Skip all front matter: Jump to Page 1

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **Expanding the Use of Time/Frequency Difference of Arrival Geolocation in the Department of Defense**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **RAND Corporation,1776 Main Street, P.O. Box 2138,Santa Monica,CA,90407-2138**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The U.S. Department of Defense (DoD) faces a tightening budget in the coming years. Despite the lean budget years, unmanned aircraft systems (UAS) are expected to be a priority. Secretary of Defense Leon Panetta has pledged to maintain or even increase spending in critical mission areas, such as cyber offense and defense, special operations forces, and UAS (Shanker and Bumiller 2011). Due to their usefulness for intelligence collection in irregular warfare (IW) and counterinsurgency (COIN), UAS were quickly fielded and sent to theater without analysis of how their intelligence sensors complemented each other (Isherwood 2011). There are ways for DoD to improve the methods of employment and the integration of multi-intelligence capabilities on assets to better leverage the systems it currently owns. The general aim of this research is to explore an area in which DoD can operate ?smarter? with its proliferating UAS fleet. Specifically, this research investigates how DoD can better leverage UAS and improve multi-intelligence capabilities by expanding its geolocation capacity through the use of time/frequency-difference-ofarrival (T/FDOA) geolocation on UAS. The research sheds light on important questions that need to be answered before investing in T/FDOA-capable UAS. I first demonstrate the potential of T/FDOA geolocation in the context of how we use UAS today. I then show what some of the ?costs? of adding a T/FDOA geolocation capability to UAS might be. Finally, I explore how T/FDOA geolocation could improve multi-intelligence operations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**123**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

This product is part of the Pardee RAND Graduate School (PRGS) dissertation series. PRGS dissertations are produced by graduate fellows of the Pardee RAND Graduate School, the world's leading producer of Ph.D.'s in policy analysis. The dissertation has been supervised, reviewed, and approved by the graduate fellow's faculty committee.

DISSERTATION

Expanding the Use of Time/Frequency Difference of Arrival Geolocation in the Department of Defense

Kimberly N. Hale

This document was submitted as a dissertation in September 2012 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the Pardee RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of Brien Alkire (Chair), Carl Rhodes, and Sherrill Lingel.

RAND PARDEE RAND GRADUATE SCHOOL

The Pardee RAND Graduate School dissertation series reproduces dissertations that have been approved by the student's dissertation committee.

Published 2012 by the RAND Corporation
1776 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
1200 South Hayes Street, Arlington, VA 22202-5050
4570 Fifth Avenue, Suite 600, Pittsburgh, PA 15213-2665
RAND URL: http://www.rand.org
To order RAND documents or to obtain additional information, contact
Distribution Services: Telephone: (310) 451-7002;
Fax: (310) 451-6915; Email: order@rand.org

Abstract[1]

The U.S. Department of Defense (DoD) faces a tightening budget in the coming years. Despite the lean budget years, unmanned aircraft systems (UAS) are expected to be a priority. Secretary of Defense Leon Panetta has pledged to maintain or even increase spending in critical mission areas, such as cyber offense and defense, special operations forces, and UAS (Shanker and Bumiller 2011). Due to their usefulness for intelligence collection in irregular warfare (IW) and counterinsurgency (COIN), UAS were quickly fielded and sent to theater without analysis of how their intelligence sensors complemented each other (Isherwood 2011). There are ways for DoD to improve the methods of employment and the integration of multi-intelligence capabilities on assets to better leverage the systems it currently owns.

The general aim of this research is to explore an area in which DoD can operate “smarter” with its proliferating UAS fleet. Specifically, this research investigates how DoD can better leverage UAS and improve multi-intelligence capabilities by expanding its geolocation capacity through the use of time/frequency-difference-of-arrival (T/FDOA) geolocation on UAS. The research sheds light on important questions that need to be answered before investing in T/FDOA-capable UAS. I first demonstrate the potential of T/FDOA geolocation in the context of how we use UAS today. I then show what some of the “costs” of adding a T/FDOA geolocation capability to UAS might be. Finally, I explore how T/FDOA geolocation could improve multi-intelligence operations.

[1] This manuscript was formatted assuming that the reader would have access to a color copy. Interested readers who obtain a copy that is difficult to read may contact the author at hale.kimberly@gmail.com for a color copy.

SUMMARY

The U.S. Department of Defense (DoD) faces a tightening budget in the coming years. Despite the lean budget years, unmanned aircraft systems (UAS) are expected to be a priority. Secretary of Defense Leon Panetta has pledged to maintain or even increase spending in critical mission areas, such as cyber offense and defense, special operations forces, and UAS (Shanker and Bumiller 2011). Due to their usefulness for intelligence collection in irregular warfare (IW) and counterinsurgency (COIN), UAS were quickly fielded and sent to theater without analysis of how their intelligence sensors complemented each other (Isherwood 2011). There are ways for DoD to improve the methods of employment and the integration of multi-intelligence capabilities on assets to better leverage the systems it currently owns.

The general aim of this research is to identify and explore an area in which DoD can operate "smarter" with its proliferating UAS fleet by leveraging geolocation. Geolocation is the identification of the physical location of an object. Specifically, this research investigates how DoD can better leverage UAS and improve multi-intelligence capabilities by expanding its geolocation capacity through the use of time/frequency-difference-of-arrival (T/FDOA) geolocation on UAS.

I focused on the geolocation of radio frequency (RF) emitters used in a military context. There are several different techniques to geolocate an emitter. This research investigates the use of T/FDOA geolocation on UAS and sheds light on important questions that need to be answered before investing in a T/FDOA capability for UAS.

To perform this research, I created a tool to estimate the accuracy of T/FDOA geolocation to quantify its effectiveness. The T/FDOA Accuracy Estimation Model takes a scenario for geolocation and estimates the accuracy of the cooperative T/FDOA technique, including the impact of various sources of errors. Quantifying the effectiveness of T/FDOA geolocation allows this research to answer the proposed research questions. Beyond the analysis in this dissertation, the tool

would be useful for assessing the dominant factors in T/FDOA geolocation accuracy, which can inform decisions on choosing aircraft orbit geometries to optimize performance, technology investment decisions, and comparisons of the performance of T/FDOA with alternative geolocation techniques for specific applications.

I first demonstrate the potential of T/FDOA geolocation in the context of how we use UAS today to show what a signals intelligence (SIGINT) system capable of T/FDOA would add. I contrast the T/FDOA technique with direction finding, which is the common geolocation technique used in the military today. T/FDOA geolocation is useful against many targets, particularly those in an IW/COIN environment that are difficult to geolocate using direction finding. Two of the major drawbacks to T/FDOA are the need for multiple platforms and the sensitivity to geometry. The drawbacks do not hinder employment of T/FDOA as a secondary capability on UAS.

I then show some of the requirements of adding a T/FDOA geolocation capability to UAS. Small changes are necessary to implement T/FDOA on UAS. The technology for T/FDOA-capable sensors already exists, and many UAS are nearly equipped to be capable. Today, one of the largest drivers of manpower for UAS is the processing, exploitation, and dissemination (PED) needed to turn the data collected into actionable intelligence. The manpower and cost implications appear to be small compared with the requirements to PED other sensors.

Finally, I explore how T/FDOA geolocation could improve multi-intelligence operations. Adding a SIGINT with T/FDOA capability to UAS instantly increases our ability to provide more information about targets by layering complementing intelligence, surveillance, and reconnaissance (ISR) sensors. T/FDOA geolocation provides high-accuracy geolocation very quickly, reducing the time delay between intelligence types and the area that a second intelligence, such as full-motion video (FMV), would need to search. For command, control, and communication (C3), the emerging ISR mission type orders (MTO) concept meets the C3 needs for T/FDOA geolocation in complex operating environments.

