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Optimization of passive coherent receiver system placement

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THESIS

OPTIMIZATION OF PASSIVE COHERENT RECEIVER SYSTEM PLACEMENT

by

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September 2013

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Passive coherent receiver systems are a form of non-monostatic radar (NMR) that use active emitters of opportunity (digital television, cell phone systems, and other types of emissions) as a source of reflected target energy. These systems, used within both the military and public sectors, require specific information in order to be placed properly relative to emitters of opportunity and the desired area of detection/coverage. This thesis refines and presents a method of deriving optimal NMR placement, taking into account such variables as spreading loss and terrain data. This also includes optimal placement in a dynamic electromagnetic environment, when one or more of the emitters of opportunity cease transmission/are shut down for maintenance. The majority of the modeling utilizes Matrix Laboratory (MATLAB) to generate signal strength plots which can be applied toward predicting the optimal location for passive receiver placement, as well as where detection hole/voids may be present. MATLAB was used to model the signal-to-noise ratios presented by varying the number and location of receivers. These simulations provide an analytic means to estimate the optimal placement of assets to maximize coverage for a particular geographic area.

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OPTIMIZATION OF PASSIVE COHERENT RECEIVER SYSTEM PLACEMENT

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Submitted in partial fulfillment of the
requirements for the degree of

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LIST OF ACRONYMS AND ABBREVIATIONS

AOI	area of interest
CAPRI	coherent-scatter atmospheric passive radar imager
CAF	cross-ambiguity function
dB	decibel
DTED	digital terrain elevation data
FM	frequency modulation
GPS	global positioning system
GSM	global system for mobile communications
LOS	line-of-sight
LQE	linear quadratic estimation
MATLAB	Matrix Laboratory
NATO	North American Treaty Organization
NC3A	NATO consultation, command, and control agency
NMR	non-monostatic radar
OTH	over-the-horizon
PCL	passive coherent locator
RCS	radar cross section
SNR	signal-to-noise ratio
TDOA	time difference of arrival

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I. INTRODUCTION

A. PASSIVE COHERENT LOCATION SYSTEMS

1. Configuration

Typical radar systems in use today are described as active monostatic systems. This form of radar consists of a single system in which the transmitter and receiver are co-located. The primary purpose for emissions from one of these systems is to reflect from a target object and return to the receiver antenna. Bistatic radars operate in much the same fashion with the exception of receiver location. In this method, although the transmitter is an integral part of the system, the receiver is placed some distance away from the transmitter location. The difference between mono and bistatic radars is depicted in Figure 1. This change in antenna placement can help negate certain scattering effects due to target shape. The inherent resilience to electronic countermeasures of bistatic radar systems adds another benefit to the use of these systems because the receiver position is potentially unknown.

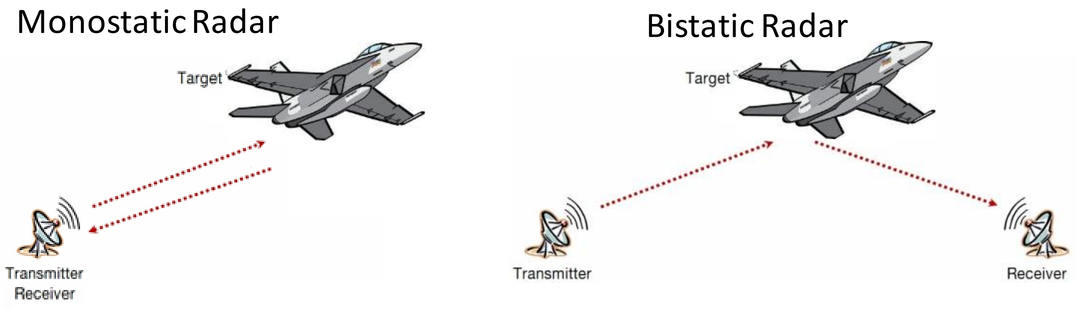

Figure 1. Monostatic and bistatic antenna positioning compared.

Passive bistatic systems, also known as passive coherent location (PCL), dispense with the requirement of dedicated transmitters by utilizing emitters of opportunity such as cell phone towers and commercial radio transmitters. This adds the benefit of lowering cost to the list of advantages for typical bistatic radars. Although the word passive is used to describe these systems, it should be noted that all radar systems require an active transmitter. These systems are considered passive because the transmitters used and not under the direct control of the PCL system and are generally unaware that their emissions are being used for another purpose.

Configurations involving more than one receiver and/or multiple transmitters are referred to as multi-static. This thesis explores varying combinations from as few as one transmitter/receiver pair up to two networked receivers and many transmitters. Because multi-static implies many antenna pairs, the term non-monostatic radar (NMR) will be referenced to indicate any configuration involving at least one transmitter/receiver pairing which are not co-located.

2. Problem Statement

NMR radar systems can be of great value; indeed, the Naval Research Laboratory estimates that such systems will be common place within the next two decades. Transmitter infrastructure, consisting of various commercial emitters, is already in place requiring only the placement of receivers capable of exploiting these signals. Developing a method to predict the optimal location for NMR, which integrates line-of-sight and signal strength, is thus of immediate (and long term) value to a variety of users. Deriving optimal locations for these receivers facilitates modeling their coverage areas to determine optimal target detection capability, as well as to determine where detection is least likely to be supported by the system.

3. Literature Review

Tuysuz, Urbina, and Lind’s paper on the development of coherent-scatter atmospheric passive radar imager (CAPRI) discusses many of the benefits of PCL systems. The system described is designed to study ionospheric F region irregularities. For this purpose they exploit transmitters of opportunity, specifically frequency modulated (FM) radio signals. They suggest that although most FM radio signals provide adequate illumination and power, the ambiguity in the signal may be insufficient for the detection and tracking of airborne targets [1].

The signal produced by Global System for Mobile Communications (GSM) base stations has low to no ambiguity which allows it to contend for use in a PCL system. Zhang and Li propose such an implementation but acknowledge a lack of detection range when using signals from these types of transmitters due to low-emitted power [2]. The majority of these base stations are directionally positioned to emit their signals toward areas on the ground. This contributes to lower ranges when utilizing a PCL system to detect airborne targets.

In 2005, Griffiths and Baker agreed that although transmissions from cell phone towers provided certain advantages, the increased height coverage provided by FM radio and television emitters was more suited to airborne detection. They proposed that through better antenna design and signal processing, PCL systems were still a viable method of target detection [3].

The proper placement for these receivers is still problematic. Zelnio and Rigling proposed a method for predicting the location of passive receivers based on previous detection history [4]. This methodology is appropriate for post-fact determination and is helpful for determining the location of existing receivers and evaluating their coverage, but does not adequately address the initial optimal placement. Anastasio et al., introduced a methodology for deriving optimal receiver placement for PCL systems in presentations to the sixth and seventh European Radar Conferences [5, 6]. These methods were limited to placement in order to detect targets along specific tracks. They contain many insights for placement constraints but are interested in target detection along certain routes as opposed to whole area coverage.

Hoyuela, Terzouli, and Wasky developed an algorithm for deriving the optimal placement of passive receivers using terrain information obtained from My Own Terrain [7]. In their process they limited receiver placement to only locations that would obtain a signal level high enough to detect their given target. Receiver positions which might suffer from direct signal interference from the transmitter were also discounted in their paper. Subsequently, Paichard and Inggs proposed that these limitations on system placement due to received signal could be overcome through new methods of signal processing. Hardware implementations could make it possible to suppress the direct signal interference through matched filters [8].

B. PRINCIPAL CONTRIBUTIONS

After refining the problem statement, a literature review was conducted and bounds for the project were established including required inputs and outputs for the desired algorithm. With these constraints in place, model development was begun.

It was determined that Matrix Laboratory (MATLAB) provided a computation environment suitable for this analysis. Line-of-sight (LOS) functions within MATLAB were evaluated and deemed appropriate for use. Areas with no direct LOS were modeled using MATLAB to create depictions of areas with zero coverage expected. The next stage of the algorithm development involved creating a program which could model the signal strength of a given transmitter/receiver pair. This initial antenna pairing was arbitrarily positioned and stationary. This stage of model development was critical to identifying useful ways of presenting the obtained data. Contour plots depicting the expected signal-to-noise ratios (SNR) for given locations were determined to be the best presentation method. The inclusion of additional transmitters followed this stage of development.

When it was demonstrated that geometries of multiple transmitters and one statically placed receiver could be analyzed, methodology for deriving the optimal placement was explored. A program loop was created that calculated and stored the result for every possible receiver position. Once this was accomplished, additional coding was included to derive the optimal placement for an increased number of receivers.

Following this development, additional factors were included in the algorithm. Terrain elevation data was used to refine distances between points as well as determine LOS. An area of interest (AOI) was established and actual data from known transmitters in this region were included at this point. The final algorithm was tested by varying the input variables and analyzing the results from these simulations.

C. THESIS OUTLINE

The remainder of this thesis formulates and solves a model for deriving the optimal placement of receivers in passive coherent location systems. Chapter II contains additional background information concerning non-monostatic radar. Chapter III discusses the mathematical formulation of the model and a solution strategy for solving it. Chapter IV presents a scenario and discusses results obtained from the model. Chapter V concludes the thesis and suggests areas for future research.

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II. NON-MONOSTATIC RADAR

As discussed in Chapter I, NMR systems retain many of the attributes and requirements of traditional mono-static radar systems. Although there are benefits associated with the use of these NMR systems, additional challenges arise in their effective utilization. While this system configuration could be designed to include a purpose-built transmitter, this thesis is concerned primarily with those systems exploiting emitters of opportunity.

