likelihood the team used a Bayesian approach to update in real-time as measurements were taken which evolves the map as new data is imported. The project noted that their approach worked, but because of their one-dimensional flight path, they cannot update the two-dimension space. This is like due to uncertainty from lateral area perpendicular to the source. This lateral uncertainty can be seen in the right side of figure 1.1.

Figure 1.1 shows the effect of one vs two passes 25 meters from the source location. The second pass shows an improvement laterally for where the source is located. Overall, their

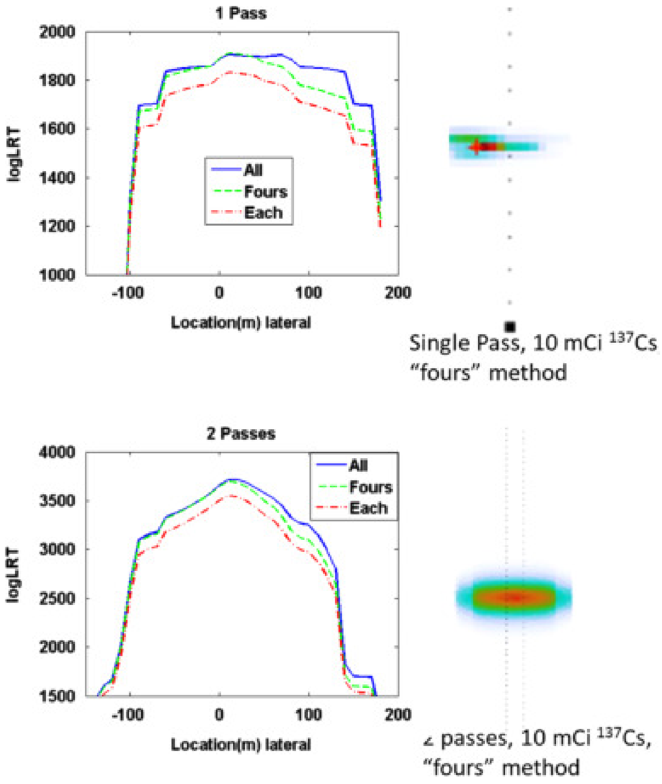

Figure 1.1: ARBL Flyover Results [11]

project ARBL has been shown to find sources on average between 10 and 20 meters away from the correct location [11]. The project also implements a Bayesian updating method showing that Bayesian is a popular choice in detection measurement algorithms.

1.3 Broad Area Search Bayesian Processor (BASBP)

Originally started by Dr. Samuel Willmon, the BASBP project looks at utilizing a Bayesian framework to improve the signal-to-noise ratio (SNR) in inherent poor conditions such as a aerial detection system. This poor ratio is generally due to either the distance of the detector to the source or a low strength source signal in the detector. Much of the original theory for BASBP is found within his dissertation [18].

Continuing on his work, this thesis details the work done to update the original theory into a working algorithm and puts the algorithm with a detector system that is capable of localizing radioactive sources in a search space. The theory for BASBP and its underlining methods can be found in chapter 2. BASBP's methodology and results shown in chapters 3 and 4, respectively.

Chapter 2

Theory

The theory of this project is heavily based on the work done by Dr. Samuel Willmon as noted earlier. The theory section will focus exclusively on Bayes' theory, the use of a bootstrap particle filter, and the MCNP gamma flux estimation used within the algorithm.

2.1 Bayes' Theory

Reverend Thomas Bayes was a statistician in the early to mid 18th century. In 1764, Richard Price published his work that looked at the potential for using subjective data to make probability assumptions. In traditional statistics the data is objective, so the probabilities created are based on impartial methods to make predictions. Thomas Bayes' theory is partial toward using previous, *a priori*, data to generate probabilities. To estimate likelihoods of an outcome, x, given you have some legitimate knowledge, z, Bayes' law can be used to obtain the *posterior conditional density* of x. That theory is generally defined by equation 2.1 [8].

$$p(x|z) = \frac{p(z|x) \cdot p(x)}{p(z)} \tag{2.1}$$

where the probability of all events occurring is $p(z)$ given by:

$$p(z) = \int p(z|x) \cdot p(x)dx \tag{2.2}$$

The conditional probability of x occurring given that z occurred is $p(x|z)$. This principle was then applied to the logistics of the Bayesian algorithm. The conditional probability $p(x|z)$ is more commonly referred to as the posterior density. This probability is the updated likelihood of each particle in our search space. It is also implemented in the algorithm's probability density function (pdf). This will be explained in more detail in the methodology. Bayes' theory can be used for iterative methods between measurements as well. Using recursive Bayes' filtering, an algorithm can utilize all previous measurements. This method is given by equation 2.3.

$$p(x_n|z_{1:n}) = \frac{p(z_n|x_n) \cdot p(x_n|z_{1:n-1})}{p(z_n|z_{1:n-1})} \tag{2.3}$$

The posterior pdf, $p(x_n|z_{1:n})$ is the pdf of x_n conditioned on all observations up to that measurement, n. To link the prior posterior update to the current posterior , the Chapman-Kolmogorov equation is used in equation 2.4 [8].

$$p(x_n|z_{1:n-1}) = \int p(x_n|x_{n-1}) \cdot p(x_{n-1}|z_{1:n-1})dx_{n-1} \tag{2.4}$$

These equations create a link between the previous posterior, $p(x_{n-1}|z_{n-1})$ and the current posterior, $p(x_n|z_n)$. Once the posterior distribution is created, this pdf becomes the new initial probability, $p(x)$, for the next measurement. Each measurement reuses the previous posterior update pdf as the newest *a priori* dataset. The example gives a simplified picture of how Bayes' theory works.

2.1.1 Bayes Theory Example

Suppose there are two identical bags of marbles. There are no discernible differences between them other than what is inside each bag. Based on impartial probability, there is an equal chance of selecting each bag. But if prior knowledge is applied about the marbles, the probability changes. Assume one bag has three times as many white balls as black. The second bag has three times as many black balls as white. If five marbles are picked out (three black and two white), a different probability will be created for each bag. The overall equation for the probability of the bag being chosen given we know about information B about the marbles is given by equation 2.5.

$$P(A_1|B) = \frac{P(B|A_1) \cdot P(A_1)}{P(B|A_1) \cdot P(A_1) + P(B|A_2) \cdot P(A_2)} \tag{2.5}$$

The initial probability of choosing either bag is equal $P(A_1) = P(A_2) = 0.5$. The $P(B|A_{1,2})$ can be read as the probability of B event happening given you know $A_{1,2}$ information about each bag. The binomial distribution gives the probabilities of choosing three black and two white balls as $P(B|A_1) = 0.13$ for bag 1 and $P(B|A_2) = 0.044$ for bag 2. This leaves the full probability of choosing from bag 1 as

$$P(A_1|B) = \frac{0.13 \cdot 0.5}{0.13 \cdot 0.5 + 0.044 \cdot 0.5} = 0.75$$

$P(A_1|B)$ is the posterior update after the measurement. This shows the new updated probability of choosing the bag 1 as 75%. This posterior pdf was based on some useful information about each bag before the measurement. If more events happen the probability can change as more information is available. While this a simple example, it shows the benefits of using prior knowledge to create more educated probabilities for a system. It should be noted that this example uses discrete values for the problem. For BASBP, Bayes' theory is applied for a probability density function encompassing the whole search space.

2.1.2 A Priori Data

One of the most difficult aspects of Bayes' theory is its vague requirements for *a priori* data. The theory has struggled in the past due to poor implementation of prior knowledge. Previous information about the system is also difficult to resolve within nuclear radiation detection as well. Within the BASBP program the *a priori* data implemented is the background count rate for a location but also the estimation of source expected at a location. Another manipulation of the Bayes' theorem is using the recursive equation to update the search space in real-time by using the posterior pdf from the last measurement as the new *a priori* data in the next measurement. This allows the algorithm or system to store only the previous pdf. This allows for quicker processing between measurements.

2.2 Bootstrap Particle Filter

The original Bayesian algorithm employed a bootstrap particle filter. A particle filter is a section of Bayesian analysis and Monte Carlo trackers that allows the user to update the probability space as each measurement about the area is made. There several important steps to a particle filter. Those can be see in table 2.1. Since BASBP originally integrated a particle filter, the capability was also implemented in the final version of the algorithm. The particle filter works as an iterative method between measurements to update the pdf. The bootstrap particle filter is a method that is easily implemented and widely used. A more detailed understanding of particle filters can be seen in Haug's text [8] or works on sequential importance sampling.