CONTENTS

Disclaimer..iii
Abstract..iii
Summary...iv
Contents..vii
Figures...ix
Tables..xi
Acknowledgments...xiii
Abbreviations...xv
1. Introduction...1
Problem Statement...1
Motivation and Background.....................................2
T/FDOA Implementation in the Military.........................9
Research Questions..11
Organization of the Dissertation..............................13
2. T/FDOA Accuracy Estimation Model...........................15
Measurement and Sources of Error..............................17
Problem Formulation...18
How the Tool Works..22
Examples of Tool..23
Example: Impact of Geometry 23
Example: Impact of Number of Receivers 25
Example: Impact of Measurement Errors 25
3. When Is T/FDOA Geolocation Useful?.........................29
A Contrast of Direction Finding and T/FDOA Geolocation........29
Types of Intelligence and Resulting Orbits....................34
Missions Have a Primary Intelligence Focus....................38
Scenario for Modeling Accuracies 38
Results from Orbit Geometries 42
Would UAS Operate Close Enough to Leverage T/FDOA?............45
Conclusion..51
4. What Is Needed to Use T/FDOA Geolocation?..................53
Equipment for Platforms to Be Capable of T/FDOA Geolocation...53
Requirements for T/FDOA 54
AT3 System 54
UAS Integration 57
Manpower for PED..64
CONOPs, Organization, and Tasks 65
PED Within Platform Crew 67
PED Within DART 68

Manpower and Costs Implications for Approaches 69
Conclusion...71

5. How Can T/FDOA Be Leveraged in Multi-Intelligence Operations?......73
Background for Multi-Intelligence Operations...................73
Impact of T/FDOA Geolocation...................................74
Operation with Direction Finding versus T/FDOA Geolocation ...74
Importance of Timing 76
Command, Control, and Communication............................77
What C3 Is Needed for Multi-Intelligence Operations with T/FDOA? 77
Using ISR MTOs 78
Conclusion...79

6. Conclusions and Recommendations...................................81

A. Direction Finding Model..85
Direction Finding...85
Theoretical Basis, the Stansfield Estimator.....................85
Errors..87
Model Implementation..88

B. Orbit Geometry Results...89
Scenario 1: Two Circular FMV Orbits.............................89
Scenario 2: One SAR, One Racetrack FMV..........................91
Scenario 3: SAR FMV 2 Cases Summary.............................93
Scenario 4: GMTI-FMV 1 Cases....................................95
Scenario 5: GMTI-FMV2 cases summary.............................97

C. CAP Allocation Model..100

D. Manpower Calculations...102

References...103

Figures

Figure 1.1 Aircraft Calculates LOBs along a Baseline 5
Figure 1.2 Signal May Have a Frequency Difference 6
Figure 2.1 Graphic Depiction of Tool Inputs and Outputs 16
Figure 2.2 Graph of TDOA and FDOA for Convexity Proof 20
Figure 2.3 Two Receiver Example with 1-Sigma Error Ellipse 24
Figure 2.4 Moving One Receiver for Poor Geometry 24
Figure 2.5 Adding a Receiver 25
Figure 2.6 Ellipse with Reduced Position Error 26
Figure 2.7 Ellipse with Reduced Velocity Error 26
Figure 2.8 Ellipse with Reduced Time Synchronization Error 27
Figure 3.1 Antenna Size vs Frequency 30
Figure 3.2 Time of Baseline impacts Direction Finding Accuracy 32
Figure 3.3 Range to Target Impacts Direction Finding Accuracy 33
Figure 3.4 SAR Requires a Straight Flight Path 35
Figure 3.5 GMTI Is Often an Elliptical Orbit 36
Figure 3.6 IMINT Does Not Dictate an Orbit 37
Figure 3.7 Racetrack Orbit for Road Surveillance and Circular Orbit for 360-degree Coverage of Compound 37
Figure 3.8 Operations Might Be in the same Area 39
Figure 3.9 Example of Geolocation Accuracies from Scenario 1 42
Figure 3.10 Histogram of Areas from Scenario 1 43
Figure 3.11 Results for 5 Scenarios: Percent Distribution of Error Ellipse Areas 44
Figure 3.12 Example Coverage with 10 CAPS 46
Figure 3.13 Area Covered by Line of Sight as Altitude Increases 46
Figure 3.14 Area Covered as CAPs Increase 47
Figure 3.15 Coverage for 5, 10, 15, and 20 CAPs at 20,000ft 48
Figure 3.16 Average Percentage of Targets Without Line of Sight at 20,000ft 49
Figure 3.17 Results of Geolocations from 15kft 50
Figure 3.18 Results of Geolocations from 30kft 50
Figure 4.1 Geolocation Error Ellipse Can Be Influenced by Location of GPS in Relation to Receiver 58
Figure 4.2 Size of Error Ellipse Increases as Position Error Increases59

Figure 4.3 Size of Error Ellipse Increases as Velocity Error Increases59
Figure 4.4 Typical Peak Data Rates for IMINT Sensors 60
Figure 4.5 Peak Data Rate as Urgency Requirement Changes 62
Figure 4.6 Peak Data Rate as Bandwidth Monitored Increases 63
Figure 5.1 Size of SIGINT Ellipse Impacts Time Needed to Find Target .75
Figure 5.2 Delay in Cross-cue Increases the Area Needed to Search 76
Figure A.1 Aircraft Calculates LOBs Along a Baseline 85
Figure A.2 Graphical Depiction of Direction Finding Model 88
Figure B.1 Example of Scenario 1: Two Circular FMV Orbits 90
Figure B.2 Histogram of Scenario 1 Error Ellipse Areas 90
Figure B.3 Example of Scenario 2: One SAR, One Racetrack FMV 92
Figure B.4 Histogram of Scenario 2 Error Ellipse Areas 92
Figure B.5 Example of Scenario 3: One SAR, One Circular FMV 94
Figure B.6 Histogram of Scenario 3 Error Ellipse Areas 95
Figure B.7 Example of Scenario 4: One GMTI, One Racetrack FMV 96
Figure B.8 Histogram of Scenario 4 Error Ellipse Areas 97
Figure B.9 Example of Scenario 5: One GMTI, One Circular FMV 98
Figure B.10 Graph of Scenario 5 Error Ellipse Areas 99
Figure C.1 CAP Model 100

TABLES

Table 1.1 Geolocation Contribution to Intelligence Tasks...............3
Table 1.2 Summary of Pros and Cons of Geolocation Techniques...........7
Table 2.1 Data for Error Model..18
Table 3.1 Line of Sight Limitations...................................40
Table 3.2 Scenarios for Orbit Geometries..............................40
Table 3.3 Orbit Inputs..41
Table 3.4 Other Model Parameters held Constant........................41
Table 4.1 System Parameters...53
Table 4.2 AT3 Sensor System...55
Table 4.3 UAS FMV Mission Crew Positions..............................67
Table 4.4 Manpower for T/FDOA PED.....................................69
Table 4.5 Costs for Manpower for T/FDOA PED in $100,000...............70
Table 5.1 Intelligence Types Provide Different Information About the Target 73
Table B.1 Orbit Parameters for Scenario 1.............................89
Table B.2 Orbit Parameters for Scenario 2.............................91
Table B.3 Orbit Parameters for Scenario 3.............................93
Table B.4 Orbit Parameters for Scenario 4.............................95
Table B.5 Orbit Parameters for Scenario 5.............................97

Acknowledgments

This research was supported by funding from RAND Project AIR FORCE (PAF) and the RAND National Defense Research Institute’s Acquisition, Technology, and Logistics Policy Center. I would like to thank my dissertation committee, Brien Alkire (chair), Carl Rhodes, and Sherrill Lingel, as well as Sarah Robinson for acting as the outside reader. I received help and advice from many outside of my committee, including Natalie Crawford, Ray Conley, and Col Mark Braisted. Asha Padmanabhan was instrumental in connecting me with contacts within the Air Force. I would like to thank the members of the 163rd at March Air Reserve Base, especially DeltaFox and others around the Air Force that have given me their insights. Finally, I am very grateful to my family and friends for supporting me throughout these three years.