A. NETWORK ATTRIBUTES

1. Emitter Properties

The primary factors of concern with the transmitters in a radar system are placement, antenna pattern, power, and waveform. In a passive system, the design, location, and operation mode of the transmitter is often not under the control of the radar designer. Fortunately, the rapid adoption and growth of technology near population centers provides an abundance of emitters to exploit. Cell phone base stations, television and radio broadcasts, as well as satellite communications such as global positioning system (GPS) are all readily available. While the placement of these emitters is generally considered to be static, the choice of which emitters to exploit is left to the system designer.

The majority of commercial transmitters utilize omni-directional antennas, with the exception of satellite and some cell phone base stations. Considering the separation distance and ground coverage of their signal, signal from satellites can be considered to cover the entirety of the area of interest. In an effort to increase the range of their signals, many cell towers utilize directional antennas aimed away from the sky which limits their usefulness in systems designed to detect aircraft. Both of these emitter types, cell tower and GPS, operate using frequencies and modulation schemes that make them very attractive to passive radar operators. Unfortunately, the directionality of cell towers and the weak signal strength of GPS make them poor candidates for inclusion in PCL systems.

Television and FM radio emitters offer a better option for use in a PCL system due to both their good overall coverage as well as emitted power. Ambiguities arise due to variations in the signal and differ between types of stations. When self-ambiguity is analyzed within the FM radio range, stations broadcasting jazz and pop music tend to have more clearly defined peaks than those stations broadcasting rock or news radio [9]. These ambiguities can be overcome by utilizing only a portion of the signal spectrum from an emitter [3]. Using this technique would increase the resolution gained from the signal but at a cost of reduced signal power. Fortunately, most television and FM radio transmitters operate with more emitted power than most other commercial sources.

An additional benefit from the use of transmitters of opportunity is the longer wavelength of their emitted signal. Typical active radar systems use high frequency emissions to decrease ambiguity and obtain higher resolution images or localization. The majority of stealth technologies currently in use have been designed with this type of emission in mind. Radars operating with frequencies below 2GHz offer the potential advantage of a higher probability to detect stealth aircraft [10].

2. Receiver Antenna Design

Directional antennas are preferred for applications of mono-static radar systems since the received signal is expected to return to the receiver from the same direction the originating signal was emitted. This application offers the advantage of increased receiver gain. Because the emitted signal does not originate from a co-located transmitter, and therefore does not have a preferred looking direction, an omni-directional receiver is preferred in a passive system [11].

Dipole antennas are an inexpensive means of achieving an omni-directional receiver. A circular array of eight dipole antennas has been tested for PCL usage by the NATO Consultation, Command, and Control Agency (NC3A) [12]. This array was designed to cover the entire commercial radio FM band from 88-108MHz. By arranging the antenna elements in a circular array, target bearings can be calculated based on direction of arrival techniques discussed later in this chapter. In addition, the use of an array allows for beam shaping. Combining the radiation patterns of several dipoles can serve to create a null in the direction of unwanted interference [13].

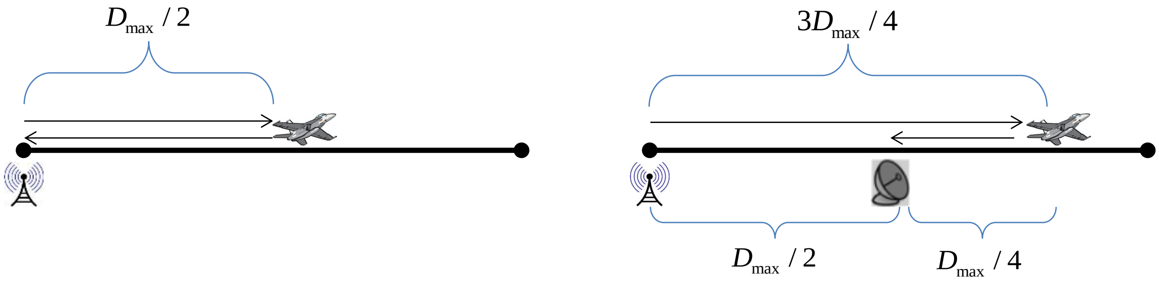
3. Geometry

By definition, the positioning of the elements within an NMR system characterizes its departure from traditional monostatic systems. The major differences are discussed in Chapter I. While this varying geometry introduces additional challenges, it offers several advantages. The passive nature of the receiver is coupled with its possibly unknown location to create a distinct advantage. This covert attribute of NMR systems is often the most attractive advantage for potential system operators.

In addition to the previously mentioned benefit of using longer wavelengths to detect aircraft utilizing stealth technologies, the multistatic nature of these systems also increases detectability of stealth targets. These targets are generally designed to not only absorb a portion of the incoming radar signal, but also to ensure that the remaining energy is reflected away from the angle of incidence. For this reason, bistatic and multistatic systems offer the advantage of an increased chance of detection due to the positioning of their receivers relative to the transmitter used.

Finally, NMR systems offer the possibility of increased effective range. A received signal threshold exists for any system below which a target cannot be detected. The two largest contributing factors to reducing received signal are noise and path loss. Considering only path loss, if $D_{\max}$ is the farthest distance a signal can travel before it no longer has enough power to be detected, then $D_{\max}/2$ is the maximum range from which a target can be detected in a monostatic system. This is due to the necessity for the signal to travel to a target and then back again.

Consider a system geometry in which the transmitter and receiver were placed approximately $D_{\max}/2$ apart. In this case, the system will have an increased detection range for any target along an extended line of bearing from the transmitter through the receiver. In both cases illustrated in Figure 2, the total distance travelled by the signal is $D_{\max}$. For this scenario, the system now has a maximum detection range of $3D_{\max}/4$, which is greater than that of the monostatic example. This geometry is afforded an increased range along certain bearings but now suffers from a decreased range in the opposite direction.



Monostatic system

Receiver offest from transmitter

Figure 2. Range difference along a line of bearing for monostatic and NMR systems

B. TARGET DETECTION AND LOCALIZATION

1. Cross-correlation

Cross-correlation, also referred to as cross-ambiguity function (CAF), measures the similarity of two waveforms. This is accomplished as a function of the time lag between the two signals and has been used in many radar systems. The signal received directly from the transmitter constitutes the emission in its original form. The reflected echo of that signal from the target will contain much of the same signal, slightly altered by the Doppler shift, but time lagged by some value. Because the transmissions from the transmitters of opportunity are generally considered to be continuous and not pulsed, calculating the time difference between the arrival of the original signal and the echo is vital. Calculating the CAF accounts for a large percentage of the time spent processing a signal [14].

This is accomplished through a convolution of both signals as a function of time, t, and delay, τ. The process of convolving two functions g and h, is defined as:

$$(f * g)(t) \equiv \int_{-\infty}^{\infty} f^{*}(\tau) g(t+\tau) d\tau \tag{1}$$

Where h^* denotes the complex conjugate of h.

Using the convolution process, the CAF can be calculated substituting the two signals, s_1 and s_2, for the functions f and g, during the interval, T. The Doppler offset, denoted by f, is also included:

$$CAF(\tau, f) = \int_0^T s_1(t) s_2^*(t+\tau) e^{-j2\pi ft} dt \tag{2}$$

The maximum value for $\left|CAF(\tau, f)\right|$ corresponds to the time delay, τ, between the two signals discussed in further detail below.

2. Time Difference of Arrival

Focused antennas with tight beam widths provide a high accuracy of bearing to a detected target. An array of many highly directional receivers aimed in varying directions would provide a means of obtaining a bearing to the target. This method does not always prove to be cost effective and fortunately other techniques exist to localize target locations from received signals.

The time difference of arrival (TDOA) method of localizing targets relies on comparing the temporal difference between signals arriving at two or more separate receivers. This concept has been used successfully in other applications for many years, most notably for navigation purposes. In order to achieve this, the time of arrive for a signal broadcast from a known position is compared to the arrival time of the same reference signal as it returns from another source as is the case with a target reflection. Using this time difference, range calculations are performed and plotted. An infinite number of positions are possible and are represented by a hyperbolic curve. If two or more receivers are used, the intersection of multiple curves represents the target location.

In actual application, TDOA systems have shown smaller localization error than traditional direction of arrival methods [15]. Although the GPS signal has been deemed too low in power to be used by PCL systems, it does utilize the TDOA method for localization and provides an excellent example of its capabilities. The proposed receiver in the previous section, composed of a circular array of eight dipoles, could provide eight separate signal inputs in order to calculate TDOA.

3. Interference and Masking

Signal interference must be overcome in any radar system in order to differentiate valid targets from unwanted signals. In passive radar systems, a large source of interference is encountered in the reference signal. The direct path signal from the emitter of opportunity may interfere with the system's ability to detect valid target echoes. Two commonly used techniques to handle this problem are matched filters and antenna nulls.

In PCL systems, a direct path reference signal is required from the transmitter being exploited. This gives a baseline from which target reflections can be compared. Unfortunately, the presence of this reference signal may interfere with the target return. In this case, since the reference signal is known, a matched filter can be employed to cancel much of this interference. The incoming reference signal is often a mixture of direct and multipath signals, which makes the use of a matched filter less precise [16]. The presence of a target return near the transmitter may be masked by the filter as well.

Another method for cancelling the direct path signal from the transmitter is the use of beamforming to create nulls in the radiation pattern of the receiver. This procedure is effective, but makes the assumption that no desired target returns are present along the line of bearing to the transmitter. In this example, the target returns would not be masked but would be absent altogether.

