HEURISTIC APPROACH TO OPTIMAL RECEIVER PLACEMENT FOR GPS-BASED BI-STATIC RADAR IN AMERICAN COASTAL WATERS

THESIS

Brandon J. Hufstetler, Capt, USAF

AFIT-ENS-MS-20-M-#

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Brandon J. Hufstetler, B.S.M.E.

Capt, USAF

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Brandon J. Hufstetler, B.S.M.E.
Capt, USAF

Committee Membership:

Lt. Col. Bruce A. Cox, Ph.D.
Chairman

Dr. Brian J. Lunday, Ph.D.
Reader

Dr. Julie A. Jackson, Ph.D.
Reader

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Abstract

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HEURISTIC APPROACH TO OPTIMAL RECEIVER PLACEMENT FOR GPS-BASED BI-STATIC RADAR IN AMERICAN COASTAL WATERS

I. Introduction

1.1 Background

Existing reliable transmission sources of opportunity provide an environment where bistatic radar can be employed cheaply and covertly. Passive coherent location (PCL) has demonstrated its usefulness in identifying targets of interest without compromising the location of the detector. With a omnipresent transmission source, such as the Global Positioning System (GPS) satellite constellation, it is possible to execute PCL globally with modern technology. One area where GPS based PCL may be of interest is the detection of smuggling aircraft traveling between North and South America. Early identification of uncooperative aircraft will provide authorities with a larger opportunity to interdict these aircraft.

The quantity and location of sensors to provide an adequate probability of detection for all targets is a simple geometry problem when not considering budgetary constraints. Describing the deployment of equipment for this task as an optimization problem with competing goals of minimizing cost and maximizing probability of detection lies in a class of known Non-Deterministic Polynomial-Time Hard (NP-Hard) problems. This class of problems are not solvable to optimality in a reasonable amount of time, so heuristic methods are employed to provide good solutions, although not guaranteed to be optimal, in a short amount of time.

1.2 Problem Statement

Annually XX aircraft traffic XX lb of illegal goods from South America to North America. Current interdiction methods require near real time information about shipments underway for successful interception. Radar and observational sources are limited and costly. Currently the US Coast Guard employs XX ships and XX aircraft with a footprint of XX. There are not enough resources available to identify and track all nefarious aircraft. This goal of this paper is to describe a deployment of GPS sensors to act as the receive antennas for a bistatic radar system that uses the forward scatter phenomenon to locate target aircraft with a reasonable probability of detection and for an acceptable cost.

1.3 Research Questions

- Can an uncooperative aircraft be identified or tracked using only GPS receivers and software via forward scatter bistatic radar methods?
- Can a heuristic method solve for an acceptable set covering solution to maximize probability of detection and minimize cost for a GPS based bistatic network.

1.4 Approach

This research develops a mathematical model to track the radar shadows created by an aircraft as it flies under GPS satellites. By implementing various heuristic search methods, the research solves a set covering problem of identifying an optimal quantity and location of receive antennas to maximize the probability of detection of an aircraft while minimizing the quantity of receivers. A simulation of trafficking routes and flights is developed to test the effectiveness of the system under multiple satellite and target geometries.

1.5 Summary

Chapter II details current known trafficking routes and interdiction techniques as well as the physics of the bistatic radar system proposed to augment current capabilities. It also gives background on heuristic search methods to optimize the stated objectives and describes the modeling techniques employed to evaluate the system. Chapters III - V elaborate on the topic being discussed.

II. Literature Review

2.1 Overview

This paper was initially intended to focus on observation of air and maritime smuggling vessels in support of US Coast Guard trafficking interdiction operations [18]. However, further investigation into the topic of backscatter bistatic radar for the detection of small smuggling vessels [21] [4], it was determined to be outside the scope of this document. This report will focus on the detection of aircraft expected of transporting illegal goods.

2.2 Trafficking Routes

The Caribbean Sea offers smugglers a largely unguarded passageway between South and North America [5] [1]. Many of the trafficked goods eventually make their way to the United States of America. Section 888 of the Homeland Security Act of 2002 categorizes "drug interdiction" as one of the United States Coast Guard's (USCG) Homeland Security Missions [23]. The methods by which the USCG carries out this mission are outlined in Coast Guard Joint Publication 1-0 [30]. Resources for drug interdiction are limited and unable to fully combat the problem of detecting and intercepting nefarious aircraft en route [6]. This thesis seeks to outline a fiscally responsible method for detecting aircraft as they cross the Caribbean in support of the USCG's drug interdiction mission.