Table 2.1: BASBP Bootstrap Particle Filter

A. *Initialize Filter*

1. Initialize random particles in search space
2. Initialize particle weights

B. *Sequential Importance Sampling*

1. Weight update based on posterior update
2. Weight normalization of particles
3. Resample particles from updated pdf
4. Roughen particles to prevent clustering
5. Update posterior pdf

Repeat section B for duration

A working particle filter was created for the BASBP project including the current Python version of the algorithm. One shortfall of particle filtering can be found in the resampling stage of the method. This resampling can cluster particles to the same location. To prevent clustering of particles, the roughening (broadening) of particles can be implemented to spread out the particles.

Clustering is a serious concern for the premise of BASBP. With each measurement the posterior pdf of the search area changes. Only a small portion of the pdf can justifiably change because there is insufficient information about particles large distances away from detector measurements. The posterior pdf of BASBP remains fairly uniform across the search area until the whole area has been measured for radiation count rates. Particle clustering can occur in just several iterations of sampling. BASBP may make greater than 100 measurements before finding any source injection of note. The roughening of particles can only restrain the clustering for so many measurements.

Because of clustering complications with particle filtering, the bootstrap particle filter resampling is inactive in the current iteration of BASBP. Future iterations may be able to utilize the resampling assuming they can use information required to do so. The weight update and normalization still occur with each measurement in BASBP.

2.3 MCNP Flux Estimation

One of the more important steps is to estimate source flux at the detector system. This step provides one of the key methods for weighting the particles in the search space. With low signal strengths likely for a long distance, it is important to account for all attenuation and scattering of gamma rays that may occur. The general theory for the gamma flux at distance, r, from the source is given by equation 2.6.

$$\phi = \frac{S_0}{4\pi r^2} e^{-\mu x} \tag{2.6}$$

Where ϕ is the radiative flux,
S_0 is the decay rate of the isotope,
r is the radial distance to the source, and
x is the depth of shielding with attenuation coefficient, μ.

While equation 2.6 would be suitable for general calculations, the scaling of BASBP could be hindered by an analytical equation. To model the flux more accurately for complicated systems, the team implemented the Monte Carlo N-Particle (MCNP6) transport code to create gamma flux data. MCNP6 provides a powerful tool to create search environments to more accurately predict gamma flux and subsequent detector count rate for a given source at a known distance. It also gives information about the gamma interactions during the simulation. Some of the more dominant interactions include photoelectric effect, Compton scattering, and pair production for higher energy gammas. A tool like MCNP6 becomes more useful as the problem space becomes more complicated and more shielding is added into the equation or other objects that could alter the flux calculations.

MCNP is based on Monte Carlo analysis which uses randomly created particles and simulates how they will interact in an user-defined environment. This is done all within the MCNP program environment. With adequate computer power to run the MCNP simulations, a well defined gamma flux can be created using tallies across the whole search area. These MCNP simulations are an important step in the BASBP algorithm for correctly estimating where a source might reside. More detailed information on MCNP6 can be found in the program's user manual [6].

Chapter 3

Methodology

To implement a novel algorithm that was unique to aerial search methods, there are several special features within the BASBP algorithm to achieve increased detection. The overall process of the algorithm is discussed in the proceeding chapter to accurately define the process of creating the final BASBP program. This includes discussion of different methods implemented at various times of the project. Because source search is a broad body of work, it is necessary to define the limits of the Bayesian algorithm. There were several assumptions made for BASBP and the subsequent hardware integration.

3.1 Search Characterization

With any problem, there have to be boundaries. It is important to consider the limits of BASBP's capabilities in finding radioactive sources. These boundaries are outlined and still fairly consistent with the original constraints implemented by Dr. Willmon in his research [18]. For the purpose of this project, it is assumed that:

- The search space is defined by a known perimeter in a given location.
- The source(s) are stationary and will not move during the entirety of the search.
- The search area has a known gross background count rate.

- The source(s) are at or near ground level.
- The source isotopes are gamma-emitting nuclei.
- The activity of the source will remain constant throughout the measurement.
- The background variation is constant for identical land use areas.
- The gamma flux is independent of the aerial system's velocity.

The team assumes that large acquisition times will not work for the aerial detector search. It has been shown that source localization is helpful with long-term stationary measurements but for the search platform, this is not feasible. It is also assumed that the team searching the area has acceptable equipment to fly the aerial system in a defined flight path and also control its movement. It is also anticipated that hardware will not alter the functions of other equipment via detector noise, position errors, or poor communication signals. These limitations provide the scope for the algorithm and the methodology implemented within the program. Varying any of the above constraints would likely require extensive adjustments to the BASBP algorithm.

3.2 Algorithm Methodology

3.2.1 FORTRAN

The original theory behind the BASBP algorithm was created by Dr. Samuel Willmon. He wrote the original code in FORTRAN 90 with only simulation methods implemented. The initial obstacles in the project revolved around the code execution. Initial tasks like commenting and executing the original algorithm files was difficult to achieve. The code had complications and nuances that only the original coder would understand quickly. Also, the code was in a legacy format which was void of commenting throughout the program. This produced a considerable delay in the integration of the code with the hardware. Another considerable impediment was use of multiple source files. In FORTRAN, the user is required to stipulate what files need to be compiled in the correct order. This nuance of the FORTRAN language requires the user to create the order of file compilation for the computer. With sizable files and no commenting this process took longer than the team anticipated. Ultimately after consider work, successful compilation of the original code was achieved.

With the FORTRAN language, there are some distributions of compilers that will not compile all input files. In this instance, the FORTRAN files were created using an Intel FORTRAN compiler. This compiler comes with extra functions that were used in the original BASBP code. This required the team to utilize the same Intel compiler to compile the BASBP algorithm. This approach becomes extremely cumbersome for users to test the program. Even after using the correct compiler and successful compilation of the FORTRAN code, the executable would still create run-time errors.

To fix both the issue of compilation and execution, the original files were rewritten to use with any FORTRAN compiler including open-source versions. This allows all users to compile the algorithm and use it for testing. This alteration kept the language as FORTRAN 90 but all team members were able to execute the code regardless of the system that was used to compile and execute the scripts.

After successful transfer to a more user-friendly version in FORTRAN, the run-time errors continued since much of the original code remained intact. After significant debugging, the source of the errors was located within the detection decision algorithm. This was likely due to the Poisson distribution used within the algorithm. The most difficult and time consuming part of the original code was the lack of commenting throughout. Because of the continual obstacles in the FORTRAN algorithm, it was decided to adjust the algorithm for future use. The language would need to execute correctly and communicate with the hardware in the project going forward. Python was the language chosen based on its user-friendly platform and convenient hardware integration.

3.2.2 Python

As noted, the code was ultimately pushed toward a more flexible code. When deciding on the new coding language instead of FORTRAN, the language needed to run not only the algorithm but communicate well with the other hardware involved in the search method. This gave Python an initial advantage over other languages. Some of the initial detector, global positioning system (GPS), and radio modules were written in Python beforehand. This created a more seamless integration by writing the algorithm in the same language as the hardware scripts. Python also has readily available libraries to assist in the algorithm creation. Because Python is an open-source language, it provides easy testing for any user.

With the change in language and hardware integration, the overall methodology had to change as well. The original FORTRAN code used only simulation tools within the project, while the Python code needed to handle using both simulation and real-time data. This is discussed within the components of BASBP. It includes the setup of the hardware at the beginning of BASBP and then discusses the internal setup of the algorithm.

3.3 MCNP Implementation

MCNP provides the Bayesian algorithm with important flux measurements. Those gamma calculations are then used to fit a Gaussian model to the gamma spatial data provided by MCNP. This curve fit is then added to the BASBP processor based on the source isotope used in MCNP. This data fit provides useful gamma distribution models for individual isotopes and also for source injection purposes. The models are created for varying search elevations to account for aerial distance to the source as well. The MCNP curve fits also tell the Bayesian processor how to update the weight of particles around the measurement position. Figure 3.1 shows MCNP's output gamma flux per source particle that was used to make the Gaussian source models. These gaussian models were of 2^{nd} or 3^{rd} order Gaussian distributions to most accurately fit the MCNP data. Those models are then stored based on the elevation of the distribution.