Target masking occurs in most radar applications but is more profound in PCL systems due to the lower SNR return. This occurs when more than one target echo is present in a received signal. The stronger echo can be easily identified using traditional methods, but the weaker target return may be masked by the stronger signal. Masking cancellation can be accomplished by applying similar techniques to those used to cancel ground clutter [17].

C. TARGET TRACKING

Tracking a target after detection and localization can be thought of as a subsequent iteration of detection. Once the target is localized, it is re-detected and localized after a given span of elapsed time. Over successive re-localizations, the target is considered to have tracked.

The environment in which electromagnetic propagation exists is rarely ideal. Noise, multipath, interference, and other anomalies combine to create a chaotic mixture of variables that makes accounting for them all unrealistic in every situation. The Kalman filter is an algorithm which uses a series of measurements observed over time and estimates the base state of the system with more accuracy than a single observation. The algorithm produces linear functions representing the system at each measured instance, inserting variables for any uncertain data points. These functions are then solved using a method known as linear quadratic estimation (LQE). With enough observations, this recursive algorithm derives an optimal estimation of the underlying system state.

This technique provides adequate estimates when observed measurements can be expressed linearly and the noise is assumed to be Gaussian. If either of these conditions is not met, either the Extended Kalman filter or the Unscented Kalman filter should be used [18]. In these methods, non-linear functions are instead used to model the system state. This is critical in multi-target tracking. A deterministic sampling technique is used to select a minimal set of sample points from the collected data and propagate their mean values through the non-linear functions to derive a probable estimate. Once the system's base state has been estimated, it can be applied to predict future observations.

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III. MODEL FORMULATION

A. CONSTRAINTS

In this section, three different types of constraints are discussed. Two of these constraints result in areas of the region being excluded from possible receiver positioning and the last pertains to easing the computational load of the algorithm.

1. Geographical Constraint

This thesis is concerned with finding the optimal placement of receiver systems that take advantage of existing stationary transmitters of opportunity. The physical size and required stabilization of the receiver system is currently notional but certain assumptions were made. For this model, the assumption has been made that the receiver system would be stationary and located on land. Areas of water such as lakes, seas, and oceans are excluded from possible receiver positioning. Digital terrain elevation data (DTED) is used to differentiate areas of land and water in this methodology. This constraint exists for the model discussed in this chapter, but may be removed from future examples should it be deemed appropriate.

2. Line-of-sight Constraint

In order for a reflected signal to reach the receiver, the LOS must remain clear between the transmitter and the target, as well as from the target to the receiver. Blockages along this path by terrain of other features will render no received signal. Additionally, an unobstructed LOS must exist between the transmitter and the receiver. This requirement stems from the need to obtain a clear reference of the original signal in order to compare with the incoming reflected waveform. Diffusion, ducting, multi-path and scattering along terrain features have not been included in the current proposed model. Chapter IV will discuss recommendations for including these factors in future research.

3. Computational Constraint

The number of data points and computations involved is large and grows quickly as the area of interest increases in size or more emitters are included. In order to maintain a reasonable program run time, the target is simulated by a spheroid object with a constant radar cross section (RCS). Additionally, the receiver and transmitters are assumed to be notional isotropic antennae arrays with identical gains. This differs from a true omni-directional antenna whose propagation pattern resembles a torus with propagation dropping to zero along the antenna's axis. The implementation of these constraints avoids adding additional computations to derive aspect angles and incident lobe calculations. The use of DTED level 0 data contributes to faster processing. Elevation information in DTED level 0 is segmented into data points corresponding to slightly less than one square kilometer. Higher resolution terrain data, would increase the number of computations required to determine optimal placement of receivers. In addition to enabling faster computational speeds, DTED level 0 offers the advantage of accessibility. Elevation data at this resolution is freely available to the general public through the U. S. National Geospatial Intelligence Agency.

B. INFLUENCING FACTORS

1. Power and Gain

Power received at the receiver, P_r, is a function of transmitter power, transmitter gain, receiver gain, frequency, and radar cross section (P_t, G_t, G_r, F, RCS):

$$P_r = P_t + G_t + G_r - 39 + 20\log(F) + 10\log(RCS) \tag{3}$$

The model focuses primarily on the influence of line-of-sight, transmitter power, and network geometry. Receiver gain will affect the signals received from each transmitter equally and will be considered to equal 1 for this model. Adapting the model to reflect a different value for receiver gain will affect the SNR levels plotted but should not change the derived optimal receiver placement.

2. Noise

Background noise must be calculated in order to demonstrate its effects on received power using the signal-to-noise ratio. Noise, N , is a factor of Boltzmann's constant, temperature, noise bandwidth, and noise factor (k, T, B, N_f):

$$N = kTBN_F \text{(dBm)} = -114 + 10\log(B/1MHz) + 10\log(N_F) \tag{4}$$

3. Path Loss

The effects of path loss on electromagnetic emissions must be included determining the position for optimal receiver placement. The effects of atmospheric attenuation vary from location to location. In order to maintain computational efficiency, attenuation due to atmospheric conditions has been assumed to be constant in all areas and altitudes of the model. As this assumption allows for equal effects on all transmitters, it has been ignored in the present calculations in favor of focusing on path loss due to signal spreading.

As an electromagnetic signal propagates in free space, the wave front in the far-field takes on the form of an ever increasing sphere. A finite amount of energy is contained in each wave front which must now be spread over a greater area. Upon reaching an obstacle or target, only a small portion of the original energy makes contact as the remaining energy has been spread out over a larger area. This loss, L_s , due to spreading is a function of frequency, F , and distance, d , traveled:

$$L_s = 32 + 20\log(F) + 20\log(d) \tag{5}$$

Emissions suffer spreading path loss from the transmitter to the target. The energy reflected from the target is also affected by spreading path loss as it approaches the receiver. These two losses, L_{s1} and L_{s2} , are represented in Figure 3.

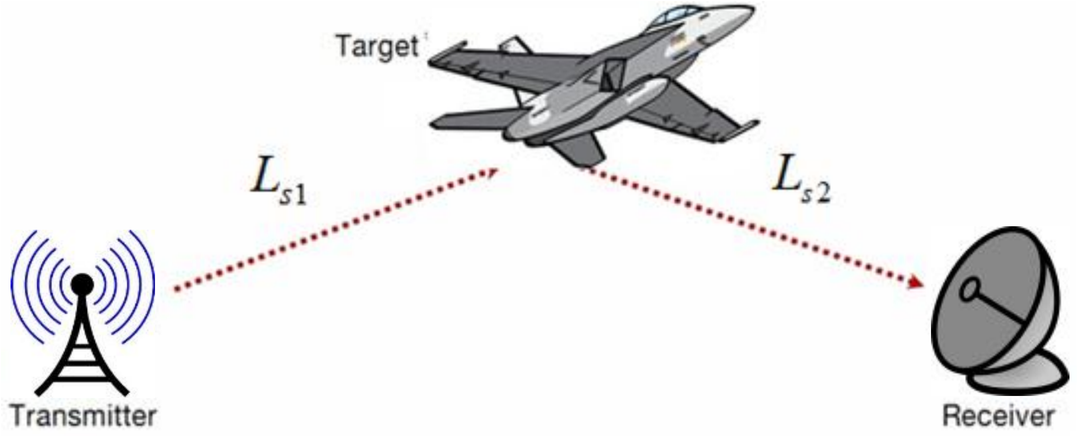

Figure 3. Signal path from transmitter to receiver.

Each path produces loss which must be taken into account. The total path loss in this example would therefore be $L_{total} = L_{s1} + L_{s2}$ and will be subtracted from the received power, P_r, to account for this spreading. After accounting for spreading losses final received power is:

$$P_r = P_t + G_t - L_{s1} - 39 + 20\log(F) + 10\log(RCS) - L_{s2} + G_r \tag{6}$$

4. Line-of-sight

As discussed previously in the constraints section, an unobstructed LOS is vital to the receipt of reflected signals. If a signal emitted from a transmitter is blocked before it reaches its target, no reflection can occur. Likewise, if the blockage occurs between the target and the receiver, the signal again fails to reach the receiver. Without receiving a reflected signal, the target is not detected.

Most modern radar utilizes focused beam emissions capable of reaching targets over-the-horizon (OTH). The emitters of opportunity used in this research are omni-directional transmitters broadcasting relatively low amounts of power. Due to this, OTH detection is not explored in this thesis. Line-of-sight determination is based solely on straight point to point calculations. Any disruption of this path by obstructions or terrain will be classified as having no LOS causing zero power received by the system.

For this model, MATLAB is used for all calculations. A built-in function exists within MATLAB that is utilized to determine whether a valid LOS exists between any two points. Elevation data from DTED is stored in matrix form. The elevation data for each point is referenced in the matrix and straight line path, represented as a vector, is created between these two points. Elevations along this vector are compared to the elevation data in the DTED matrix to determine if the two points are mutually visible.

C. SOLUTION STRATEGY

In the model, a geographic area represented by latitude and longitude is converted to a x, y coordinate grid utilizing the dimensions of the corresponding DTED information for the area. Transmitter data in the form of location, antenna elevation, frequency, and power are included as inputs to the algorithm. These, along with a designated target altitude of interest, will be used to calculate paths between the points. The paths generated are used to determine whether a valid line of sight exists, as well as for the distance measurements needed for accurate path loss calculations. An arbitrary receiver position is also chosen. A simplified four-by-four grid with a transmitter, receiver, and target is shown in Figure 4.