ABBREVIATIONS

AOA	angle of arrival
AT3	Advanced Tactical Targeting Technologies
BAMS	Broad Area Maritime Surveillance
C2	command and control
C3	command, control, and communication
CAN	correlation analyst
CAOC	Combined Air Operations Center
CAP	combat air patrol
CEP	circular error probable
CONOPs	concept of operations
DARPA	Defense Advanced Research Projects Agency
DART	DCGS Analysis and Reporting Team
DCGS	Distributed Common Ground System
DIRLAUTH	direct liaison authority
DoD	U.S. Department of Defense
EIRP	effective isotropic radiated power
EO	electro-optical
FDOA	frequency difference of arrival
FMV	full-motion video
GEOINT	geospatial intelligence
GMTI	ground moving target indicator
HF	high frequency
HUMINT	human intelligence
HTS R7	Harm Targeting System Revision 7
IA	imagery analyst
IED	improvised explosive device
IMINT	imagery intelligence
IMS	imagery mission supervisor
INS	Inertial Navigation System
IR	infrared
IRE	Imagery Report Editor
ISR	intelligence, surveillance, and reconnaissance

ISRD	ISR Division
JTIDS	Joint Tactical Information Distribution System
LOB	line of bearing
MASINT	measurement and signature intelligence
MOC	mission operations commander
MP	mission planner
MSA	multi-source analyst
MTO	mission type order
NASIC	National Air and Space Intelligence Center
NIB	non-interference basis
OSINT	open-source intelligence
PLLS	Precision Location and Strike System
SAM	surface-to-air missile
SAR	synthetic aperture radar
SATCOM	satellite communication
SIDO	senior intelligence duty officer
UHF	ultra high frequency
PED	processing, exploitation, and dissemination
QDR	Quadrennial Defense Review
RF	Radio Frequency
SATCOM	satellite communication
SIGINT	signals intelligence
SWAP	size, weight, and power
SNR	signal-to-noise ratio
TDOA	time difference of arrival
UAS	unmanned aircraft systems
VHF	very high frequency

1. Introduction

Problem Statement

The U.S. Department of Defense (DoD) faces steep budget declines over the next decade. Military acquisition and research, development, test, and evaluation will likely be the hardest hit by spending cuts (Eaglen and Nguyen 2011). Despite the lean budget years, unmanned aircraft systems (UAS) are expected to be a priority. Secretary of Defense Leon Panetta has pledged to keep the spending constant or even increase spending in critical mission areas, such as cyber offense and defense, special operations forces, and UAS (Shanker and Bumiller 2011). As part of the plus-up to fight the wars in Afghanistan and Iraq, DoD invested heavily in UAS for intelligence, surveillance, and reconnaissance (ISR). The result was quickly fielding and sending to theater complex systems. The UAS inventory surged from 163 in February 2003 to over 6,000 today (Bone and Bolkcom 2003; Kempinski 2011). These UAS were rapidly amassed and employed, with very little analysis of how the different ISR sensors complemented each other (Isherwood 2011). There are ways for DoD to improve the methods used to employ UAS and the integration of multi-intelligence capabilities on assets to better leverage the systems it currently owns. The general aim of this research is to identify and explore one area in which DoD can operate "smarter" with its proliferating UAS fleet by leveraging geolocation. Geolocation is the identification of the physical location of an object. This research focuses on a method of employment coupled with small technological changes that can significantly improve the geolocation capabilities of DoD.

Specifically, this research investigates how DoD can better leverage UAS and improve multi-intelligence capabilities by expanding its geolocation capacity through the use of time/frequency-difference-of-arrival (T/FDOA) geolocation on unmanned assets. This advancement in geolocation would improve several aspects of ISR. It would increase the hunting ability for UAS, which are often termed hunter-killer platforms, potentially shortening the kill chain. Focusing on ISR, improved geolocation would enable better cross-cueing between platforms or self-cueing on multi-intelligence platforms, creating a richer intelligence picture. Incorporating T/FDOA geolocation would require changes. A new concept of operation (CONOP) needs to be developed for the execution of T/FDOA from ISR platforms and the incorporation of multi-intelligence sources. Payload modifications, though hypothesized to be modest, need to be quantified. The impacts on the processing, exploitation, and dissemination (PED) process also need to be evaluated to determine the efficacy of this concept. This research is intended to inform DoD policy by showing that an expanded use of T/FDOA geolocation on UAS would improve multi-intelligence capabilities.

Motivation and Background

The 2010 Quadrennial Defense Review (QDR) stresses the importance of increased ISR to support the warfighter. The QDR articulates several priorities involving the growth of ISR, including expansions of the "intelligence, analysis, and targeting capacity" and of "unmanned aircraft systems for ISR" (Department of Defense 2010). The *Unmanned Systems Integrated Roadmap FY2009-2034*, published by the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, outlines priorities for future investment in unmanned systems and echoes similar themes. The top two priorities for future investments in UAS are improvements in reconnaissance and surveillance, particularly multi-intelligence capable platforms, and improvements in target identification and designation, including the ability to precisely geolocate military targets in real time (Under Secretary of Defense for Acquisition, Technology, and Logistics 2009).

Geolocation is the identification of the physical location of objects on the earth. The term is used to refer to both the action of locating and the results of the localization. There are numerous ways to accomplish geolocation. This research focuses on the geolocation of radio frequency (RF) emitters used in a military context. Geolocation of RF emitters is critical to a wide variety of military applications. In conflicts, geolocation is vital for both targeting and situational awareness. RF emitters of interest range from elements of an integrated air defense system and communications nodes in a major combat operation to insurgents communicating with push-to-talk radios. A key difference in military geolocation is the non-cooperation of targets. An enemy usually attempts to disguise emissions using evasive techniques that complicate geolocation. For example, the time of transmission might not be known. The military uses signals intelligence (SIGINT) to take advantage of the electromagnetic emissions intercepted from targets. These electromagnetic emissions can provide information on the intention, capabilities, or location of adversary forces (AFDD 2-0).

Many intelligence tasks depend on geolocation; however, each task does not require the same level of accuracy. Table 1.1 summarizes specific intelligence tasks requiring geolocation, comments on the value of geolocation, and gives an idea of the accuracy needed. Although these accuracies are intended to be ballpark figures, they highlight the need for significant accuracy for certain tasks, such as precision location.