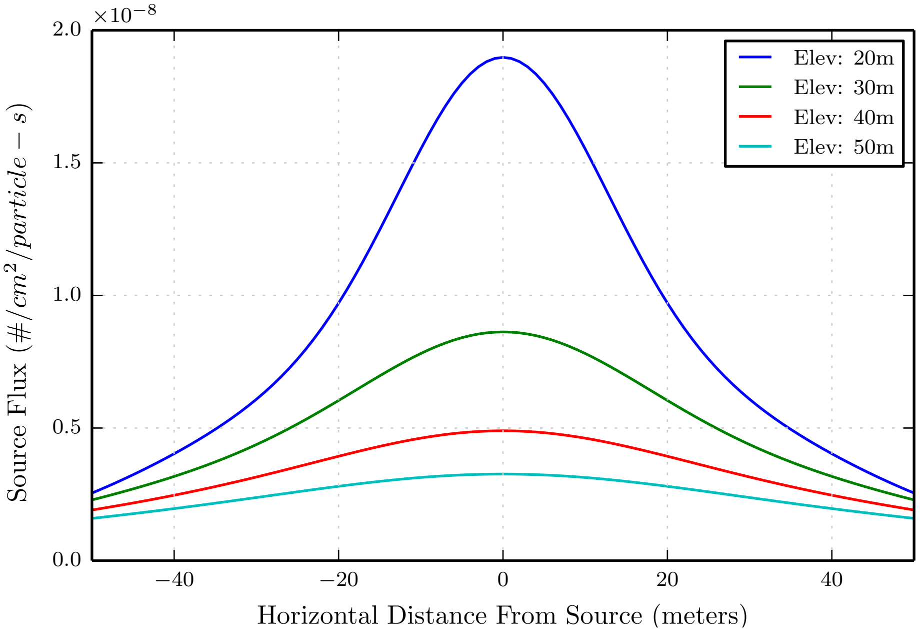

Figure 3.1: Gamma Radiation Flux for Varying Elevations.

3.3.1 A Priori Data

As generally discussed earlier, BASBP has the capability to utilize known data to more appropriately weight likelihoods in the search zone. One variable in BASBP is the minimum estimated source strength. The more accurate the estimated source activity is, the more likely the true location of the source will be found. For example, if the estimated source strength is weaker than the actual data from a source, BASBP may locate a substantial source flux away from the correct position of the isotope. If the estimated source activity is above the actual source strength in the field, the algorithm will never find the source if it assumes it is stronger than the actual data. So a more accurate estimation of the source strength is a helpful tool to localize the source more accurately.

Another data point that can be utilized in BASBP is initial radiation source identification. BASBP does not currently implement spectroscopic information, but if a source isotope is known, the expected energy distribution can be analyzed in the detector. By discriminating the energy range, the background count rate can be noticeably reduced. This is discussed more in the detector methods section. Also, the MCNP models for each isotope would more accurately estimate the source strength at the detector.

3.4 Background Estimation

One of the hardest problems to solve in the BASBP algorithm was the correct estimation of the background in a search area. A significant reason for the initial difficulty in locating any type of source is the uncertainty and fluctuation in the measurements. The Space Science division of the U.S. Naval Research Laboratory investigated the gamma and neutron background in US metropolitan areas. They noted that previous mapping of the United States consisted of measurements in the 1970's with pixel sizes of 3 km x 3 km. This resolution is too coarse for adequate background characterization. The team also characterized the naturally occurring potassium, uranium, thorium (KUT) background measurements of urban cities [12]. This KUT characterization can be beneficial in eliminating naturally occurring background radiation. With an already low signal-to-noise ratio (SNR), there is desire to extract KUT from the background to improve the SNR in any way. BASBP also looked at removing background measurements like KUT for known area of interest, but the detector does not utilize spectral information that would be needed to account for such background.

A team from Leidos and LLNL looked at applying prior land data to the statistics for calculating background. They assert that using knowledge from the land pixels, they can estimate a specialized background for that pixel and subsequently characterize the background of search measurements more precisely based on the location of the measurement. The team ultimately implemented a maximum likelihood algorithm for measurements to account for Poisson noise in the gamma count rate [15]. Similar to the LLNL research on land pixels, BASBP imports land cover data, but creating background for each land use type would require additional research and detector measurements at each type of land use in the search space.

BASBP's background characterization looks at several methods including utilizing those discussed in research. Originally, an inverse-distance weighting (IDW) algorithm was created to estimate the background at areas that had not been measured. This method was ultimately unused in the final version as the search perimeters were not large enough to justify using the IDW method.

The current version of BASBP uses non-discriminated detector data from the search area for background. It then fits a Gaussian model to the data collected. The mean and standard deviation of that Gaussian model are then used within BASBP for simulations. When the detector is connected to BASBP, only the expected mean count rate of the search area is used by the algorithm.

3.4.1 Land Use Estimation

BASBP has several methods to appropriately search a large area of space. As Lawrence Livermore National Lab (LLNL) also implemented within their search methods, the land use files are integrated into the BASBP program. By doing so, these files are able to weight certain areas more likely for search compared to others. The land use is imported from United States Geological Survey (USGS) geotiff files. This data was created in 2011 with open source data readily available to the public. The resolution of the land use data is not ideal at pixel sizes of 30m x 30m. While this is acceptable for creating background in a search area, the lack of resolution is difficult for specialized search patterns. BASBP imports this land use file to update the initial probabilities of the search space. The land use map for the University of Tennessee Arboretum search area is shown in figure 3.2. The information from the land cover data creates initial probabilities for the Bayesian particles which can be seen in the search example in chapter 4.

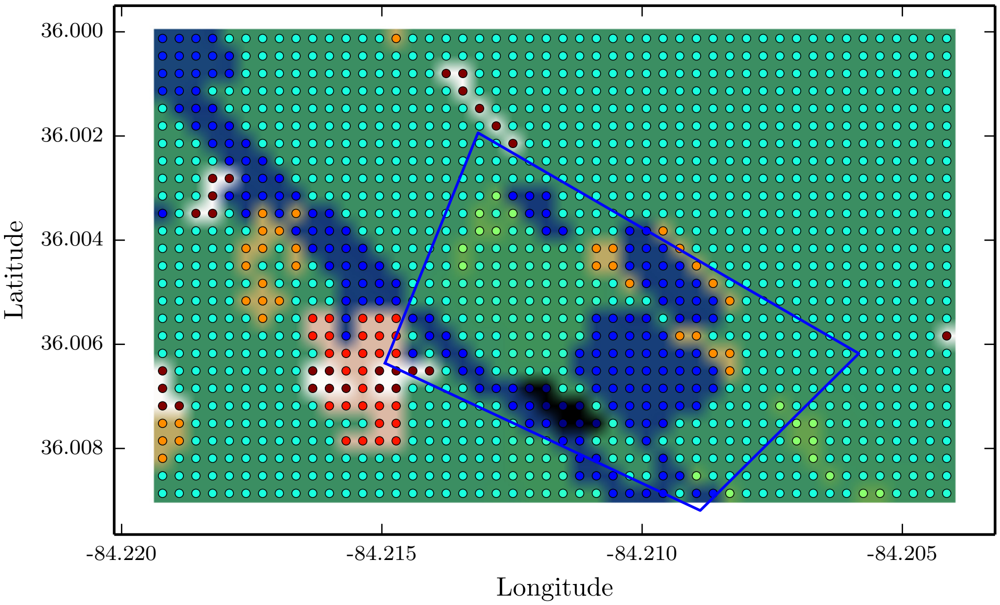

Figure 3.2: USGS land use for University of Tennessee Arboretum .

3.5 Hardware Integration

To integrate the algorithm into a working platform, there are several hardware pieces to implement into the project to complete the aerial detection system.

3.5.1 NaI(Tl) Detector

Detector configurations can improve low-level source detection and especially localization. Techniques like coded aperture or multi-detector imaging can give more directional information about impinging radiation and thus source position. Livermore National Lab looked at the idea of using imaging to detect sources and how it improves detection by an order of magnitude compared to a single detector. They state that although you can improve a detector size which improves the SNR, in practice the spatially varying background impacts the SNR and it can be assumed constant at any detector size [19].

BASBP algorithm does not focus on the radiation detector configuration. The BASBP project looked at detectors that would be light enough to attach to a drone or another unmanned aerial system (UAS). A limit of BASBP is the use of one downward facing detector retrieving only gross counts with no spectral or direction information from the impinging radiation. The team decided to use a NaI(Tl) scintillating detector that was light enough to fly on a drone. Other considerations could be made for alternatives to this detector, especially when only gross counts are required. Either a light plastic scintillator or another relatively efficient option that could be attached to a drone if gross counts are the desire output from the detector.

The operation of the detector is all done by BASBP. Codes were created to communicate with the detector for any reason including discrimination of energy levels. When BASBP is running with a detector, it will use a different start up sequence that includes turning on the detector and configuring it for measurements. This process will include not only turning on the high voltage supply but also taking measurements and calibrating the detector.