2.3 Bistatic Radar

Advances in bistatic radar and the proliferation of electromagnetic transmission sources has created a global environment ripe for passive radar observation [14] [34].

Bistatic radar, specifically with GPS as the transmission source has already demonstrated potential for providing altitude measurements [22] [20], topology mapping [8] [2], synthetic aperture radar [7], ocean level monitoring [11], target tracking [33], wind speed measurements [31] [27], and passive coherent location [17] [19].
While it is physically possible for GPS to be used in a backscatter bistatic configuration [32] [16], the weak signal power at the receiver makes target identification and tracking very difficult [9] [21]. It is far easier to identify when a target enters the detection region using a forward scatter configuration [10]. With a sufficiently large and adequately placed sensor array, GPS can be used for aircraft detection in a bistatic radar system [3] [24].

2.4 Heuristic Approaches

The competing goals of maximizing probability of detection and reducing cost is an optimization problem. Most optimization problems are solvable through deterministic means in a reasonable amount of time but some combinatorial problems, like the one being proposed here, require too much time or computational effort to be solved to optimality. In these cases a heuristic search method can be employed to get an acceptable solution in a reasonable amount of time [26]. This type of set covering geometry optimization problem has been attempted before in a bistatic system configuration [25], but not with the same requirements as outlined in this thesis.

2.5 Conclusion

To determine an acceptable system configuration to augment the USCG drug interdiction mission, capable of providing a reliable probability of detection at a reasonable cost, the author of this thesis will employ a variety of methods. A simulation will be used to used to model the behavior of drug smuggling aircraft. A mathematical model will be developed to model the satellite/aircraft/receiver geometries over the time frame of the simulation. Finally, a metaheuristic will be tailored to solve the set covering problem of where to employ GPS receivers for the forward scatter bistatic radar network.

III. Methodology

3.1 Overview

The methodology used in this thesis is broken down into three main sections. First, the physical properties of the forward scatter bistatic radar system will be calculated. The radar detection zone will be modeled as a simple cone emanating from a target aircraft with some expansion angle extending for some distance. This represents a significant simplification of the actual radar mechanism but is adequate for the purpose of evaluating the optimization technique that is the focus of this thesis.

Second, the computer model of the system is described. The model consists of scenarios built in Software Toolkit (STK), a product from Analytical Graphics, Inc (AGI). each scenario is comprised of a set of aircraft flying on potential paths from South America to North America via the Caribbean Sea, the entire GPS constellation, and a set of GPS receivers located on the surface of the sea. The scenarios are designed in the Python programming language and executed in STK to calculate an objective function value.

Finally, the optimization function is delineated. The goal of this thesis is to use a metaheuristic to determine the best locations for a set of GPS receivers in order to minimize the probability that an aircraft is able to travel along any of the potential routes undetected. An initial pool of solutions is evaluated and a genetic algorithm (GA) is used to determine the following pool of solutions using the objective function values. This will require a lot of computational power, so a high powered computer (HPC) is used to reduce the evaluation time.

3.2 Radar Properties

The objective function of the optimization algorithm developed in this thesis is tallies the number of aircraft that are able to complete their entire flight unobserved by a sensor. An aircraft is considered to be observed when it creates a measurable signal amplitude response at the receiver. This signal amplitude response occurs when the aircraft is near enough to the line-of-sight vector connecting any GPS satellite to a receiver. To compute whether or not an aircraft has been observed, a detection region is defined for each transmitter-receiver combination. If an aircraft enters this detection region, it is labeled as detected. Only one detection is required along the flight of each target aircraft. This section elaborates on the numerical definition of the detection region.