Table 1.1
Geolocation Contribution to Intelligence Tasks

<table>
<tr><th>Objective</th><th>Value</th><th>Accuracy Needed</th></tr>
<tr><td>Weapon sensor location (self-protection)</td><td>Allows threats to be avoided or negated through jamming</td><td rowspan="2">Low ($5km^2$)</td></tr>
<tr><td>Emitter differentiation</td><td>Allows sorting by location for separation of threats for identification processing</td></tr>
<tr><td>Enemy asset location</td><td>Allows narrowed reconnaissance search</td><td rowspan="3">Medium ($1km^2$)</td></tr>
<tr><td>Electronic order of battle</td><td>Locate emitter types associated with specific weapons/ units. Provides information on enemy strength, deployment, etc.</td></tr>
<tr><td>Weapon sensor location</td><td>Allows threat to be avoided by other friendly forces</td></tr>
<tr><td>Precision target location</td><td>Allows direct attack</td><td>High ($100m^2$)</td></tr>
</table>

SOURCE: Table adapted from Adamy, D. (2001). EW 101. Boston, Artech House. p. 144.

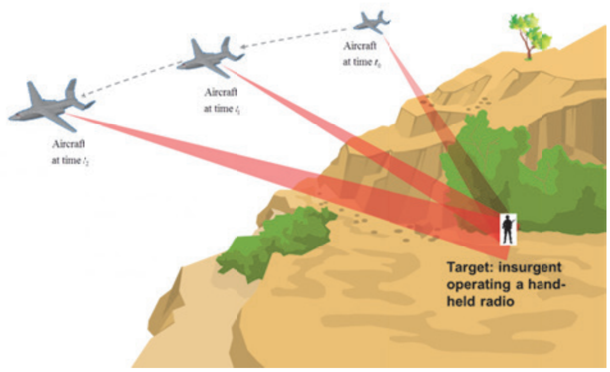
There are several techniques currently used to geolocate an RF emitter. These techniques include using the angle of arrival (AOA) of the emission, using coherent time-difference-of-arrival (TDOA) at a single platform, using non-coherent TDOA for the emission to multiple receivers, and using the frequency-difference-of-arrival (FDOA) for the emission to multiple receivers. Each of the techniques depends on precise measurements. Errors in the accuracy of the measurements impact the accuracy of geolocation, resulting in some amount of error inherent in the geolocation.

The errors involved and the impact on the accuracy of the geolocation depend on the technique used. These errors include such things as positioning errors (how well the aircraft knows its own position), signal measurement errors (how well the receiver can capture the received signal), and noise inherent in the signal. To reduce error, techniques can be combined and used together, for example T/FDOA geolocation leverages both TDOA and FDOA to determine position more accurately. Regardless of the system used, the geolocation accuracy is dependent on the accuracy of the chosen technique and how the SIGINT system is designed to minimize error (Adamy 2001).

The military traditionally uses direction finding, also known as triangulation, to fix the position of an emitter using specialized manned aircraft. In direction finding, an aircraft would measure the AOA at multiple locations along a baseline to create lines of bearing (LOBs) between the receiver and the emitter. Two or more LOBs enable the emitter to be fixed at the intersection of these different LOBs. Figure 1.1 depicts a pictorial of direction finding. Single-receiver direction finding requires one receiver to measure the signal at one position and then move and re-measure the same signal. Multi-receiver direction finding requires at least two geographically separated receivers collecting LOBs on the same target. There are many algorithms available to calculate the emitter location. These range from plotting LOBs on a common map to calculations based on statistical techniques such as least-squares error estimation and the discrete probability density method (Poisel 2005).

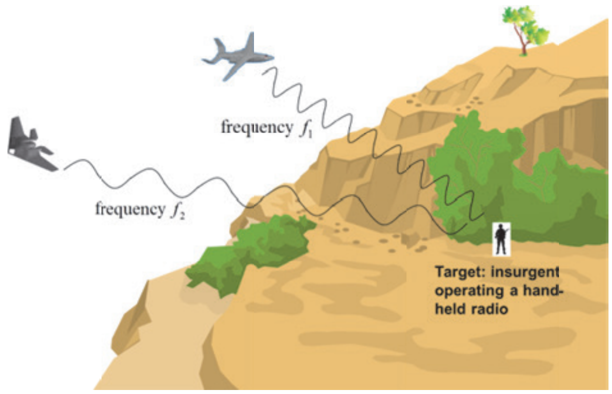
There are limitations to direction finding. It requires a directional antenna, which can be bulky and expensive. The accuracy of direction finding can be severely hampered by the duration of the emission as well as target movement. Cooperative T/FDOA geolocation is not subject to these limitations.

Figure 1.1
Aircraft Calculates LOBs along a Baseline



Cooperative T/FDOA is the combination of two techniques that enable receivers to quickly geolocate a signal. For both TDOA and FDOA, at least two receivers are needed to calculate a difference of arrival. In TDOA, the difference in the time that a signal arrives at the two receivers is proportional to the difference in the ranges of the two receivers from the target. One TDOA measurement provides a contour in the shape of a hyperbola of potential positions of the signal. In FDOA, the difference in the frequency of arrival is proportional to the difference in the frequencies measured by the two receivers. Figure 1.2 shows a pictorial of FDOA. One FDOA measurement provides a contour of potential sources of the signal. When the contours of potential sources of the signal (one from TDOA and one from FDOA) are intersected, the position of the source of the signal is at the intersection.

Figure 1.2
Signal May Have a Frequency Difference



TDOA and FDOA are straightforward to describe mathematically. The equations for TDOA and FDOA are described by position, velocity, and signal characteristics. Let τ denote a TDOA measurement and ϕ denote a FDOA measurement. Let $v \in \mathbf{R}^n$ and $w \in \mathbf{R}^n$ denote the positions of the pair of receivers in n-space. Similarly, let $\bar{v} \in \mathbf{R}^n$ and $\bar{w} \in \mathbf{R}^n$ denote the corresponding velocities of the pair of receivers. Let c denote the speed of light and f denote the center frequency of the emitter. The equations to calculate TDOA and FDOA are as follows[2]:

TDOA equation: $$\tau = \frac{1}{c}\left(\|v-x\| - \|w-x\|\right)$$

FDOA equation: $$\phi = \frac{f}{c}\left(\bar{v}^T \frac{(v-x)}{\|v-x\|} - \bar{w}^T \frac{(w-x)}{\|w-x\|}\right).$$

Finding the emitter source using T/FDOA is not as easy to describe mathematically, due to errors causing inconsistent measurements of TDOA and FDOA. The T/FDOA Accuracy Estimation Tool, developed as part of this dissertation, simulates the various errors that impact T/FDOA geolocation and predicts the accuracy that could be expected from a T/FDOA geolocation given a specific application. This tool is used throughout the analysis and is explained in detail in Chapter Two.

---

[2] For more information on TDOA and FDOA equations, see Stewart (1997).

Direction finding and T/FDOA are difficult to directly compare. The accuracy of each technique is dependent on the specific application, and so it is more useful to contrast the advantages and limitations of each technique. Table 1.2 shows advantages and limitations for direction finding with a single receiver, direction finding with multiple geographically separated receivers, and T/FDOA.

Table 1.2
Summary of Pros and Cons of Geolocation Techniques

	Direction Finding (Single Receiver)	**Direction Finding (Multi-Receiver)**	**T/FDOA**
Requires directional antenna	Yes	Yes (on each platform)	No
Signals of interest	Low power, high frequency	Low power, high frequency	Low power, low frequency
Time needed for geolocation	2-3 minutes	Nearly instantaneous	Nearly instantaneous
Requires multiple aircraft	No	Yes	Yes
Sensitive to target movement	Yes	No	No
Sensitive to geometry	No	Yes	Yes

Adding a T/FDOA geolocation capability to UAS would increase both the capacity and capability for geolocation. Today, the number of large UAS owned by the Air Force is on par with the number of manned

ISR/command and control (C2) platforms. Placing T/FDOA geolocation on these UAS would more than double the number of collectors capable of geolocation.[3] The UAS inventory is also expected to increase in the coming years, potentially bringing the number of group 4/5 UAS to over 500 for the Air Force and Navy alone. Using T/FDOA geolocation would also expand the overall capability for geolocation. Signals that are difficult to geolocate with direction finding for a variety of reasons, such as length of emission, range from collector, and the frequency used, can be located with good accuracy using T/FDOA geolocation. The techniques are contrasted in more depth in Chapter Three.