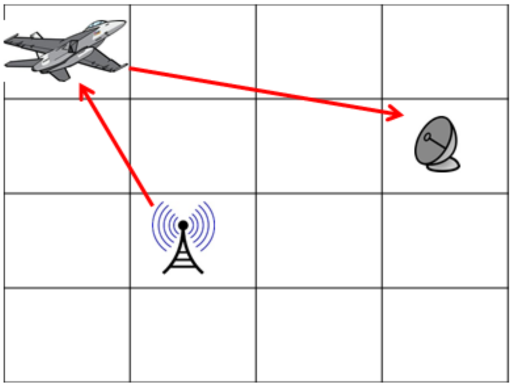

Figure 4. Four-by-four grid with transmitter, target, and receiver.

A matrix of identical dimensions to the grid is also created. Positions within the matrix correspond to grid positions. Line-of-sight calculations are performed for both the path from the transmitter to the target, and from the target to the receiver. If line-of-sight along either path is determined to be blocked, the received power is said to be zero. Otherwise, the received power is calculated according to Equation (4). This value is inserted into the matrix in the position corresponding to the targets position on the grid as shown in Figure 5.

$$\begin{bmatrix} P_{1,1} & & & \\ & & & \\ & & & \\ & & & \end{bmatrix}$$

Figure 5. Matrix with received power inserted for a target in grid position (1, 1).

The target position within the grid is moved to an adjacent grid square and the calculations are repeated as shown in Figure 6. This process is repeated until the target has been moved through all grid positions and the matrix is filled.

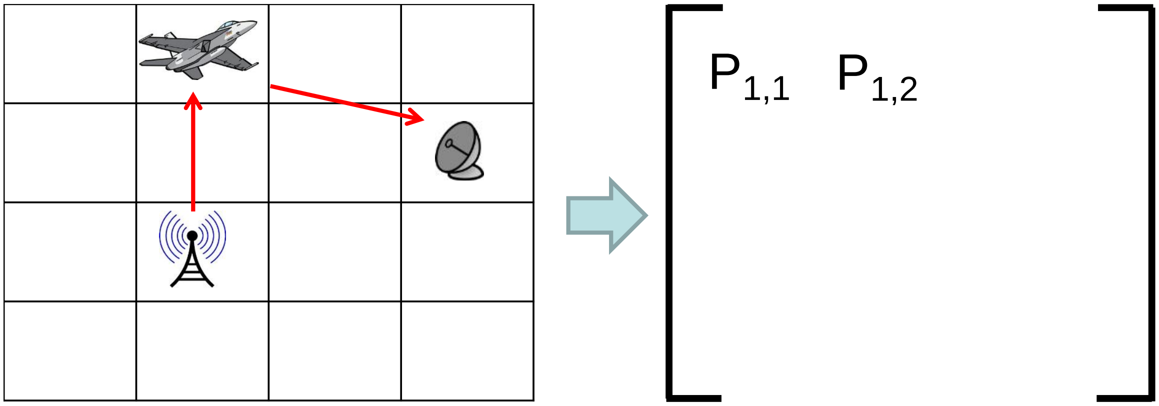

Figure 6. Matrix with received power calculated for two target positions.

Once received power has been calculated for all possible target grid positions, the matrix will be filled. These values of power represent the signal received. By comparing the signal received to the noise, we obtain the SNR for each target location which are inserted into a new matrix of identical dimensions as shown in Figure 7.

$$\begin{bmatrix} P_{1,1} & P_{1,2} & P_{1,3} & P_{1,4} \\ P_{2,1} & P_{2,2} & P_{2,3} & P_{2,4} \\ P_{3,1} & P_{3,2} & P_{3,3} & P_{3,4} \\ P_{4,1} & P_{4,2} & P_{4,3} & P_{4,4} \end{bmatrix} \Rightarrow \begin{bmatrix} SNR_{1,1} & SNR_{1,2} & SNR_{1,3} & SNR_{1,4} \\ SNR_{2,1} & SNR_{2,2} & SNR_{2,3} & SNR_{2,4} \\ SNR_{3,1} & SNR_{3,2} & SNR_{3,3} & SNR_{3,4} \\ SNR_{4,1} & SNR_{4,2} & SNR_{4,3} & SNR_{4,4} \end{bmatrix}$$

Figure 7. Matrix of received power values converted to SNR values.

This matrix of SNR values can be used to plot the radar coverage area of a receiver in the position currently assigned. The SNR values would correspond to levels expected from a target in the position shown on the plot at the altitude previously specified. In order to derive an optimal receiver position, the current position will need to be compared to the other possible placement locations. This is accomplished by utilizing the same grid and matrix process while changing the receiver position relative to the transmitter as shown in Figure 8.

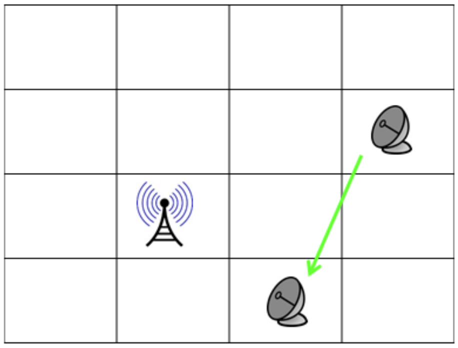

Figure 8. Receiver position moved from previous iteration.

At this step, a new matrix is created and filled using the same process as before for this new receiver position. When complete, it can also be plotted and compared to the results from the previous position. In order to assess which position is more optimal, the SNR values in each matrix must be converted from decibels to their linear equivalent. The mean of each matrix is then compared. The receiver whose matrix has the higher mean is considered to represent a more optimal position than that with a lower mean.

In this example, 16 different receiver positions are possible on the four-by-four grid used. The number of admissible receiver positions may be adjusted based on geographic constraints such as the presence unusable terrain such as body of water completely comprising the corresponding grid square as discussed in the previous constraints section. After matrices for all possible receiver positions have been compared, the optimal receiver position for the AOI is determined by the matrix with the highest mean SNR values.

Deriving matrix sums for comparison removes one calculation for each possible receiver position and yields a value that can still be used to optimal placement comparison. For a transmitter location (x_t, y_t) and receiver location (x_r, y_r) on a grid with dimensions $(x_{\max}, y_{\max})$, this matrix sum $R(x_r, y_r)$ can be calculated:

$$R(x_r, y_r) = \sum_{x=1}^{x_{\max}} \sum_{y=1}^{y_{\max}} 10\log(RCS) - 20\log(F) - 103 - 20\log D\left(x_t, y_t\right) - 20\log D\left(x_r, y_r\right) \qquad (7)$$

The functions $D(x_t, y_t)$ and $D(x_r, y_r)$ represent the distances from the target to the transmitter and the receiver respectively. The values for z_t, z_r, and z represent the heights of the transmitter antenna, receiver antenna, and target altitude all referenced above sea level.

$$D(x_t, y_t) = \sqrt{|x - x_t|^2 + |y - y_t|^2 + |z - z_t|^2} \tag{8}$$

$$D(x_r, y_r) = \sqrt{|x - x_r|^2 + |y - y_r|^2 + |z - z_r|^2} \tag{9}$$

To obtain the optimal receiver positioning for this grid a similar strategy is used whereby the matrices for discrete receiver positions are compared. The coordinates $(\hat{x}_r, \hat{y}_r)$ represent optimal placement.

$$\hat{R}(\hat{x}_r, \hat{y}_r) = \max\{R(x_r, y_r)\} \tag{10}$$

In order to derive optimal placement for a receiver when multiple transmitters are utilized, two options arise. First, matrices can be calculated for each receiver/transmitter pairing. For example, in a situation involving one receiver and two transmitters, two matrices would be derived: one for the receiver and transmitter #1 and a second for the receiver and transmitter #2. These resultant matrices would be added together to obtain the total $R(x_r, y_r)$ value.

The second method follows the initial steps provided at the beginning of this section but involves making two calculations, one for each transmitter, as shown in Figure 9 as red and green paths. The resultant values are summed and placed in a single matrix.

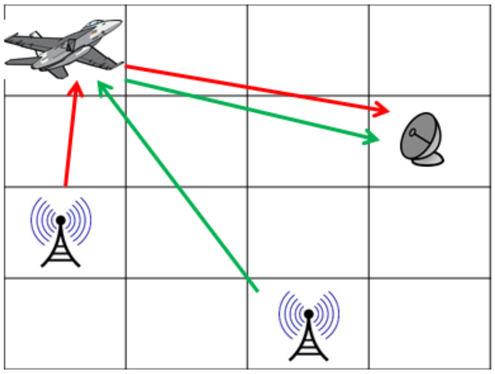

Figure 9. Four-by-four grid with two transmitters and one receiver.

The first method presented, in which different matrices are derived for each receiver/transmitter pair, enables a faster determination of which transmitter is more influential to the receiver's coverage of the given area. This is accomplished by comparing the means of the matrices of each receiver/transmitter pair. The transmitter corresponding to the higher mean has the greatest impact of the received power. This result is important to understanding the effects on coverage when a transmitter is rendered inoperable due to maintenance. Since the SNR values for each transmitter/receiver pair are contained in separate matrices, various combinations of operational and non-operational transmitters may be compared.

IV. MODEL APPLICATION

A. SCENARIO

1. Terrain

Monterey Bay was chosen as the geographical area for this scenario and is defined as the area from 36.4°N to 36.9°N, and 121.5°W to 122.0°W. This area of interest (AOI) is composed of just over 2,500 square kilometers. The main features contained within its bounds are the Pacific Ocean and Monterey Bay to the west, low lying elevation extending from the center towards the northern boundary, and the mountains surrounding Carmel Valley to the south. These varying terrain elements present the chance to demonstrate their effects on optimal receiver placement.