The detection region is first defined from the perspective of an aircraft. This region models the forward scatter bi-static radar effect and is analogous to a shadow being cast by the target aircraft. This shadow is simulated mathematically as a cone originating at a target. The shadow cone expands away from the target along the directional vector from the transmitter to the target. The cone's limits are defined such that any receiver positioned inside of the shadow cone is considered to be able to detect the target solely on the change in transmitter signal amplitude measured at that receiver. Two parameters will be used to model each detection cone in this thesis: the cone angle, θ, which is the angle of expansion of the cone away from the target, and maximum distance to the receiver $D_{r_{\max}}$, which is determined by the signal reduction as the cone expands and the shadow diffuses. The next few paragraphs provide calculations for the cone angle and the maximum distance that the cone extends.

Figure 1 illustrates the geometry being modeled here. Only four metrics are necessary to determine the probability of detection of the target via forward scatter radar. These metrics are the baseline, L, which is the distance between the transmitter and receiver, the distances from the target to the transmitter and receiver, D_t and D_r respectively, and the bistatic angle, β.

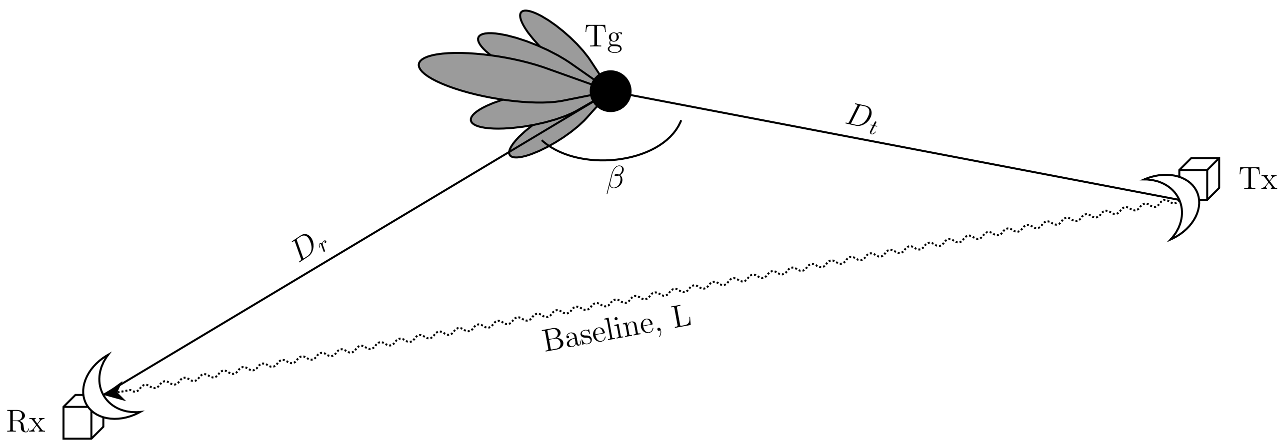

Figure 1. Basic Forward-Scatter Bistatic Radar Geometry

Channel	Wavelength, λ (m)	Frequency (MHz)	Bandwidth ΔF (MHz)	Transmitter Power at Surface (dBW)
L1	0.1905	1575.42	20.46	-161.5
L2	0.2445	1227.60	20.46	-164.5
L5	0.2548	1176.45	24	-157.9

Table 1. GPS Signal Properties

Table 1 shows the properties for three signals broadcast by GPS Block II obtained from the GPS technical documents [12][13]. The three signals are referred to as Link 1 (L1), Link 2 (L2), and Link 5 (L5). A comparison of each GPS link as the transmission source for a bistatic radar was performed by Behar [3] and Sakhawat[28]. They show that the L5 signal is the superior choice for a bistatic radar configuration because the L5 signal is four times stronger than the L1 signal and the bandwidth is ten times wider than the bandwidth of the L1 signal. This thesis uses their recommendation and analyzes only L5 as the transmission source to model the detection region.

The wavelength of a transmitted signal, the size of the target, and the distances that separate the target from the transmitter or receiver are used to determine what kind of scattering effect the target has on the signal. According to Hecht [15], there are two significant types of scattering that may occur.

The first type of scattering is Fresnel diffraction, which occurs in the near-field, and is characterized by constructive and destructive interference patterns caused by obstacles in the signal path. Ufimtsev [29] shows that this type of diffraction is more difficult to model because the wavefront must be modeled as spherical rather than planar. This diffraction region is even more complicated in the forward scatter bistatic configuration because of the interaction of shadow radiation with the original waves. Also, the phase differences are non-constant for a curved wavefront causing the amplitudes of each wavefront to vary from point to point, increasing the complexity of the model.