If the source isotope is known, the system has the ability to select a typical range of energy values for the source's full energy peak and thus will only look at the counts in those bins of the spectrum. This will lower the background count rate, and improve the signal to noise ratio (SNR). For example, many gross count measurements in the lab space were around 244 count/s for a range of 25 keV to 6 MeV. Figure 3.3 shows a histogram breaking down the background count rate in the lab and the variation in counts between one second measurements. If a ^{137}Cs source is expected, then the source will decay to $^{137\mathrm{m}}$Ba which predominantly emits a 662 keV gamma ray. If the source isotope is known, the Sodium Iodide detector's energy spectrum could be constrained to the energy range around 600 keV to 720 keV depending on the resolution of the spectra. This range would be dependent on the energy resolution of the detector used. In the lab, this energy constraint eliminates low energy noise and reduces the background count rate to less than 20 count/s. This lower count rate allows the threshold of detection to be met more easily by weak isotopes.

The plot in figure 3.3 shows the background count rate in a stationary location. It was made using the team's NaI(Tl) detector with minimal discrimination of the incoming signal. It shows that the variance in detector is nearly equal to the root of the mean count rate.

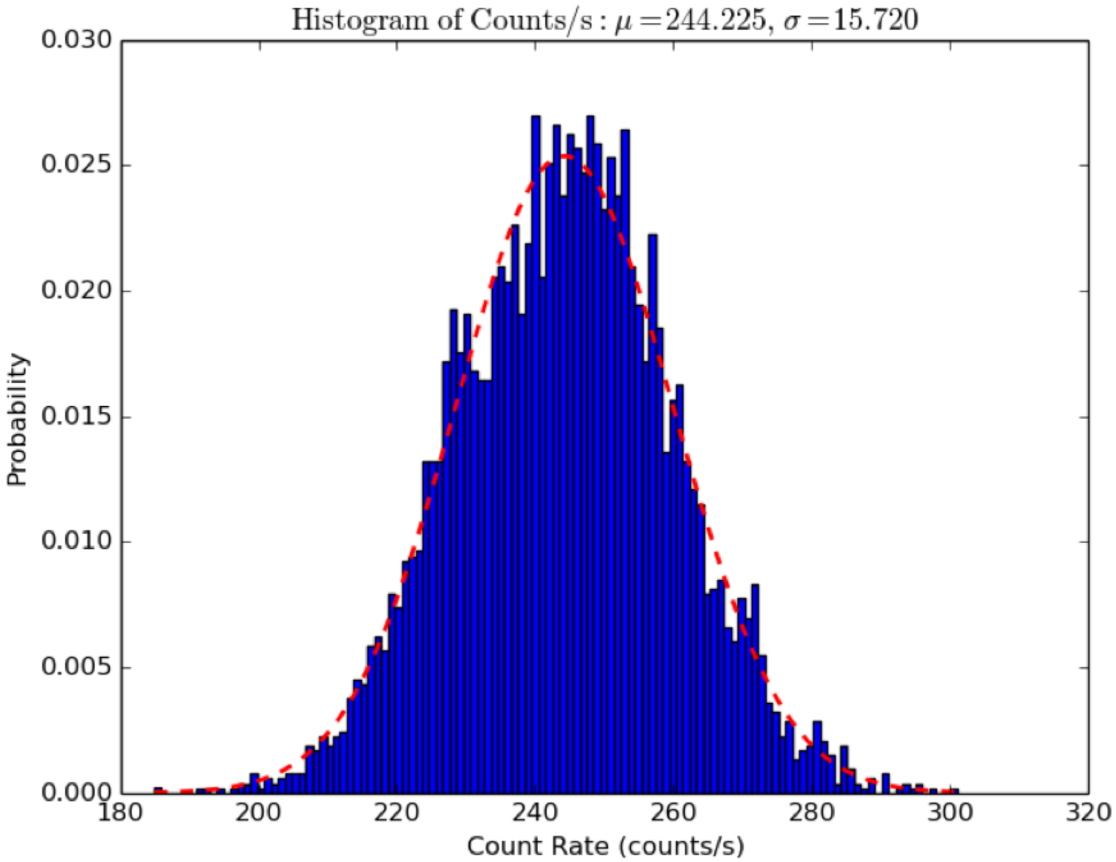

Figure 3.3: NaI Detector Gross Counts Histogram

Measurements like these are made for any area of interest and used for background and standard deviation in the program.

3.5.2 GPS Setup

The algorithm depends greatly on the geospatial location of the gamma detection measurements. While a UAS is typically equipped with a GPS, the data from the team's DJI GPS module would be difficult to quickly integrate into the existing BASBP iteration. A second more user-friendly GPS was integrated into the program. The BASBP hardware uses an Adafruit GPS module that includes a serial output to a USB dongle. This GPS module provides real-time location strings from the GPS and then BASBP will flush the stream buffer to get the most recent GPS strings. After some in-code string manipulation, the coordinates are extrapolated to use in BASBP. For in-flight measurements that move the detector over a search space, two GPS measurements are taken and the algorithm location is the average coordinates between the two positions. If no GPS module is selected in program setup, the coordinates are created within the BASBP program.

3.5.3 Radio Communication Setup

For the full implementation of a UAS with a home computer monitoring system, the initial setup of the radio communication system happens well before running the Bayesian algorithm. The radio communication is responsible for talking between the computer mounted to the UAS and the home station. It also is vital in making user inputs to the system before it starts the BASBP algorithm. It consists of two radios for transmission and receiving.

The initial radio modules were acceptable at short distance communication but as the radios move further apart and background interference increases, the communication decreased. To improve the distance of radio communication, two more powerful radio modules were loaned to the team with high gain antennas attached. These antennas provided a larger distance that the drone could communicate with the ground system.

After detector setup, the BASBP program also initiates the communication system between the radio transmitters. These radios transmit important data like gross counts and GPS location to the ground receiving system. The communication system is also responsible for sending a detection threshold signals to the ground system to tell the user where to fly the drone.

3.6 BASBP Logistics

There are two methods to operate the BASBP algorithm. One method has been designed for field tests and the other for simulation purposes only. The simulation algorithm is much simpler to use since it uses the BASBP program exclusively. These laptop simulations do not require a radio module to operate. The benefit of simulations is the ability to control all variables in the system and test its capabilities. The simulation also produces a figure coined "BASBPView". BASBPView a heatmap image of the current posterior density function across the search space. Higher probabilities are labeled in red and lower probabilities in blue. This heatmap image shows the user what BASBP "views" with each measurement. The BASBPView can be seen in the results of chapter 4.

The field test algorithm uses several different codes for different parts of the hardware. In the field test, the algorithm runs on the team's Raspberry Pi mini computer. The Raspberry Pi has the detector, GPS, and radio modules connected via USB ports. All the equipment is attached to the independent drone. The Raspberry Pi has a computer script to turn on the computer and wait for a user input to the Raspberry Pi from the radio module connected to it. The radio module speaks directly to another radio on the ground station laptop. That laptop runs a separate script to communicate back to the Raspberry Pi. The GPS and detector are then tested to confirm they are sending correct data to the ground station. The BASBP program is then started. In the field test BASBPView is unavailable since the radio data transfer rate is insufficient. Once BASBP is started, only the count rate and GPS location are sent to the ground station. BASBP runs exclusively on the Raspberry Pi and only sends vital information to the user. If a source is located, BASBP will stream coordinates of the likeliest position of a potential source. If the count rate is high enough, BASBP will notify the user that a source was found and then ask the user to continue searching the area of interest.

Chapter 4

Results

BASBP is a working program that has been tested in the simulation state and also with partial equipment. Flight tests with BASBP were tested at the Law Enforcement Information Center (LEIC) area at the University of Tennessee Arboretum. Figure 4.1 shows the initial picture created by BASBP at the test site. This location is on University of Tennessee property near Oak Ridge, TN at the Arboretum site. This venue not only provides a large area to search, but also is permitted to use UT-owned radioactive sources on-site for experiments. This land also provides several different types of terrain as seen in the land use file for this location. For flights on site, the maintained area in the bottom left part of the search area was used. All simulations were done using the same site information including the land use and background count rate. In BASBPs' simulation flights, the full search area is used without hardware limitations.

4.1 BASBP Simulation

Before using the algorithm in field-tests, it was necessary to simulate the program with probable data. To show the user an updated search area, the graphical window, BASBPView, is created within the algorithm to show the probability map for the search perimeter in BASBP.