This mixture of mountains, sea, and low-lying ground was specifically chosen in order to gauge their effects on receiver placement. It is expected that the mountainous terrain in the southern portion of the AOI will block LOS with targets behind them when those targets are below the terrain elevation. Receivers and transmitters are also expected to gain an advantage when placed in these areas of increased elevation in that the vertical separation between them and the target is decreased thereby lowering overall path loss.

The western section of the AOI is dominated by the Pacific Ocean. While targets may be located flying above that area, we have restricted placement of transmitters and receivers to land-based positions. This constraint will affect the geometry of possible receiver positions in relation to the transmitters.

Elevation data for this area was obtained from the National Geospacial-Intelligence Agency. MATLAB was used to interpret the DTED level 0 data as shown in Figure 10.

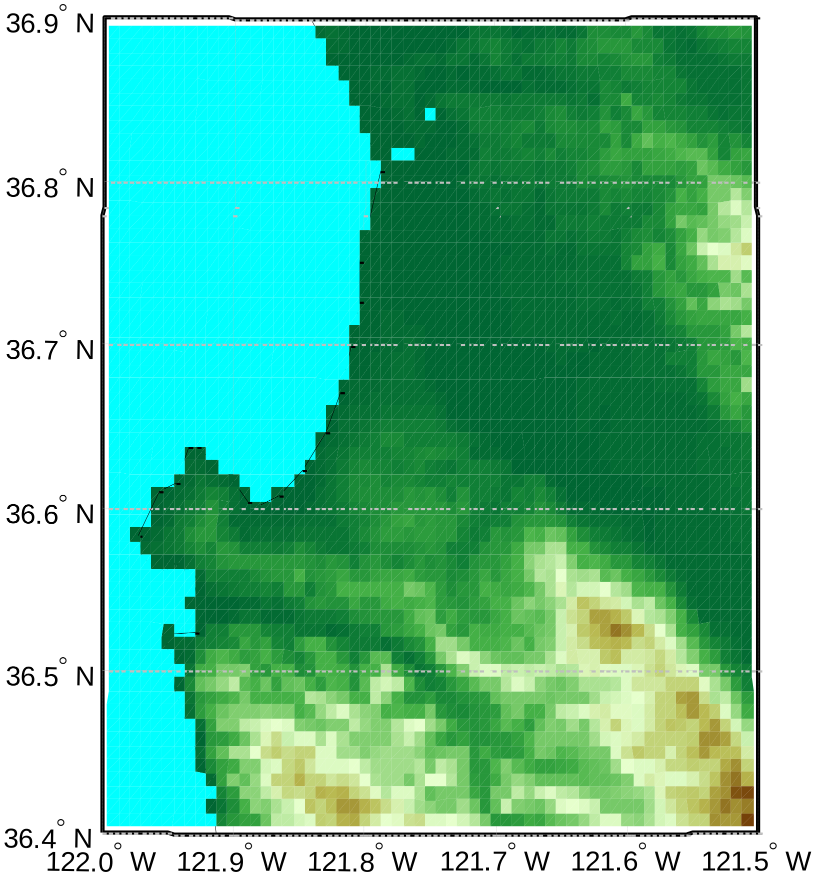

Figure 10. Map of AOI as rendered with DTED level 0.

It should be noted that the Monterey Regional Airport is located approximately 5 kilometers north of the Carmel Valley at 36.59°N 121.85°W. This position delineates the transition from higher elevations in the south to the lower plain extending to the north of the AOI as well being situated within close proximity of the coastline. The airport will provide a focal point of interest in interpreting results of receiver placement.

2. Emitters

Approximately 400,000 people reside in the defined AOI [19]. This level of population results in a wide range of available transmitters to exploit. Cell phone towers, television stations, and radio stations are all present in the immediate vicinity. Three FM radio towers were selected for inclusion in this scenario. The number of chosen transmitters was kept at a minimum to alleviate the computational load of the algorithm.

The three transmitters are: KPIG located at 36.84°N 121.71°W, KSPB located at 36.59°N 121.92°W, and KAZU located at 36.55°N 121.79°W, as depicted in Figure 11. They will be referred to as transmitters one, two, and three and their defining attributes are shown in Table 1.

Table 1. Transmitter attributes

Transmitter	KPIG	KSPB	KAZU
Frequency	107.5 MHz	91.9 MHz	90.3 MHz
Power	5400 W	1000 W	3400 W
Antenna height above ground	16 m	23 m	31 m

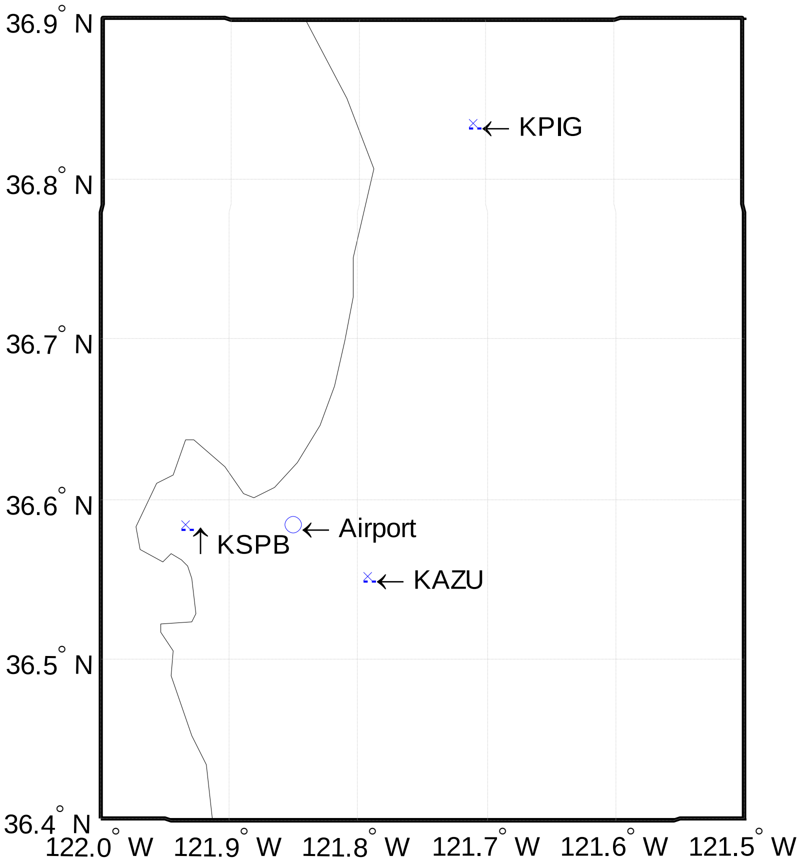

Figure 11. Transmitter positions in relation to Monterey Regional Airport.

B. RESULTS

Using the transmitter information provided, optimal receiver position is derived once a target altitude is determined. The maximum terrain elevation contained in DTED for the selected AOI is 1241 meters. A target altitude of 1500 meters was chosen for the first derivation of optimal receiver position which is shown in Figure 12. The SNR levels in decibels are overlaid to show the change in coverage throughout the area.

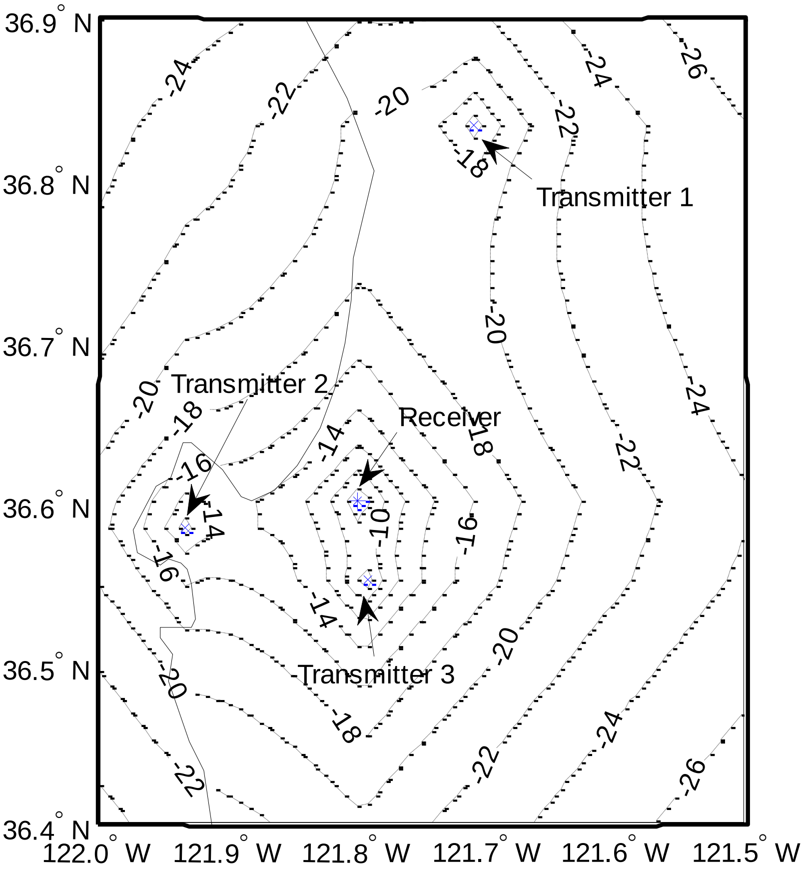

Figure 12. Optimal receiver position for a target at 1500m showing SNR levels in dB.