The expansion of capability and capacity would benefit several aspects of ISR. Higher-accuracy geolocation yields better intelligence. T/FDOA geolocation is able to achieve high enough accuracy to be targetable. Targetable accuracy geolocation determined by a multi-role UAS, such as an armed MQ-9 Reaper, could shorten the sensor-to-shooter timeline. Geolocation is also very useful for cross-cueing. Today, we use UAS predominantly for their FMV sensors. Unfortunately an FMV sensor has a limited field of view, often compared to looking through a soda straw. SIGINT has a much wider field of view, potentially only limited by the line of sight to the radar horizon. A geolocation tip on a known adversary frequency could be used to cue an FMV sensor to identify and perhaps neutralize the target. The increase in geolocation capacity equates to more information about targets that might not have been captured previously. More and better quality geolocation that is catalogued would have impacts on the later phases of PED, such as forensics. Forensics draws together intelligence derived from multiple sources to provide an in-depth analysis. An example of forensics would be an analysis of a roadside bomb explosion. The analysis would pull all available intelligence to try to determine details about the incident, such as when the bomb was placed, when it was detonated, etc. If catalogued, the expanded collection and geolocation from using

[3]As of Jan 2012, the number of manned ISR/C2 assets (U-2, MC-12, E-3B, E-4B, E-8C, RC-135B/S/U/V/WH, EC-130) was 145 aircraft (according to fact sheets on www.af.mil). The number of large (group 4/5) multi-role/ISR UAS is approximately 180 aircraft (according to the Aircraft Procurement Plan FY2012-2041).

T/FDOA on UAS could increase the available information for forensic analysis.

T/FDOA Implementation in the Military

For several decades, the military invested in technologies to improve geolocation through the implementation of T/FDOA geolocation, although to date this technology has not been incorporated on UAS. The Precision Location and Strike System (PLSS) was one of the first efforts to use TDOA geolocation. Throughout the 1970s, this program attempted to quickly triangulate hostile emitters with high enough accuracy to target with weapons using a combination of TDOA and other techniques (U.S. Congress Office of Technology Assessment 1987). It utilized three aircraft collecting electronic intelligence data. These data were then relayed to a ground station that used TDOA, direction of arrival, and distance measuring equipment to fix the position of the target. The Air Force spent millions of dollars on the development of PLSS, but the project never succeeded because of technical challenges (Pocock 2008).

The advent of GPS, improvements in computer processing power, and higher-bandwidth communications since the early 1990s enabled more recent attempts to use T/FDOA geolocation for near-real-time precision location of hostile emitters from the air. In 1991, the Army upgraded its Guardrail Common Sensor system to have a limited TDOA capability that depended on an initial cue.[4] In 1997, the Defense Advanced Research Projects Agency (DARPA) began work on Advanced Tactical Targeting Technologies (AT3), the first system designed and built to fully employ T/FDOA geolocation. DARPA’s goal was to develop and demonstrate the enabling technologies for a cost-effective, tactical targeting system for the lethal suppression of enemy air defenses. The idea was to generate and distribute highly precise location of radars within seconds using T/FDOA geolocation. Emitter collection packages would be hosted on combat aircraft, obviating the need for any dedicated collection platforms. Instead, collection would be opportunistic, with

---

[4] Subsequent upgrades to the Guardrail system added a true T/FDOA capability.

minimal pre-coordination required. The DARPA system has been incorporated in the F-16 HARM Targeting System, greatly improving the ability of F-16 Block 50s to quickly locate and engage an emitting target (Cote 2010). Another program, Net-Centric Collaborative Targeting (NCCT), greatly expanded the geolocation capabilities of manned ISR assets. Integrated on assets such as the RC-135, RC-130, EC-130, U-2, and EP-3, NCCT allows separate sensors to cooperatively geolocate a target (Anonymous 2008). To date, such technologies are not incorporated on unmanned ISR assets, such as MQ-9 Reapers or MQ-1C Grey Eagles.

Academic research on T/FDOA geolocation centers on methods of estimation and the impact of errors on accuracy. Chestnut (1982) determined relationships between errors in measurement and geolocation accuracy. Bardelli, Haworth, and Smith (1995) found that the Cramér-Rao lower bounds on T/FDOA measurement are typically so small[5] that positioning errors and other measurement errors predominate. Musicki and Koch (2008) devised a method to estimate emitter location accuracy using T/FDOA and compared it with geolocation results from a direction finding approach. Musicki, Kaune, and Koch (2010) proposed a method for recursive tracking of a mobile emitter using T/FDOA. This research expands on academic literature by examining important questions that need to be answered before investing in T/FDOA-capable UAS.

Much of the academic research on geolocation with UAS focuses on using autonomous, often small UAS that cooperate as a swarm (Okello 2006; Marsh, Gossink et al. 2007; Scerri, Glinton et al. 2007; Liang and Liang 2011). These works highlight advantages of small UAS, including their lower cost and higher mobility. Although small UAS have some characteristics that lend themselves to being used for geolocation, larger UAS provide a significant opportunity to leverage T/FDOA geolocation. This research focuses on larger UAS. Group 4/5 UAS, defined as UAS that have a gross weight of larger than 1,320 lbs, show potential for hosting a T/FDOA capability. Some examples of these UAS include the Army’s MQ-1C Grey Eagle, the Air Force’s MQ-9 Reaper, and

[5] A Cramér-Rao lower bound gives a lower bound on the variance of any unbiased estimator.

the Navy's MQ-4C BAMS. These UAS have characteristics that make them a logical choice for integrating a T/FDOA geolocation capability. Their large size gives them the payload capacity needed to host multiple sensors. Their long endurance and employment altitude allow for long collection times over significant geographic areas. The large and growing inventory of group 4/5 UAS provides the required ability to mass numbers of equipped platforms over one geographic area.

Research Questions

The chapters that follow each focus on one question to inform the overall recommendation of integrating T/FDOA geolocation on UAS platforms to expand the geolocation capacity and increase multi-intelligence capabilities. The analysis leverages mathematical modeling techniques and geospatial analysis to answer the following research questions:

1. When would T/FDOA geolocation be useful on UAS?
2. What is needed to use T/FDOA geolocation on UAS?
3. How can T/FDOA geolocation be leveraged in multi-intelligence operations on UAS?

Each research question is divided into several tasks that help to answer the questions.