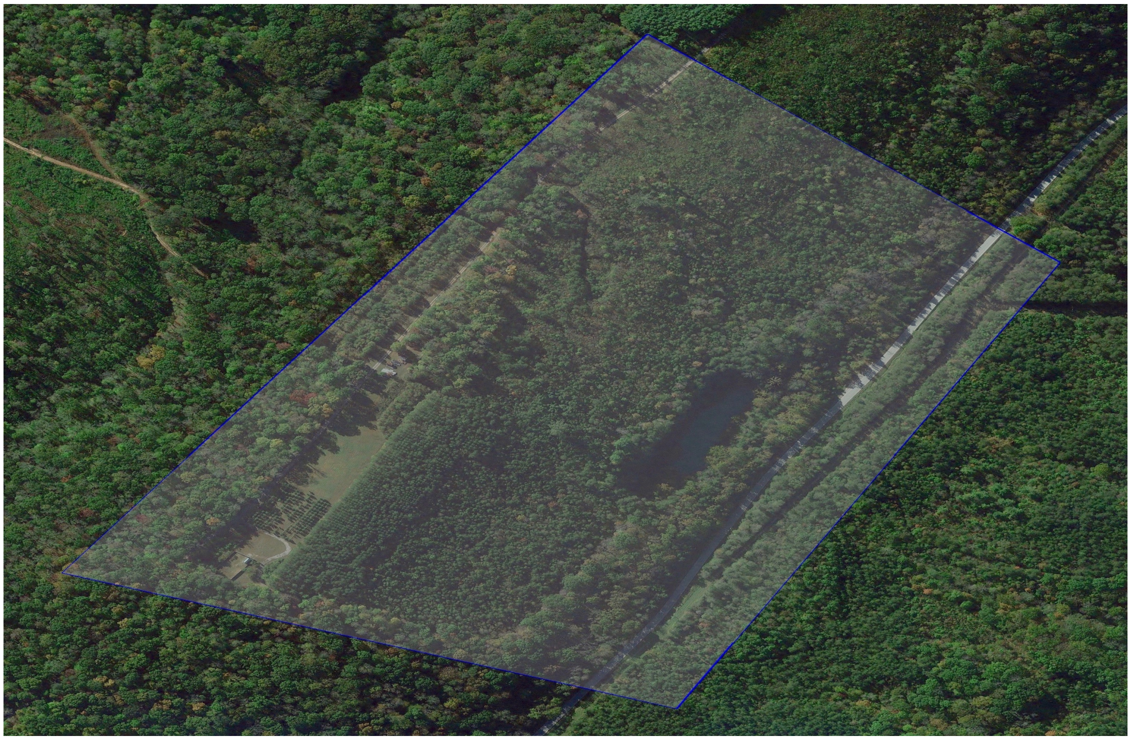

Figure 4.1: Google earth aerial view of the Law Enforcement Information Center Area at the University of Tennessee Arboretum center [5].

There are several key assumptions created for this simulation below. The first is that the drone or UAS is flying at 20 meters above the ground. There are two simulated ^{137}Cs radioactive sources in the search area, one is 30 mCi and the second is 25mCi. The algorithm is unaware of these source strengths, and they are only used to inject counts into the measurements based on distance from the source. The second assumption is that the flight pattern is 40 meters. Each aerial measurement is taken 40 meters away from the last measurement. The simulation creates measurements in a snake pattern across the search area at this distance. Optimally, the flight pattern would be as small as reasonably justified to make the most measurements in the search space. For the simulation, the count time for each measurement is set at 1 second. The background count rate for each measurement is a random value extracted from the previously calculated Gaussian model. For this site, there is a mean background count rate of 300 gross counts per second. This Gaussian model is created by the data collected by the Sodium Iodide detector but with more counts for the background to add noise to the system. Because the background is random, each BASBP iteration with these same conditions could lead to a different outcome. This specific test case highlights some of BASBP's unique qualities.

BASBPView is the graph created in the next figures of this example. BASBPView can be seen in figure 4.2. It shows the BASBP algorithm probability density visualization after importing the land use file. This map shows the capability to change the initial probabilities of search locations based on the likelihood of a source at different types of land use. In a more complicated search area it may be necessary to import more detailed cover data compared to the generally available data from USGS which covers thirty meters per pixel.

Figure 4.3 depicts the second measurement of the search space. The map is largely unchanged except that the probability of a source at the location measured (bottom left) is very unlikely based on prior knowledge about the estimated source strength and background count rate. Again, the probability density function is being shown across the entire search space. With the newest measurement, the pdf is then updated using the previous pdf. This

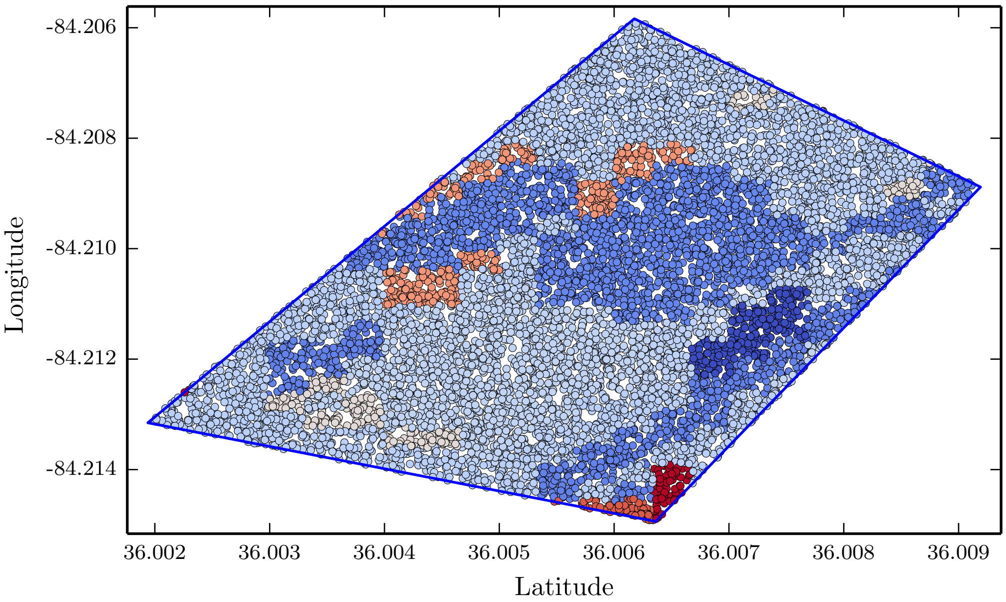

Figure 4.2: BASBP adjusted for Land Use Data

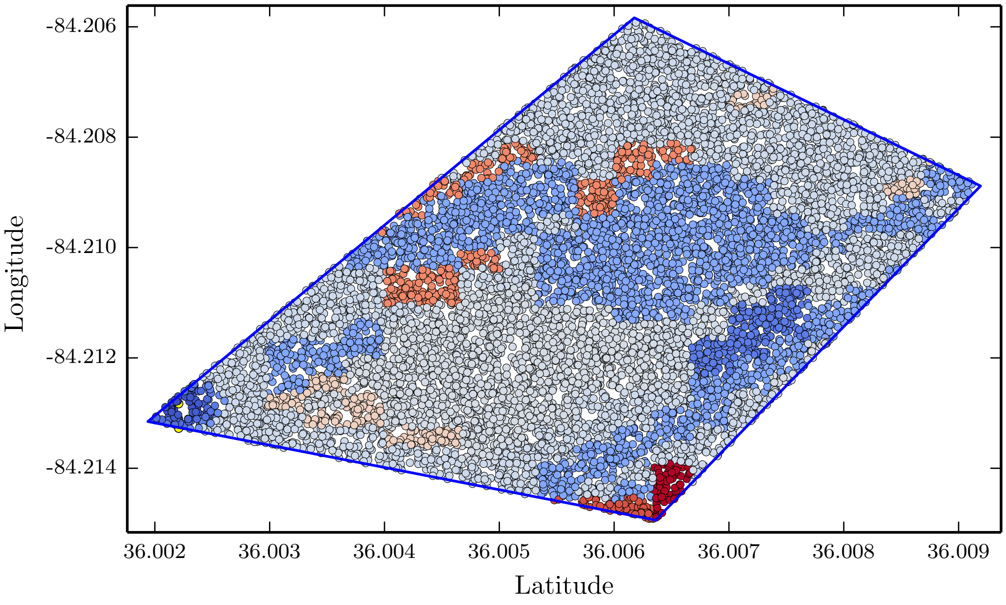

Figure 4.3: BASBP Search Updated after Two Measurements

is one useful aspect of Bayesian updating in the processor. Again, a radiation source is not expected by the algorithm because the count rate is below the expected values for a source.