The second type of scattering is Fraunhofer diffraction, or far-field diffraction, which occurs when the distances from the target to the transmitter or receiver differ much less than the wavelength of the signal. In Fraunhofer diffraction, the propogation patterns for each wavelet can be treated as parallel.

The Fresnel Number, F, as defined by Hecht, is used to determine in which diffraction region a target resides. A Fresnel number greater than 1 is in the Fresnel region and less than one is in the Fraunhofer region. The Fresnel number is calculated using Equation 1 where a is the largest single dimension of the target and λ is the wavelength of the signal. The targets under consideration are Cessna-172 aircraft with height $h = 2.72$ m and length $l = 8.3$ m.

$$F = \frac{a^2}{D_r \lambda} \tag{1}$$

The radar equations used in this thesis assume that the target is always flying in the Fraunhofer diffraction zone. To prove this, the boundary between the near- and far-field is found by setting the Fraunhofer number in Equation 1 to 1 and solving for the distance. Since the transmitter is located in a Medium Earth Orbit and the target is in the Earth's atmosphere, it is assumed that the receiver will always be closer to the target than the transmitter. Thus, only the distance between the target and the receiver, D_r, will be considered. Equation 2 is used to solve for the boundary between Fresnel and Fraunhofer diffraction regions. The targets will be in the Fraunhofer diffraction zone if their distances to each receiver is greater than $D_{r,\text{boundary}}$

$$D_{r,\text{boundary}} = \frac{a^2}{\lambda} \tag{2}$$

$$D_{r,\text{boundary}} = \frac{8.3^2}{0.2548} \approx 270 \text{ m}$$

According to Equation 2, the boundary between the near and far-field is approximately 270m. The targets in this model are aircraft being flown at an altitude of 3050m and the receivers are located at sea level, thus the forward scatter radar equations for the Fraunhofer diffraction zone are appropriate.

Griffiths [14], Hecht[15], and Willis [32] define the bistatic metrics required for this model. First, the bistatic forward scatter radar cross section (RCS), σ_f, as measured in the Fraunhofer diffraction zone is shown in Equation 3, where A is the cross sectional area of the target. The forward scatter bistatic RCS is one of the parameters required to determine the change in signal amplitude caused by the target. Second, the cone angle of the detection zone is equal to the total angular width of the main diffraction lobe plus two side lobes of the signal scattered by the target. The cone angle is calculated using Equation 4.

$$\sigma_f = \frac{4\pi A^2}{\lambda^2} \tag{3}$$

$$\sigma_f = \frac{4 \times \pi \times (8.3 \times 2.72)^2}{0.2548^2} = 98651.8 \text{ m}^2$$

Evaluating 3 shows that the aircraft in a forward scatter bistatic radar configuration create an incredibly large RCS. The ability to detect a target with radar increases with RCS.

One of the advantage of this large RCS is that small targets are easier to detect in a forward scatter configuration. Another advantage is that a target may be detected at farther distances from the receiver than in a back scatter configuration.

Among the disadvantages is that other small objects, such as birds, may also have a large RCS, causing a high false positive detection rate. Another disadvantage is that the forward scatter effect is only detectable in a narrow area extending out from the target. The spread of this area is directly related to the wavelength of the signal. According to Davis [9], GPS L5 is operating at a much smaller wavelength than traditional forward scatter bistatic radar systems, restricting the detectable region even further. Equation 4 is used to calculate the cone angle, or spread, of this detectable region.

$$\theta_f = \frac{5\lambda}{a} \tag{4}$$

$$\theta_f = \frac{5 \times 0.2548}{8.3} = 0.153494 \text{ rad}$$

$$\theta_f = 0.153494 \times \frac{180}{\pi} \approx 8.8 \, \text{deg}$$

Solving Equation 4 shows that the forward scatter radar effect casts an approximately 8.8 degree conical shadow along the pointing vector from the transmitter to the target.