The first research question focuses on whether T/FDOA geolocation would be useful if we were to add the capability to UAS operating today. Specifically, I am interested in whether T/FDOA would fill a gap and be a practical capability on UAS. The accuracy of geolocation of a signal is dependent on the method of geolocation used, the characteristics of the scenario, and the signals of interest. Direction finding is a common geolocation technique used today. T/FDOA geolocation offers distinct advantages over direction finding. First, I explore these advantages using a simple model of direction finding to contrast the two techniques. This model is described in Appendix A. Two major drawbacks of T/FDOA geolocation are that it requires multiple equipped platforms and that the geolocation accuracy is extremely sensitive to the geometry of the receiver platforms in relation to the target emitter. Today, multi-intelligence capable platforms are tasked with one intelligence priority (e.g., signals intelligence-prime), and the orbit flown is optimized for that mission. I examine the impact of these orbit geometries on the expected accuracy given different intelligence priorities using the T/FDOA Accuracy Estimation Tool. For T/FDOA geolocation, the multiple equipped platforms must be operating within line of sight of the same target. Using a combination of geospatial analysis and the T/FDOA Accuracy Estimation Tool, I analyze the line of sight coverage overlap and the resulting accuracy available for specific targets in the current operating environment.

Any modification to how a mission is accomplished will have ramifications and cost implications in other areas. The second research question investigates some of these implications. Before T/FDOA is implemented, the requisite hardware and software modifications to platforms need to be determined. I research DARPA's AT3 program as an example of successful T/FDOA geolocation implementation. An addition of T/FDOA capability will likely impact the already manpower constrained processing, exploitation, dissemination (PED) enterprise. I examine the workload for T/FDOA PED. Then, using the current PED operations conducted by the Distributed Common Ground Systems (DCGS) as a baseline, I determine whether the workload requires additional personnel and calculate the total additional personnel burden. As mentioned in the introduction, fiscal constraints faced by DoD will be severe in the coming years. To recommend using T/FDOA in this climate, an understanding of what the potential cost implications for T/FDOA is necessary. I estimate the cost implications of the additional personnel.

Most UAS are equipped with several different types of sensors. DoD would like to capitalize on these multi-intelligence capable platforms to collect more complete information on targets and use one intelligence collection to cue another intelligence collection. The third research question explores how T/FDOA can improve multi-intelligence operations. T/FDOA geolocation can provide highly accurate geolocation within seconds.[6] This combination of accuracy and speed can in turn aid in multi-intelligence collection through improved cueing. The time burden of T/FDOA geolocation is impacted by the command, control, and communication (C3) channels used to pass the geolocation from the analysis source to the warfighter. Today's C3 channels were designed to pass geolocation from manned intelligence platforms, commonly using direction finding, where timeliness is not as important. I examine the kind of C3 needed to enable multi-intelligence cross-cueing.

The research outlined above sheds light on important questions that need to be answered before investing in T/FDOA-capable UAS. The first research question demonstrates the potential of T/FDOA geolocation in the context of how we use UAS today. The second question shows what some of the "costs" of adding a T/FDOA geolocation capability to UAS might be. The third question explores how T/FDOA geolocation could improve multi-intelligence cueing. Each research question helps to inform the overall policy recommendation of better leveraging UAS and improving multi-intelligence capabilities through the use of T/FDOA geolocation.

Organization of the Dissertation

Chapter Two presents the T/FDOA Accuracy Estimation Tool that will be used throughout the analysis. Chapter Three discusses when T/FDOA would be useful in the context of today's operations. Chapter Four examines what is needed to use T/FDOA geolocation focusing on the requisite system modifications and the impacts on the PED enterprise. Chapter Five shows how T/FDOA geolocation could be leveraged in multi-intelligence operations. Chapter Six summarizes the conclusions and policy recommendation. Several appendixes are included to provide further information on the models used and results summarized in the body of the dissertation.

---

[6] An example error ellipse with good geometry would give in a semi-major axis of 37m and a semi-minor axis of 19m, resulting in an area of 2,210m. See Chapter Two for more examples.

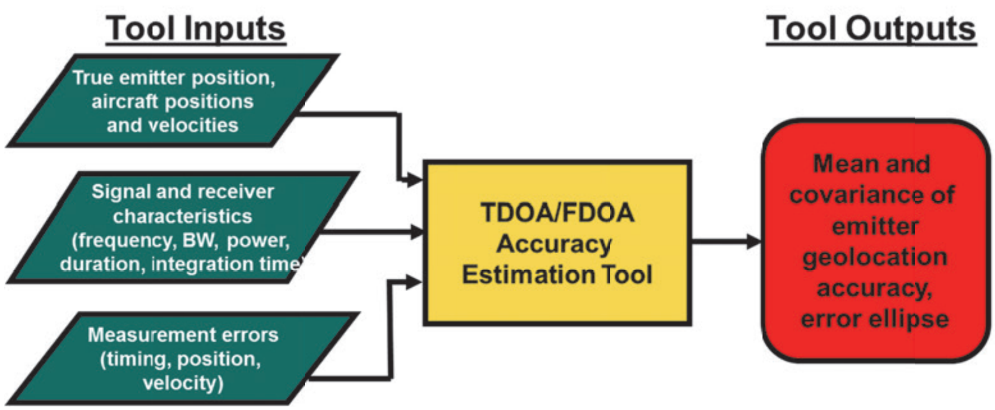
2. T/FDOA Accuracy Estimation Model

The T/FDOA Accuracy Estimation Model takes a scenario for geolocation and estimates the accuracy of the cooperative T/FDOA technique, including the impact of various sources of errors. The tool improves on other tools to estimate the accuracy of T/FDOA in the literature by including errors in the measurement of the aircraft state vector. The tool was needed to evaluate the accuracy of T/FDOA as a means of quantifying the benefits of T/FDOA geolocation for this dissertation. Beyond this research, the simulation provides a useful tool for assessing the dominant factors in T/FDOA geolocation accuracy that can inform decisions on choosing aircraft orbit geometries to optimize performance, technology investment decisions, and comparisons of the performance of T/FDOA with alternative geolocation techniques for specific applications.

There are several methods to solve for TDOA and FDOA in the academic literature. Ho and Chan (1993) show how to estimate position at the intersection of two or more hyperbolae using TDOA measurements. Chestnut (1982) derives formulas for cooperative T/FDOA. Ren, Fowler, and Wu (2009) use the Gauss-Newton method for non-linear least-squares to estimate the emitter location using cooperative T/FDOA. Prior work on the estimation of accuracy for cooperative T/FDOA takes into account the precision for the measurement of time difference and frequency difference known as Cramér-Rao lower bounds. Bardelli, Haworth, and Smith (1995) found that the Cramér-Rao lower bounds on TDOA and FDOA are often so small that equipment errors predominate. Equipment errors in the aircraft state vector, such as error in the estimation of position and speed by the platforms conducting the geolocation, have been noted but not explicitly included in previous research. The T/FDOA Accuracy Estimation Model expands on previous research by including measurement errors of the aircraft state vector as well as the traditional Cramér-Rao lower bounds on the measurement of TDOA and FDOA.

Geolocation using T/FDOA is a complex function of geometry, signal characteristics, and navigational precision. Due to measurement errors and noise, there are limitations on how well an emitter can be geolocated. I use a simulation-based approach to determine the accuracy with which an emitter's position can be geolocated using cooperative T/FDOA. An outline of the inputs and outputs of the T/FDOA Accuracy Estimation Model is show in Figure 2.1.

Figure 2.1
Graphic Depiction of Tool Inputs and Outputs



For each run, I use non-linear least-squares optimization to determine the emitter position most consistent with the simulated measurements. In formulating the least-squares for TDOA and FDOA equations, it is apparent that both functions are not convex, resulting in a non-convex optimization problem. For a non-convex optimization, a good initial estimate is required. I use the true emitter position as an initial estimate to mitigate the possibility of non-convergence.[7] The least-squares fit is also non-linear. I use the Gauss-Newton Method with an approximation of the Hessian for the non-linear least-squares optimization.[8] I then calculate statistics for the distribution of the

[7] The non-convex nature of the problem causes global techniques to fail. Using the true emitter position as the initial estimate guards against non-convergence. The optimization may still fail, and the tool notifies the user of instances of non-convergence.