The subsequent step determined which of the three transmitters would provide the greatest impact on SNR levels should it be rendered unable to transmit. Although Transmitter 1's emitted power is much higher than the other two transmitters, it is shown to have less effect due to its proximity to the edge of the AOI. The algorithm determined that the loss of signal from Transmitter 2 would have the largest effect on the coverage area of the receiver. This can be seen in Figure 13.

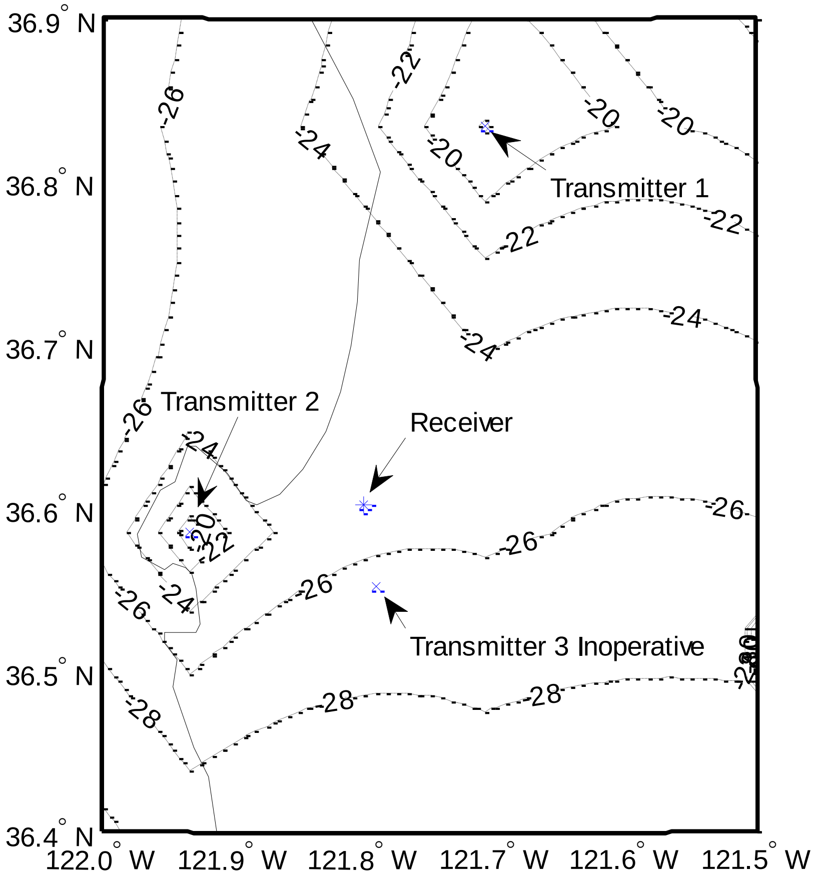

Figure 13. SNR levels in dB for receiver optimally placed to detect a target at 1500m when most influential transmitter is inoperative.

In order to derive the optimal placements when two receivers are utilized, two different approaches are explored. In the first case, the optimal placement for the first receiver has already been determined and the receiver placed in this position. The algorithm would then determine the optimal placement for a second receiver added consecutively to the first receiver. This type of approach would be useful if the receivers were perhaps costly and difficult to reposition. The first receiver would be placed in the optimal position. When the decision to add a second receiver is made, repositioning the first not prove to be either possible or cost effective. The placement for both receivers in this scenario is shown in Figure 14.

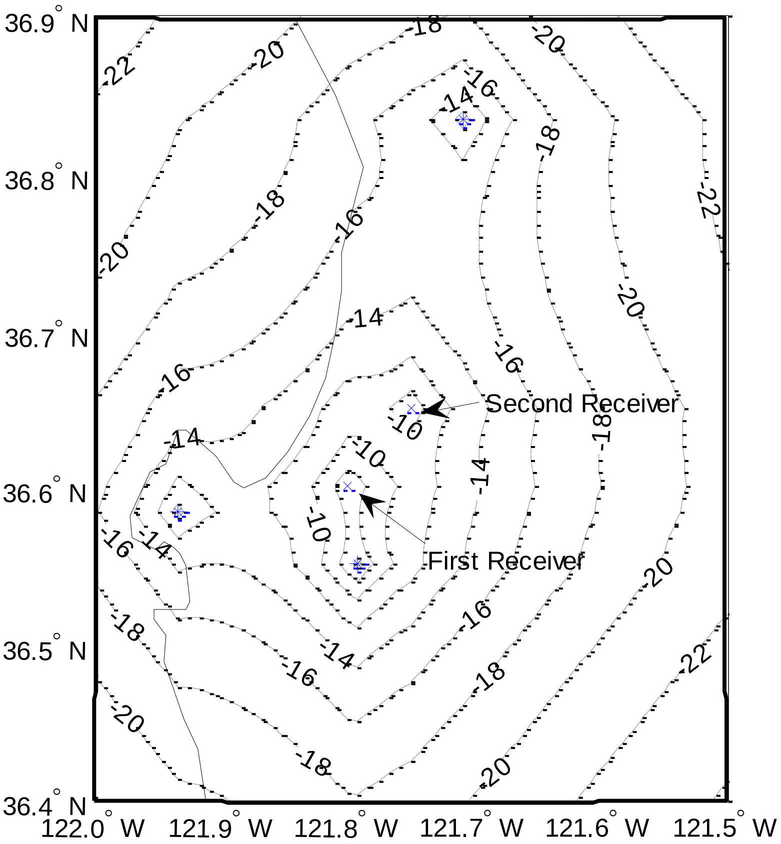

Figure 14. SNR levels in dB for two receivers consecutively placed to detect a target at 1500m.

A second scenario for utilizing two receivers would be concurrent placement. An example for this case would be if two receivers were initially procured or if they were mobile enough that the first could be repositioned when adding a second. This concurrent placement of two receivers in optimal positions is shown in Figure 15.

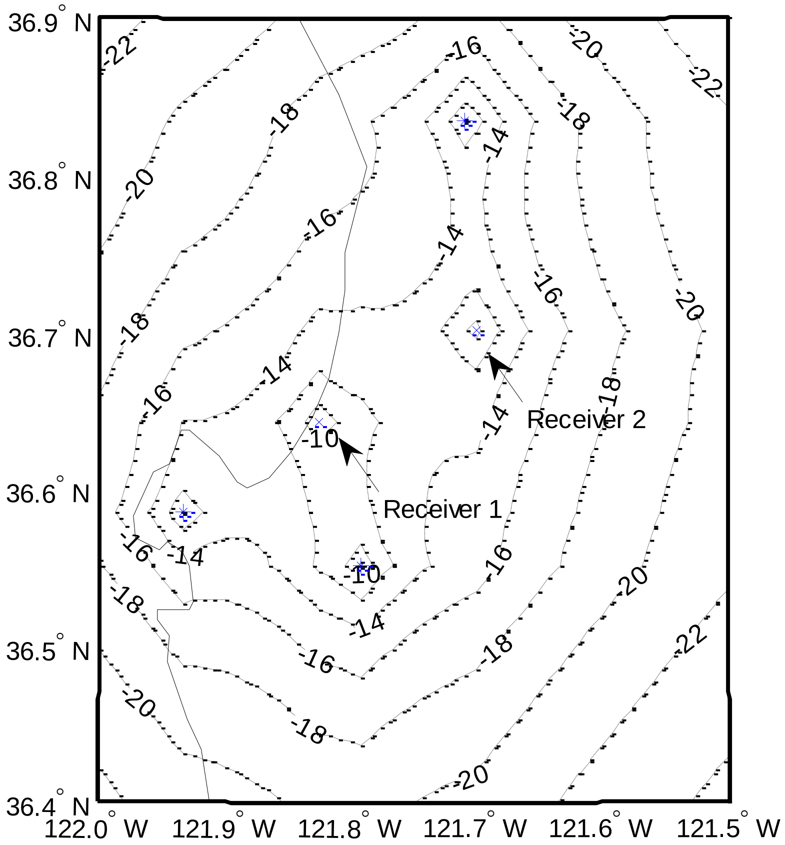

Figure 15. SNR levels in dB for two receivers concurrently placed to detect a target at 1500m.

Predicted target altitude is important to deriving optimal receiver positioning. A receiver optimally placed to detect targets at 1500 meters will have a different coverage area for targets at lower or higher altitudes than the altitude used to derive optimal placement. The coverage area for targets at 500 meters from a receiver optimally placed for targets at 1500 meters is shown in Figure 16.