Figure 4.4 shows the search space after the UAS has made several more measurements in the search area. As shown in the figure, the dark blue areas show a very low likelihood of that space having a source relative to the rest of the search space. This is because the count rate was at or well below the average. As before, the pdf is continually being updated based on the previous posterior update and current posterior density. The brighter areas on the map still are show that the land use weighting plays a significant role in the weight of each particle in the search space. This will only change when noticeable source strength is present to change the relative weights of each particle in the posterior update.

Figure 4.5 shows the first measurement where the algorithm has a measurement count rate above the threshold for a source. When measurements are above the threshold, the weights of the particles around the measurement are raised above the average weight. The relative weights of the other particles in the search space are subsequently lowered by the particle normalization step in the particle filter.

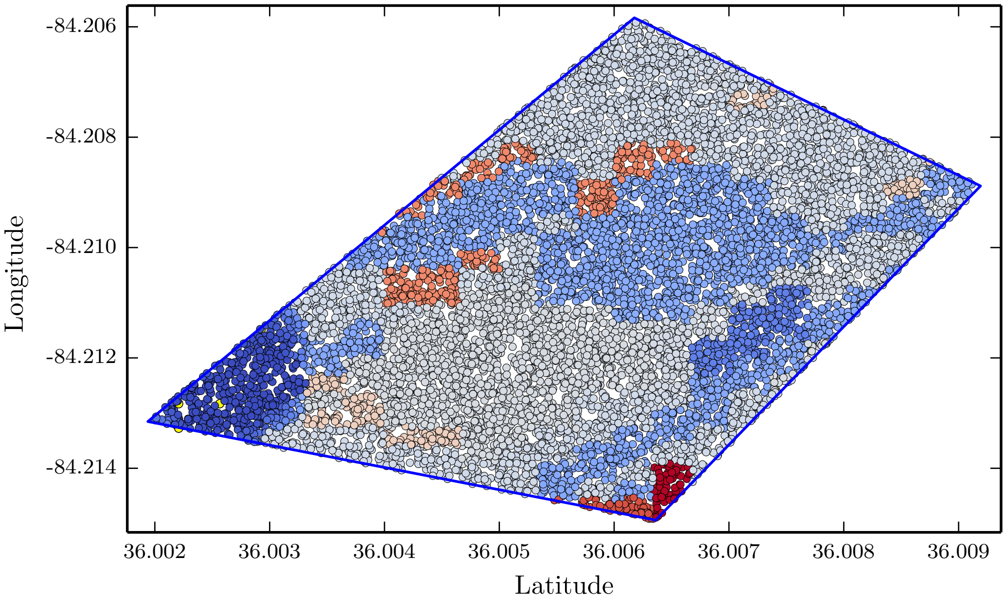

Figure 4.4: BASBP view after 9 measurements

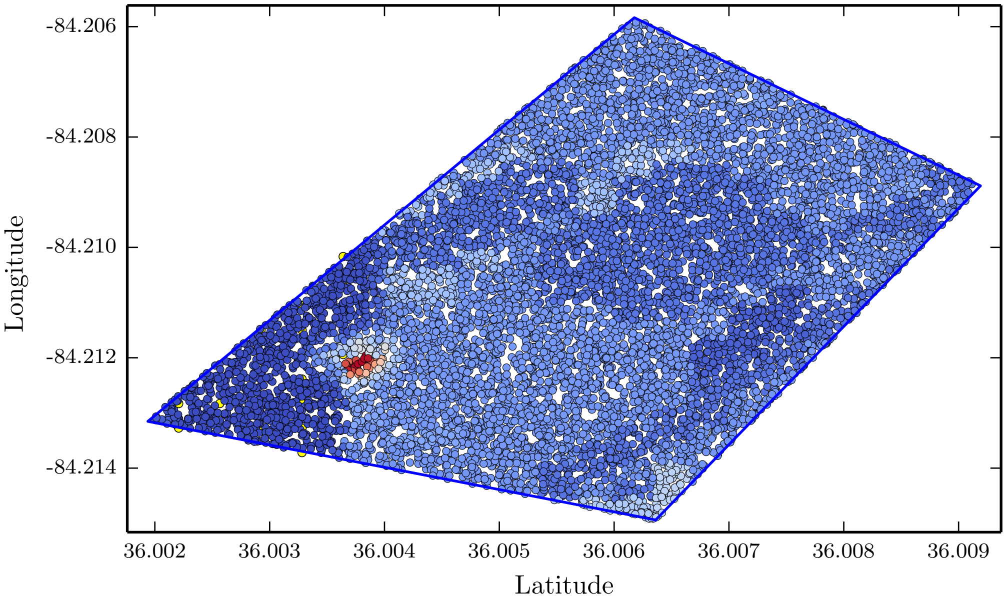

Figure 4.5: BASBP view after 22 measurements.

This action in the visualization creates the higher probabilities in the red area. This also shows that the weight of the land use data is playing a smaller role than the previous measurement weights. The land use is barely showing in varying shades of blue in the map. Also it's important to note that where the measurement was taken is not the highest likelihood spot on the map. This happens when the algorithm triggers but the source is expected to be higher. The Bayesian algorithm weights some particles near the area higher based on that assumption.

Figure 4.6 is several measurements after the source originally triggered in figure 4.5. After the threshold was hit earlier in the search, several measurements are made around the source area. After the measured gamma count rate hits the estimated source count rate, the algorithm leaves that location labelling it as a source location. This final location is seen in Figure 4.7. It shows a tighter probability area than the previous figure 4.6. If the user continues searching, this injected simulation source will no longer produce counts. The pdf will adjust based on the lower count rates in the area. This action is similar to removing a radioactive source from the search space after locating it correctly.

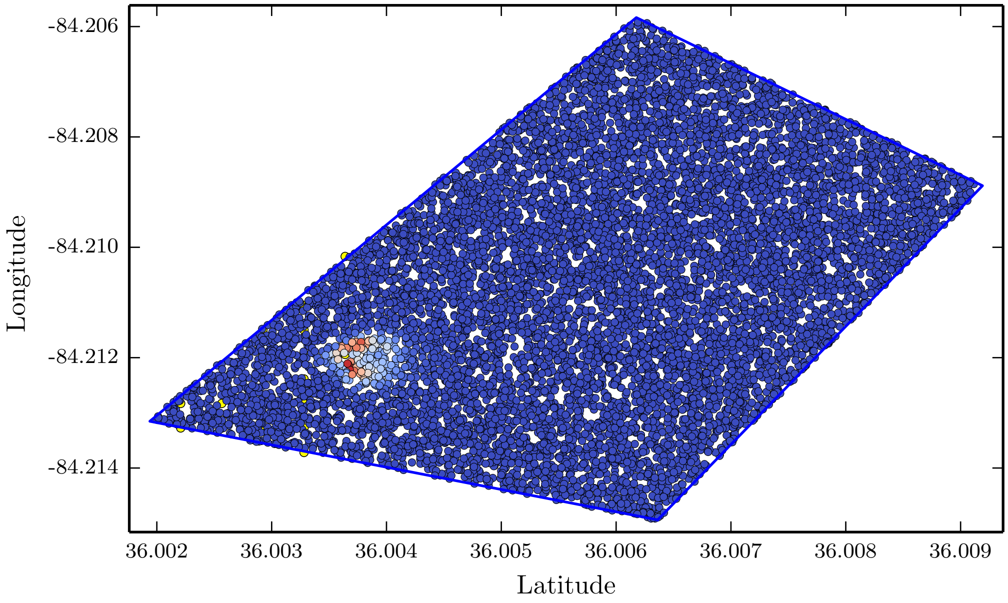

Figure 4.6: BASBP view after threshold met.