[8] The Gauss-Newton method is a standard optimization technique for non-linear least-squares optimization. It avoids the direct computation of the Hessian by approximating it, and the approximation improves as

estimated positions. I use the sample covariance matrix to determine an error ellipse. The output of the tool is this error ellipse.

MEASUREMENT AND SOURCES OF ERROR

The equations for TDOA and FDOA are described by position, velocity, and signal characteristics. Let τ denote a TDOA measurement and ϕ denote a FDOA measurement. Let $v \in \mathbf{R}^n$ and $w \in \mathbf{R}^n$ denote the positions of the pair of receivers. Similarly, let $\bar{v} \in \mathbf{R}^n$ and $\bar{w} \in \mathbf{R}^n$ denote the corresponding velocities of the pair of receivers. Let c denote the speed of light and f denote the center frequency of the emitter. The equations to calculate TDOA and FDOA are as follows:

TDOA equation: $$\tau = \frac{1}{c}\left(\|v-x\| - \|w-x\|\right)$$

FDOA equation: $$\phi = \frac{f}{c}\left(\bar{v}^T \frac{(v-x)}{\|v-x\|} - \bar{w}^T \frac{(w-x)}{\|w-x\|}\right).$$

As noted in Okello (2006), T/FDOA geolocation requires precise data on the distance between each sensor and a precise clock to synchronize the timing of measurements. Due to measurement errors, TDOA and FDOA measurements are rarely consistent, meaning that an exact solution that satisfies both the TDOA and FDOA equations rarely exists. Our model considers several different sources of error. Consistent with other works, these measurement errors are assumed to be zero-mean Gaussian (Musicki and Koch, 2008). There is error inherent in a receiver's ability to measure its own position and velocity, σ_p and σ_v, respectively. The measurement of TDOA and FDOA each introduce errors due to noise in the receivers, σ_τ and σ_φ. TDOA measurement also includes clock synchronization error, σ_T. The errors and their values are listed in Table 2.1.

---

one approaches convergence. Also, the approximation is always positive definite, which ensures we obtain a descent direction, even for a non-convex problem such as this.

Table 2.1
Data for Error Model

Error	Value of Error
σ_p	Default is 10.2 m, based on GPS P(Y) code error
σ_v	Default is 5 cm/s, based on typical error for GPS or low grade IMU
$\sigma_\tau \geq \frac{1}{2\pi B_{rms}\sqrt{BTS_e}}$	I use Cramér-Rao lower bounds (Musicki, Kaune et al. 2010)
$\sigma_\phi \geq \frac{1}{2\pi T_{rms}\sqrt{BTS_e}}$	I use Cramér-Rao lower bounds (Musicki, Kaune et al. 2010)
$\sigma_T = 100\times10^{-9}$ sec	Default is times the worst-case GPS satellite clock error.

Problem Formulation

I formulate the problem as a non-linear least-squares optimization problem to find the emitter position that minimizes the deviation from zero for every T/FDOA measurement. I first fit a least-squares optimization to the T/FDOA equations. I want to find the emitter position that is most consistent in the least-squares sense; that is, the emitter position that minimizes the sum of the squared residuals. Let τ_i denote the i^{th} TDOA measurement for $i=1,\cdots,m$. Similarly, let ϕ_i denote the i^{th} FDOA measurement for $i=1,\cdots,m$. Let $v_i \in \mathbf{R}^n$ and $w_i \in \mathbf{R}^n$ denote the positions of the i^{th} unique pair of receivers for $i=1,\cdots,m$. Similarly, let $\overline{v}_i \in \mathbf{R}^n$ and $\overline{w}_i \in \mathbf{R}^n$ denote the corresponding velocities of the i^{th} unique pair of receivers. Let c denote the speed of light and f denote the frequency of the emitter. Then x^* is given by:

$$x^* = \arg\min_{x\in\mathbf{R}^n} \left\| \begin{matrix} \|v_1 - x\| - \|w_1 - x\| - c\tau_1 \\ \|v_2 - x\| - \|w_2 - x\| - c\tau_2 \\ \vdots \\ \|v_m - x\| - \|w_m - x\| - c\tau_m \\ \overline{v}_1^{\,T} \frac{(v_1 - x)}{\|v_1 - x\|} - \overline{w}_1^{\,T} \frac{(w_1 - x)}{\|w_1 - x\|} - \frac{c}{f}\phi_1 \\ \overline{v}_2^{\,T} \frac{(v_2 - x)}{\|v_2 - x\|} - \overline{w}_2^{\,T} \frac{(w_2 - x)}{\|w_2 - x\|} - \frac{c}{f}\phi_2 \\ \vdots \\ \overline{v}_m^{\,T} \frac{(v_m - x)}{\|v_m - x\|} - \overline{w}_m^{\,T} \frac{(w_m - x)}{\|w_m - x\|} - \frac{c}{f}\phi_m \end{matrix} \right\|^2 .$$

This is a non-convex optimization problem. I can show that a least-squares fit is non-convex through counter examples. If a function were convex, then the entire function would lie on or below a line segment connecting any two points on the function. Mathematically, this is stated as:

$$g(ax+(1-a)y) \le ag(x)+(1-a)g(y), \text{ for any } 0 \le a \le 1 .$$

The function for the normalized TDOA fit would be:

$$g(x) = (\|v-x\| - \|w-x\| - c\tau)^2 .$$

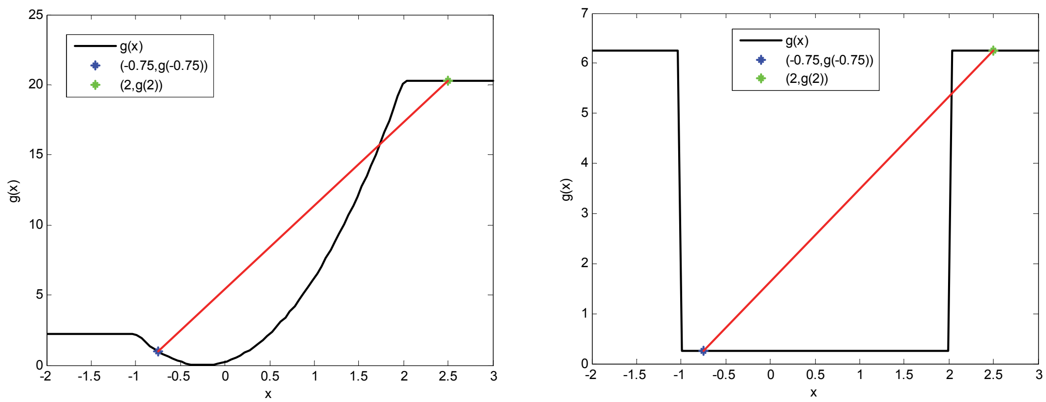
Let $v = 2, w = -1,$ and $c\tau = 1.5$. I can then check the convexity for this example by graphing. The graph on the left in Figure 2.2 shows clearly that the least-squares fit to TDOA is not convex. Similarly, the function for the normalized FDOA fit would be:

$$g(x) = \left(\bar{v}^T \frac{(v-x)}{\|v-x\|} - \bar{w}^T \frac{(w-x)}{\|w-x\|} - \frac{c\phi}{f} \right)^2 .$$

If we set the data, let $\bar{w} = \bar{v} = 1, v = 2, w = -1, and\ c\phi/f = 2.5$, we can graph the function. The graph on the right in Figure 2.2 shows that the least-squares fit to FDOA is also not convex.