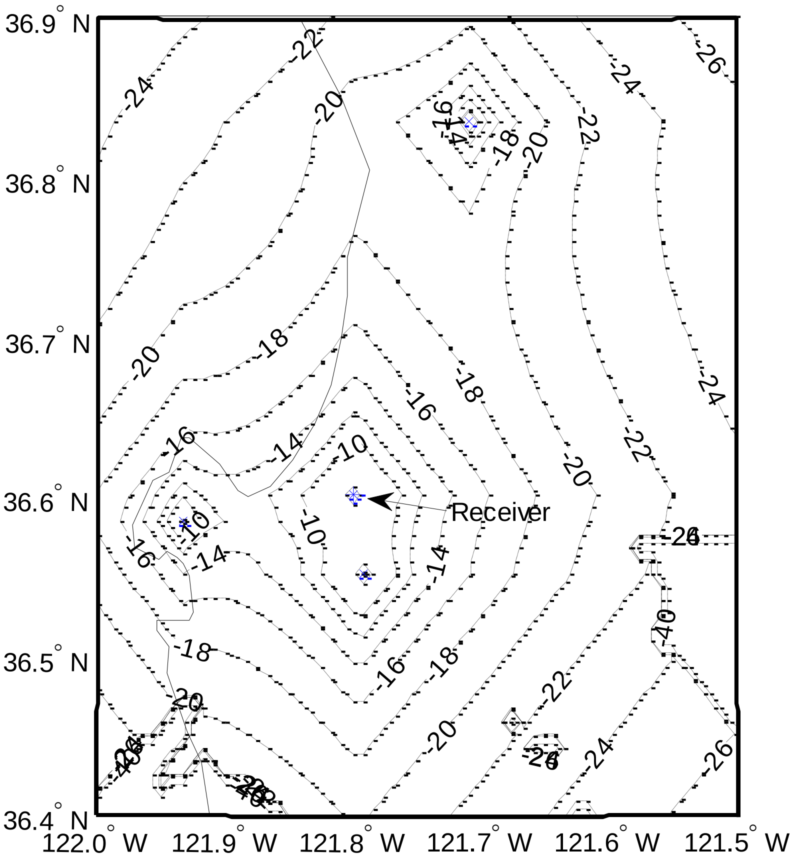

Figure 16. SNR levels in dB at 500m for a receiver optimally placed to detect targets at 1500m.

The optimal receiver placement for targets at 500 meters is derived in order to demonstrate the difference in coverage area from the previous mismatching of predicted and actual target altitudes. This updated positioning and coverage area is shown in Figure 17.

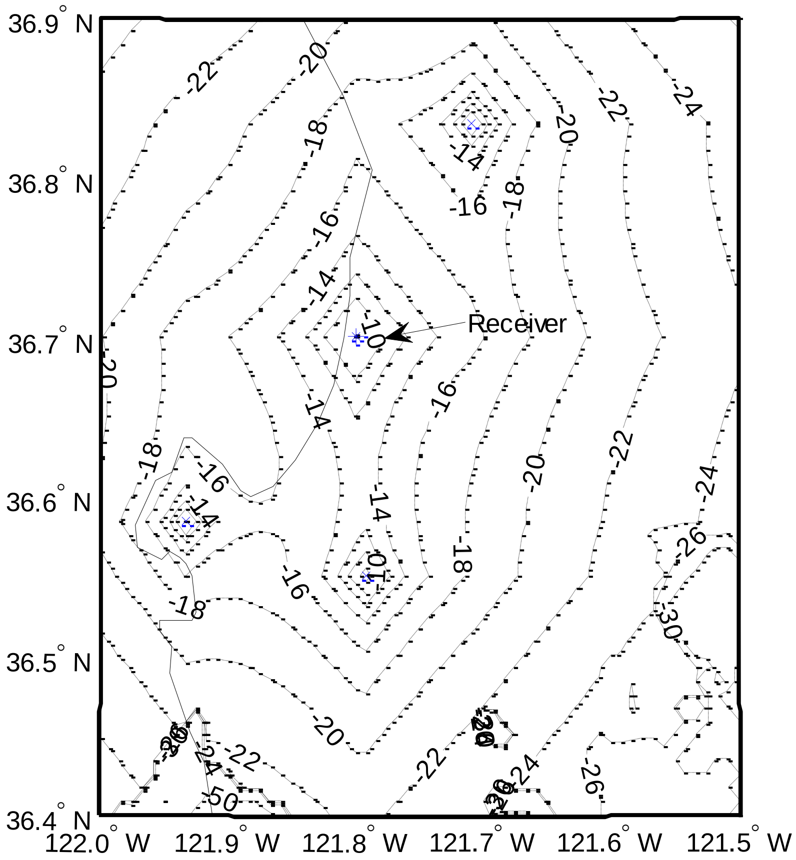

Figure 17. SNR levels in dB at 500m for a receiver optimally placed to detect targets at 500m.

As the target altitude to which the receiver position is optimized to detect changes, the optimal location for the receiver changes as well. In Figure 18, the optimal positions are plotted for various target altitudes. The subscript indicates the altitudes in meters to which that receiver position is optimal.

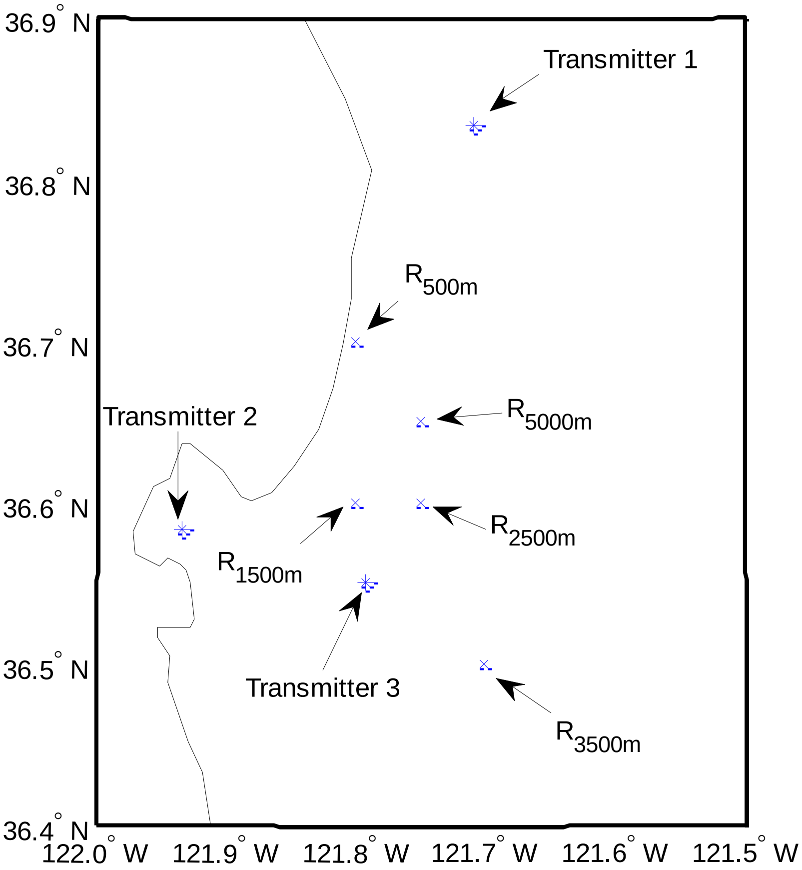

Figure 18. Optimal receiver positions for various target altitudes.

It appears that at lower altitudes, LOS considerations heavily influence optimal receiver placement. Positions near the center of the transmitter geometry are favored when target altitudes are below the highest terrain features. Barring terrain obstacles in the center of the AOI, this placement ensures that LOS can be established with the maximum number of transmitters possible while maintaining low path loss. This is clearly seen in the placement of the receiver for the target altitude of 500 meters.

As target altitudes increase toward the maximum terrain elevation, optimal positions for receivers gravitate toward areas of increased elevation as shown by positions for 1500 and 2500 meters. The increased elevation alleviates LOS blockages while lowering path loss due to spreading of the signal. This transition toward higher elevations for receiver positions is highlighted at the position denoted for 3500 meters. This location corresponds to the area of highest elevation in the AOI.

A critical transition is made as target altitude continues to increase. The benefits of increased elevation on reducing path loss are eventually negated by the effects of transmitter geometry and proximately to the edge of the AOI. At the position marked 5000 meters, the optimal receiver position derived as the center of the AOI. This marks the altitude where increased receiver elevation no longer overcomes the path loss due to distances between the transmitters and receiver to targets along the borders of the AOI.

Information gained from the algorithm's LOS calculations can be used to determine areas of zero coverage. Terrain features that block line of sight either from the transmitter to the target or from the target to the receiver represent areas of concern that must be addressed by system operators. A receiver positioned to optimally detect a target at 500 meters has no coverage due to LOS blockages in the areas depicted with gray shading in Figure 19.

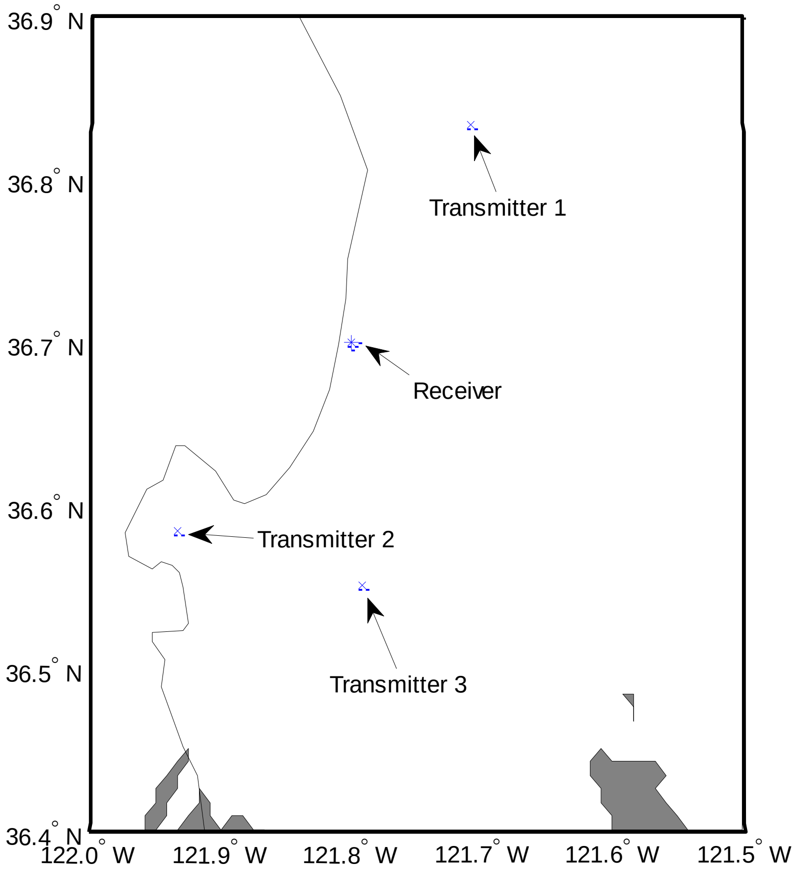

Figure 19. Areas of blocked LOS for receiver positioned to detect targets at 500 meters.