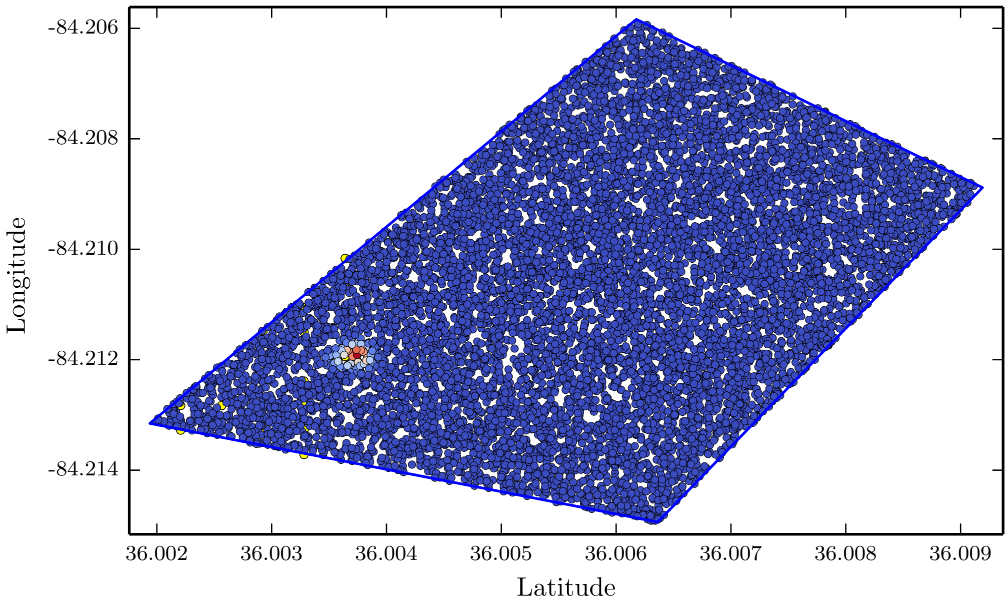

Figure 4.7: BASBP view when source is found

The algorithm has also been written to continue searching for sources. If the algorithm finds a source, it will stop at the location and send it to the user. The algorithm will then return to the original search area flight path to proceed scanning the search area for other sources. To accommodate the algorithm, it is necessary to remove the sources that have been found or the algorithm will remain in the high probability area created by the found source. In the second section of this example, the algorithm looks for another source in the search space after scanning the previous area already.

In figure 4.8 the area has now been scanned completely for sources. In many traditional methods of search, there is a detection threshold that has to be met to trigger for a source. Within BASBP there is only a threshold for stopping in a specified area to search for the source. This happened for the first radioactive source that was already found. The algorithm still knows where the higher probability locations were within the test area. After measuring the search zone fully, the algorithm looks toward the highest areas and sends the detection UAS to the highest likelihood location.

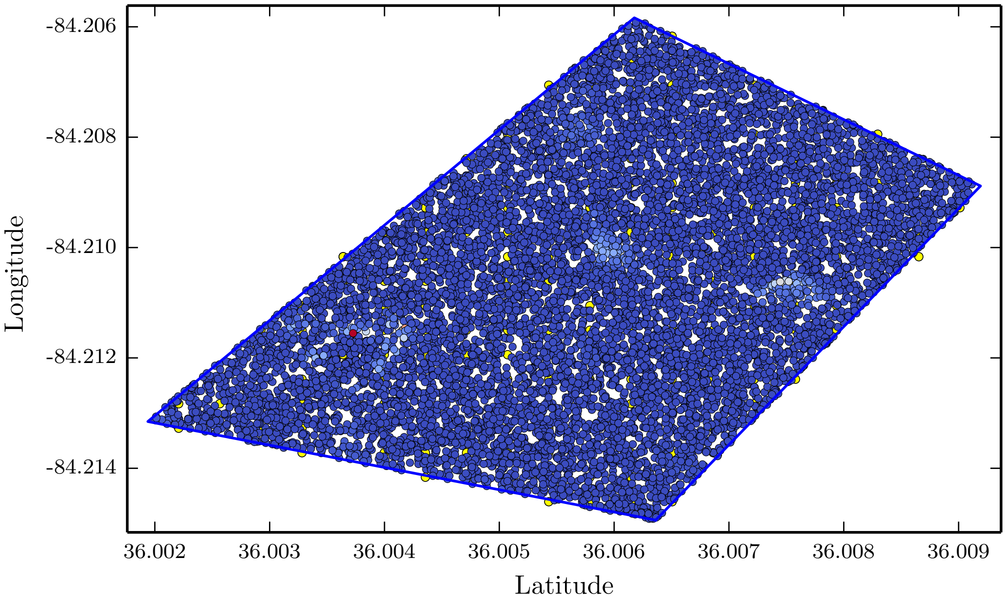

Figure 4.8: BASBP view after search space has been completely measured on the first run

In figure 4.9 the hotspots are more noticeable in the color spectrum. These spots are then searched in the same manner as the first source to justify the existence of the source and then its location if needed.

Finally, as shown in figure 4.10, the second source is found in the center of the search area. It's important to note that the source was not located initially on the first fly across the area. This could be due to the uncertainty in the background count rate of the search area. If the background is higher, the likelihood of detection would decrease further. So in a threshold of detection method, the source may have never been located, but the algorithm successfully found and located the source to a confined area. If necessary the algorithm would then ask for user input to continue looking for sources in the area until the user deems the action unnecessary. This simulation example shows the general capabilities of BASBP and its usefulness in finding low strength sources.

This example as with others created by BASBP cannot be directly replicated but similar results may be acquired. This simulation was created by a random seed sampler so the amount of background in the measurements will never be the same between two iterations

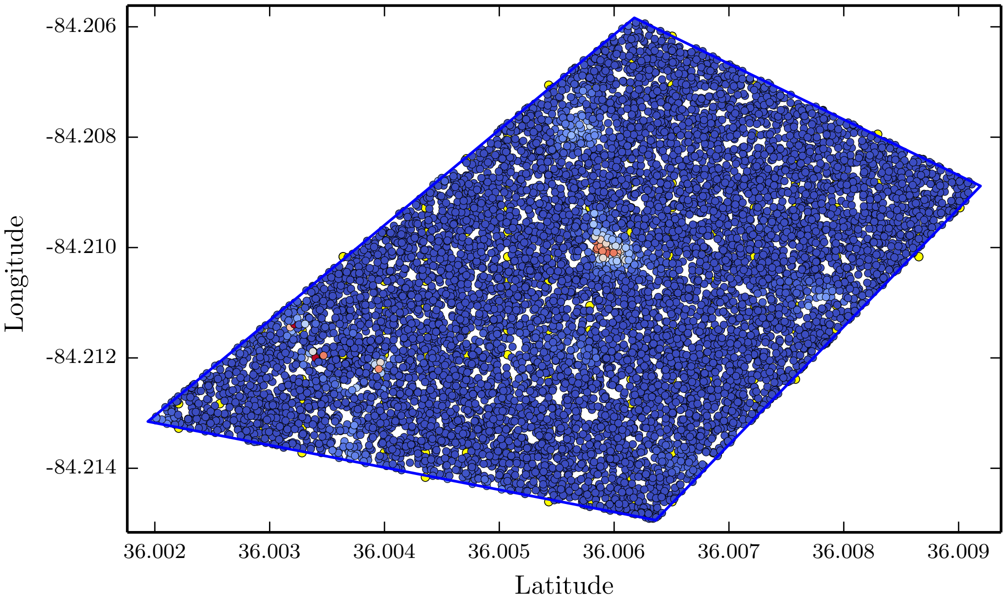

Figure 4.9: BASBP view after probabilities for the search space have been adjusted.

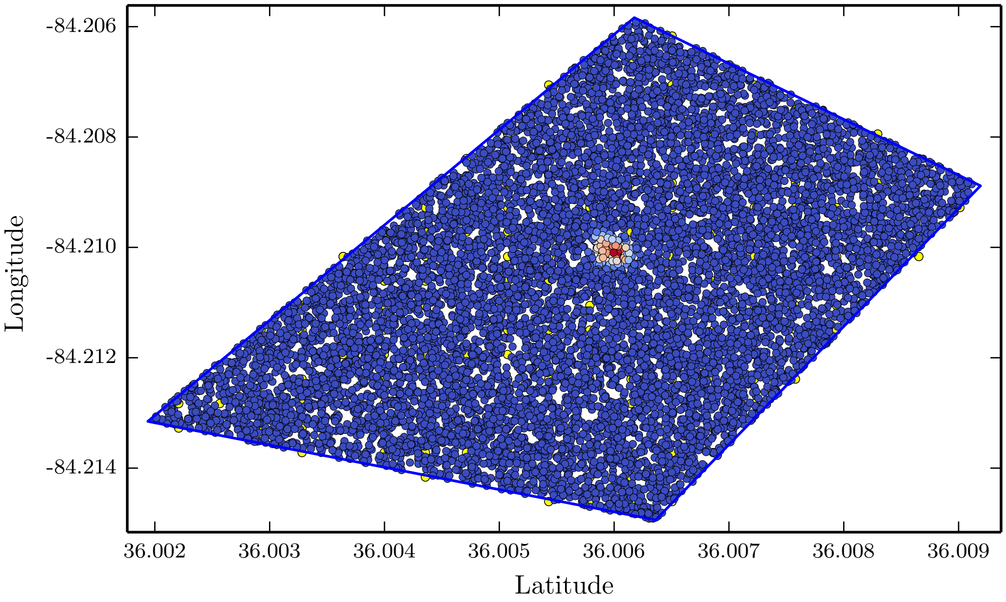

Figure 4.10: Final BASBP view after second source is located

of the BASBP algorithm. It should also be noted that not every picture that BASBPView created was used in this example. This example simply shows the more notable pictures to show the principle concept and design of the algorithm. With good information, BASBP can help identify radiation sources for the user. Even with the benefits of BASBP, the algorithm is limited by the amount of knowledge about the search space and the variability within it. These limitations and more are discussed within the BASBP limitations section.