As this cone expands away from a target, the forward scatter radar effect diffuses. Thus, the strength of the signal amplitude drop diminishes with distance from the target. According to Behar [3], the bistatic radar equation shown in Equation 5, provided by Willis [32] can be simplified and rewritten for the forward scatter case.

Willis proposes Eq 5

$$(D_r D_t)_{max} = \left[\frac{P_t G_t G_r \lambda^2 \sigma_b F_t^2 F_r^2}{(4\pi)^3 K T_s B_n (SNR)_{min} L_t L_r} \right]^{\frac{1}{2}} \tag{5}$$

Working through Behar's logic, and modeling each target as an transmission source of shadow radiation, the power spectral density (PSD) at the output of an omnidirectional antenna near the Earth's surface can be determined using Equation 6.

$$D_1 = \frac{4\pi P_t}{\lambda^2} \tag{6}$$

Where P_t is the GPS L5 signal power found in Table 1. The power of the signal reflected from the target is found using Equation 7.

$$P_{tg} = \frac{4\pi P_t \sigma_b}{\lambda^2} \tag{7}$$

The signal power at the output of the receiver antenna depends on the antenna gain per Equation 8.

$$P_{rec} = \frac{P_t G_r \sigma_b}{4\pi D_r^2} \tag{8}$$

Sakhawat [28] and Behar calculate the receiver noise, N_r to be approximately -131 dB, using equation 9.

$$N_r = kT\Delta F = KTB_n \tag{9}$$

Combining Equations 8 and 9 to determine the Signal to Noise Ratio (SNR) at the receiver, SNR_{rec} produces Equation 10.

$$SNR_{\mathrm{rec}} = \frac{P_{\mathrm{rec}}}{N_r} = \frac{P_t G_r \sigma_b}{4\pi N_r D_r^2} \tag{10}$$

Both authors further postulate that the signal could be improved through circular cross-correlation by multiplying by a signal processing gain, G_{SP}, calculated using Equation 11 where T_{Q5} is the period of the Q5 component of the GPS L5 signal. GPS L5 has two components that could be used, an I component and a Q component. The I component is modulated by a 10-bit Neuman-Hoffman code and the Q component is modulated by a 20-bit Neuman-Hoffman code. Each bit takes 1 ms, resulting in a 20 ms period of the Q component.

$$G_{SP} = \Delta F T_{Q5} \tag{11}$$

Substituting Equations 11 and 3 into Equation 10 yields Equation 12.

$$SNR_{\text{det}} = \frac{P_t G_r (hl)^2 G_{SP}}{\lambda^2 N_r D_r^2} \tag{12}$$

Solving Equation 12 for D_r produces Equation 13.

$$D_r = \frac{hl}{\lambda}\sqrt{\frac{P_t G_r G_{SP}}{N_r SNR_{\text{det}}}} \tag{13}$$

Both authors conclude that a minimum signal-to-noise ratio to detect aircraft with a forward scatter bistatic radar configuration using GPS L5 as the transmission source is 20 dB. Solving Equation 13, Behar calculates that for a Cessna-172 with $h = 2.72$ m, $l = 8.3$ m, $G_r = 25$ dB, and $SNR_{min} = 20$ dB, the maximal range of detection, $D_{r,max} = 7112$ m.

In summary, for each GPS satellite in view of a target aircraft, a detectability zone will be represented as a cone emenating from the aircraft with an angle of 8.79 degrees and extending for 7112 m.

3.3 Model

3.4 Optimization

IV. Analysis

V. Backscatter Augmentation and Analysis

VI. Conclusion and Future Research

Appendix A. Theses Examined

1. Comparison of Novel Heuristic and Interger Programming Schedulers for the USAF Space Surveillance Network - Kanit Dararutana and Dr. Cox

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Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way
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Department of Engineering Physics
2950 Hobson Way
WPAFB OH 45433-7765
DSN 271-0690, COMM 937-255-3636
Email: amy.magnus@afit.edu

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This primer aids the AFIT student in generating the first draft of their thesis using LaTeX. The primer is produced according the tenets described within the document. All source code is provided in a zip file posted to L:\Courses\PHYS\LaTeX. The file structure of this zip file demonstrates a practical way to organize a thesis with its supporting materials and—further—illustrates how your document can be produced with version control.

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