Once optimal placement for a receiver is derived, information pertaining to SNR levels may be used to differentiate which areas a receiver may have a higher or lower chance of detecting targets. Arbitrary approach routes were chosen for the Monterey Regional Airport. The approaches are illustrated in Figure 20 and represent the cardinal headings north, south, east, and west.

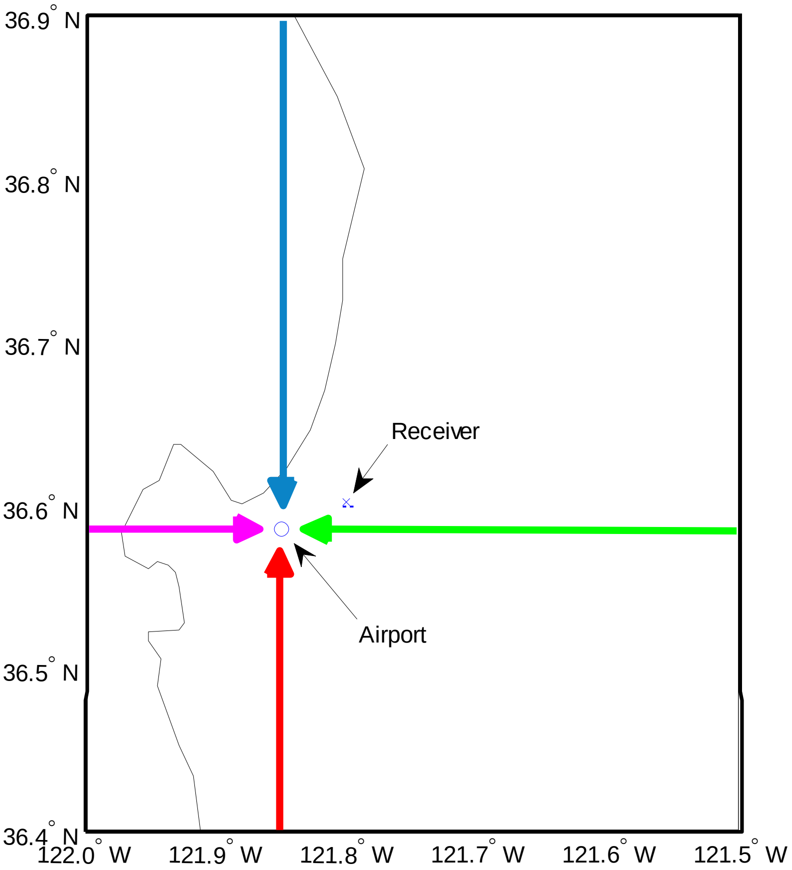

Figure 20. Monterey Regional Airport showing arbitrary approaches along cardinal headings.

Using the signal levels obtained when the optimal receiver positions were derived, the SNR levels along each of these routes can compared for a target at 1500 meters. It is expected that the peak SNR levels will be highest for the approaches from the north and east as these routes pass closest to the receiver. It can be seen on Figure 21 that the peak SNR along the approach from the west is significantly higher than that of the eastern approach. This is likely caused by the proximity of transmitter 2 to the western route's approach corridor. The approach from the south demonstrates the lowest SNR levels of the four routes until 5 kilometers away from the airport when it matches the levels of the western approach. These results show signal levels along specific flight paths as they are measured for a target at a stationary altitude. Changing the program input for a different target altitude will yield different results. As target altitude increases, the difference in signal between the various routes of approach will decrease as the influence of path loss becomes greater that network geometry.

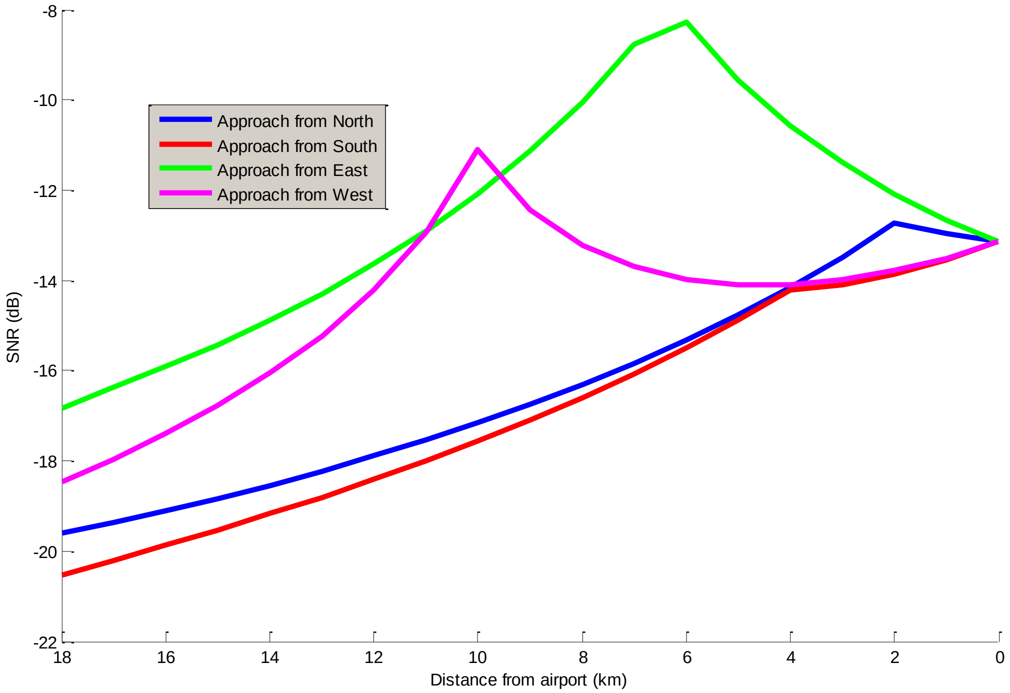

Figure 21. SNR levels in dB along cardinal approaches to Monterey Regional Airport.

Information obtained from results such as Figure 20, can be useful in determining which sectors have the highest or lowest probability of detection for targets along those approach corridors. In order to better monitor air traffic from a specific direction, it may be necessary to alter receiver positions to increase the received signals along the desired route. Additionally, alternate means of tracking may be necessary along routes which have lower coverage. The data depicted in these results is useful but it is understood that the algorithm output requirements may change according to the desired use of the information.

The current algorithm is designed to handle the inclusion of many transmitters and receivers in its computations, but the results listed previously are limited to scenarios with few transmitter/receiver pairs. The processing time for the algorithm increases linearly with the number of included transmitters and increases as the square of the number of receivers. While it is possible to make these calculations for all available transmitters and a varied number of receivers, processing time should be taken into account and a reasonable number chosen.

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V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

A. CONCLUSION

In this thesis, a model for predicting the optimal placement of passive coherent locator systems was presented. This method uses MATLAB to analytically determine signal-to-noise ratios throughout an area of interest for a given set of transmitters and possible receiver positions. The optimal placement is derived by comparing the SNR levels generated for each receiver position. Terrain information gathered from DTED ensures factors such as line-of-sight and antenna elevation create a realistic output for determining optimal placement.

The model run time is sensitive to the number of transmitters and receivers in the desired network as well as the requested geographic resolution of optimal positioning for the receivers. The inclusion of additional factors will increase the computational run time.

Changes in signal coverage for varying target altitudes as well as the factors contributing to optimal placement were explored. In addition, network geometries for more than one receiver were derived. It was demonstrated that the optimal placement for these receivers is effected by whether they are placed consecutively or concurrently. Furthermore, the model is flexible enough take into account the effects on area coverage of one or more transmitters being rendered inoperable. There are, however, aspects which could be refined and expanded upon. Some of these are discussed in the following section.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Radar Parameters and Diffusion

The model utilized factors such as line-of-sight, power, and path spreading loss, but we did not take other environmental factors into account. Geographical and meteorological features present in specific areas cause conditions affecting attenuation such as ducting and scattering of signals. In addition, terrain data in our model was used to properly predict possible receiver elevations and for line-of sight determination.

Diffusion of signals around and over terrain features was not taken into account. The inclusion of atmospheric attenuation and multi-path signals may also increase future understanding of optimal receiver placement. Further studies might enhance the model by incorporating these factors.

2. Field Test

The methodology presented in this thesis provides an analytical basis for determining optimal placement for PCL systems. Empirical data gathered from field testing would be extremely useful in refining and validating the model.

3. Program Interface

The current model requires input changes to be modified within the MATLAB script file. Familiarity with the MATLAB computing environment is required. Developing more user-friendly ways to interact with the model would further increase its usefulness to intended users.

4. Computational Efficiency

Deriving optimal receiver placement using this method can be computationally intensive for larger areas with many transmitters. Compiling the MATLAB code increases the speed at which the output is obtained, but other methods of decreasing program run times should be explored. Pre-calculated matrices for distance between grid points and transmitters may increase efficiency. Additionally, consideration should be given to utilizing other programming languages and tools to maximize operability.

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