It is important to note BASBP's ability to search even below the threshold of detection. BASBP will look more thoroughly or give options for places to look even if criteria were not met to trigger a positive result. The intrinsic BASBP thresholds are only utilized to interrupt the drone's programmed flight path to search a nearby area on its own. As discussed in the example, the second source did not hit the threshold for detection initially. But the algorithm still assumed something could be in the higher likelihood area. The algorithm reexamined the area and found the second source successfully. This shows an improvement of general methods that would not have found a source.

BASBP can more precisely estimate the location of a source assuming the estimated source strength is near the actual measurements. While other algorithms would simply trigger with one GPS location, BASBP will continue to measure until it has the highest likelihood spot for the source to be located. This is be extremely important for aerial measurements where the location of the UAS could change rapidly.

4.1.1 Field Test

The team used BASBP platform in a field test as well. This test was done at the UT Arboretum site on a maintained area of land to keep visual contact with the UAS. The team had originally planned to use a drone suitable to hold all the equipment to fly in the search area, but the load-bearing drone was crashed on initial practice flights. This eliminated to capability to use the NaI detector with the algorithm. An alternative drone was equipped with the BASBP Raspberry Pi and GPS module, and radio. The detector used in project was too heavy to fly with the smaller drone, so the background and radioactive source counts were simulated within BASBP as in the example shown in this chapter. After rewriting the GPS modules to make correct location estimations, the experiment correctly worked to locate and find radiation sources in the search field. Again, the field test iteration of BASBP did not implement BASBPView because the radio modules used were unable to quickly transfer data between the UAS and ground station laptop. In future work on the subject, a visual depiction would be beneficial to ground-station users.

4.2 BASBP Limitations

4.2.1 Minimum Detectable Activity

It is important to show the limits of BASBP source detection and localization. Table 4.1 shows some of the generic minimum detectable activities required for making a estimate of the source being seen. The table requires several assumptions to be made for the minimum activity of the sources. The first assumption is the amount of uncertainty in the background. For example, a 100 counts/s background has a standard deviation of 10 counts/s based on the square root of the mean. Many thresholds are set at least 3 to 5 standard deviations from the mean. This would require the source to produce 30 to 50 counts/s more than background to trigger a detection threshold. The MDA values in table 4.1 use 3 standard deviations from the mean as the uncertainty in the background to trigger on. BASBP also uses the same threshold to stop searching the original flight path in favor of the highest probability location. The value in this example would be what is required to trigger BASBP to stop and search a specific location. While this can cause a number of false positive detection decisions, the algorithm quickly remeasures around that location to justify if a source is present. If subsequent measurements are consistently above background, the algorithm will continue to search that location. If not, the algorithm will continue along the original path to look for other sources.

With every measurement BASBP learns more about the search area and the posterior density function shows accordingly. This also assumes the total efficiency of the detection

Table 4.1: Generic Detection Limitations

Elevation (m)	Background Count Rate (Bq)	Minimum Detectable Activity (mCi)
10	100	3.5
	200	5
	500	7.8
20	100	13.3
	200	18.8
	500	29.8
30	100	29.2
	200	41.4
	400	65.5
50	100	77.2
	200	109.3
	400	173.1

equipment is known. The detector used for BASBP was a NaI crystal that had the approximate cross section of 32 cm^2 and an assumed intrinsic efficiency of 10%. The intrinsic efficiency is an energy dependent calculation though and the efficiency of varying isotopes would be be important for determining the intrinsic efficiency. The using the detector cross section and the flux values from MCNP test cases, the geometric efficiency is more accurately given based on attenuation over a long distance.

4.2.2 Search Elevation

Original work on the project looked at the feasibility of source detection at many distances from the ground level to 200 meters above the ground. Initial work via MCNP6 models showed the requirements for running the detector at heights above 50 meters. Ultimately, the sources would have to be extremely strong or a significant portion of detector noise would need to be eliminated. Other than urban areas with considerable height buildings, the need to fly over 50 meters would be questionable.

4.2.3 Measurement Frequency

To update the area more accurately, measurements taken at more locations in a search area are recommended to resolve the search area. The current iteration of BASBP makes measurements each second. This allows the computer to see more measurements in the space. As more measurements are made in the area of interest, the quicker false positives can be eliminated and true positives can be confirmed. One method to utilize this idea would be in using multiple detectors on the same platform. Using multiple detectors to make multiple measurements would help with determining uncertainty.

4.2.4 Problems and Difficulties

Many of the problems in BASBP were found in the integration of the algorithm with actual measurement instruments including the detector, global positioning system (GPS) module, and radio modules. The Sodium Iodide detector required its own modules to be written to run with the python scripts. These scripts needed to be rewritten to correctly run with the BASBP program as well.

GPS module was initially the easiest piece of equipment to integrate into the program but there were concerns when running BASBP. If the GPS did not have a location fix, the program would break. Due to buffer build-up, the GPS would send old locations to the BASBP program which caused many issues with the algorithm testing. Work was done to figure out how to flush the stream buffer of the GPS. Each algorithm GPS would need to be a new output signal from the serial output of the GPS. This serial output was the concern for measuring the location at a specific time.

The biggest complication in the hardware revolved around the communication system between the ground system and the drone. This system of the project is vital when field testing. Theoretically, the radio modules should transfer data several miles and receive it as quick as possible. But in the field application, these radios are unable to consistently transfer data to each other likely from outside radio frequencies interrupting the signal. One problem with the radios was the lack of radio power to transmit and receive the stream of data from the drone. This is still a concern for the project moving forward, but alternative methods can be implemented to reliably transfer data between the ground-station user and the unmanned aerial system.

Chapter 5

Conclusions

The security of potentially dangerous sources is an important part of any nation's security. Radioactive sources are becoming more prevalent across the U.S., and the security of these sources can be questioned based on reports of lost sources. If used correctly, aerial detection systems can be employed to locate these radioactive sources. This work shows the promise that aerial detection can provide without the requirement to utilize many personnel to scour large areas for potential isotopes.

This research shows that the Bayesian algorithm works to localize radioactive sources in a search environment from varying search elevations and at multiple source strengths. It also can give educated probabilities on where the source is located even if the threshold for detection is not met. This can prove to be a useful technique for future aerial applications.

This work is important for the future of radiation detection methods. BASBP has shown it can locate sources quickly since the air frame is capable of quicker speeds than a ground team of radiation monitors. In the future, this technology could be semi-autonomous if drone communication was more involved in the algorithm. With quick localization of radioactive sources, the public would be less exposed to the sources.

BASBP can still be pushed further to add more features. This research focused on the creation and simulation of the BASBP algorithm, but the platform is ready to be legitimately field-tested as well. Running the system in the field would be a logical next step in the process to confirm its plausibility. Other work could include BASBP implementing more data optimization. As discussed in the detector setup, utilizing the spectral capabilities of the detector could improve decisions based on the spectral readout from each measurement. This process could have huge impacts on the measurement noise and background count rates. The newer version of BASBP also adds in the capability to adjust detector settings from the code. This includes energy discrimination.

A considerable amount of work could be done to fix the hardware. In general improvements could be made to all the hardware to improve flight time and improve location accuracy. Also the algorithm was originally designed with to use a semi-autonomous flight path. Ultimately more work to improve the communication with the unmanned aerial system would be required to effectively communicate with the algorithm and drone. A semi-autonomous drone would be useful when drone pilots are not available.

Finally, the project could use implement more complicated search spaces. One difficulty in the project was the ability to fly the drone in urban areas due to flight restrictions. Arguably, urban areas more important to search for radioactive sources based on the proximity of the population to a specified area. These areas should be modeled for BASBP in future designs.

This project has shown that there is promise in using air-based detection methods. BASBP did not use complicated arrays of multi-crystal detectors or coded aperture, but it proved that it can find radiation sources even in a low SNR environment. With a single-crystal detector, a two-dimensional search space is accurately characterized based only on gross count measurements. The process of creating a whole new algorithm in another language proved to be a considerable challenge. The integration with actual hardware was also a challenge, but the objective was met for the terms of this project. BASBP was a successful project that completed its goal to aerially locate radioactive sources in an effective manner.

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Vita

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