Figure 2.2
Graph of TDOA and FDOA for Convexity Proof

Graph of TDOA   Graph of FDOA



As a result of the non-convexity, the algorithm may not converge to a global minimum. If it is provided an initial estimate that is close to optimal, the algorithm will converge in most cases. For our application, we know the true position of the emitter and use it as our initial estimate.[9] This does not guarantee convergence for every case; however, it works in most situations. The tool informs the user if the solution did not converge, and these data are removed for the statistical calculations.[10]

---

[9] The non-convexity of this problem requires a good initial estimate, in the neighborhood of the optimal solution. Using the true position of the emitter provides an initial estimate that should be close for most cases. This initial estimate will not impact the resulting error ellipse, as the algorithm will still converge at the optimal solution.

[10] The non-convergence is a result of the non-convexity of the problem. Unfortunately, it is unavoidable. When a solution does not converge, it typical means that the initial estimate (the true position) was far from the optimal solution. This situation is the result of poor geometry. As a reviewer noted, removing the failures could impact the accuracy results, since they are the worst cases. I conducted some sensitivity analysis to see the extent of non-convergence. The Monte-Carlo simulation uses 500 iterations, and the percentage of non-convergences is typically very small, less than 5 percent. If the proportion of non-convergences reaches greater than 10 percent, the tool will inform the user that there are not enough samples to estimate the accuracy. I never encountered this situation. In general, if there is non-convergence, the geolocation from that particular application is extremely poor. Removing the failures does

I reformulate the problem to simplify the notation. Let τ_i denote the i^{th} TDOA measurement for $i = 1, \cdots, m_1$. Similarly, let ϕ_i denote the i^{th} FDOA measurement for $i = 1, \cdots, m_2$. Assume that m_3 unique pairs of receivers collect the measurements. Let $v_i \in \mathbf{R}^n$ and $w_i \in \mathbf{R}^n$ denote the positions of the i^{th} unique pair of receivers for $i = 1, \cdots, m_3$. Similarly, let $\overline{v}_i \in \mathbf{R}^n$ and $\overline{w}_i \in \mathbf{R}^n$ denote the corresponding velocities of the i^{th} unique pair of receivers. Let $T(i) \in [1, 2, \cdots, m_3]$ denote the index of the receiver pair that collects τ_i for $i = 1, \cdots, m_1$ and let $F(i) \in [1, 2, \cdots, m_3]$ denote the index of the receiver pair that collects ϕ_i for $i = 1, \cdots, m_2$.

$$\text{Let } r_i(x) = \begin{cases} \|v_{T(i)} - x\| - \|w_{T(i)} - x\| - \tau_i c & i = 1, \cdots, m_1 \\ \overline{v}_{F(i-m_1)}{}^T \dfrac{(v_{F(i-m_1)} - x)}{\|v_{F(i-m_1)} - x\|} - \overline{w}_{F(i-m_1)}{}^T \dfrac{(w_{F(i-m_1)} - x)}{\|w_{F(i-m_1)} - x\|} - \phi_i c / f & i = m_1 + 1, m_1 + 2 \cdots, m_1 + m_2 \end{cases}$$

The optimization problem is now:

$$\text{minimize } g(x) = \sum_{i=1}^{m_1+m_2} r_i(x)^2 .$$

This is a non-linear least squares optimization problem, and I use the Gauss-Newton method with a backtracking line search to solve it. The Gauss-Newton method is an algorithm for solving convex non-linear least-squares problems. The method defines a descent direction using the gradient and an approximation of the Hessian denoted H.[11] I use a backtracking line search to determine the step size. The algorithm as applied to our problem is as follows:

---

not impact the results throughout this dissertation. In the remainder of this research, I categorize the error ellipse accuracy into high (<100m^2), medium (<1km^2), low (<5km^2), and unusable. Non-convergence would only appear in applications that result in unusable accuracies.

[11] This estimate of the Hessian converges to the Hessian as the gradient vanishes.

Given an initial point $x \in \mathbf{R}^n$, tolerance $\varepsilon > 0$, parameter $\alpha \in (0,1/2)$
while $\|\nabla g(x)\| > \varepsilon$
  $H = 2\sum_{i=1}^{m_1+m_2} \nabla r_i(x) \nabla r_i(x)^T$
  $u = -H^{-1}\nabla g(x)$ (i.e., solve $Hu = -\nabla g(x)$ for u)
  $t = 1$
  while $g(x+tu) > g(x) + \alpha t \nabla g(x)^T u$
    $t = t/2$
  end
  $x = x + tu$
end

With each run, the estimated position of the emitter is saved. These estimated positions are used to calculate the mean estimated position and a covariance matrix. Using the eigenvalues of the covariance matrix, we can determine the uncertainty in each direction and plot this uncertainty to create an error ellipse.

How the Tool Works

The tool uses a Monte-Carlo simulation to estimate the accuracy of geolocation. For each run of the tool, the true TDOA and FDOA are calculated using the true positions. Then, the errors are incorporated. The errors are modeled as separate random samples each drawn from Gaussian distributions with the variance of the error parameter. During each iteration, the randomly sampled error is added to the true value. All of the errors are included in each model run. The errors for TDOA and FDOA measurement (σ_τ and σ_ϕ, respectively) are introduced using the errors from the Cramér-Rao lower bounds. Random synchronization clock error (σ_T) is also added to the TDOA measurement. Then random noise is added to the positions (σ_p) and velocities (σ_v) of the receivers to simulate the aircraft state vector measurement error. For example, if the true aircraft position was [100m, 150m, 90m] and the random error sample for position was 7.8m, the aircraft position used for that iteration would be [107.8m, 157.8m, 97.8m]. The T/FDOA measurement and positions that incorporate the errors are then used in the non-linear least-squares optimization to determine the most consistent emitter position. Statistics between this estimated position and the true emitter position are used as estimates of the geolocation accuracy.

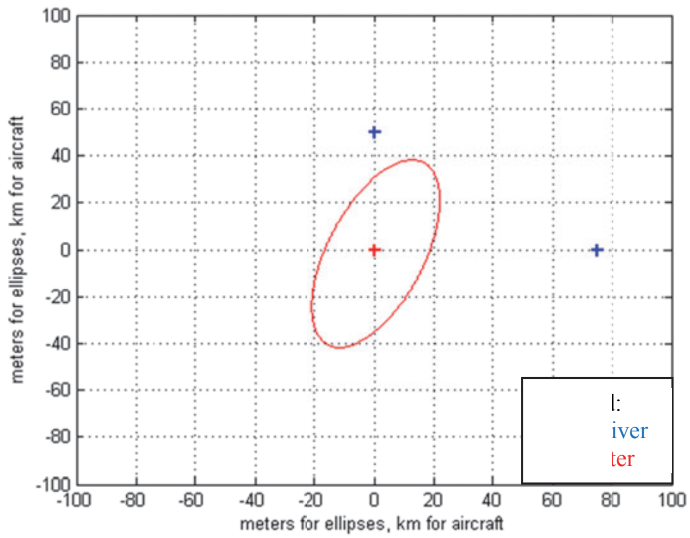
EXAMPLES OF TOOL

The T/FDOA Accuracy Estimation Model shows how the different inputs to cooperative T/FDOA impact the accuracy with which an emitter can be geolocated. The following examples are meant to illustrate the sensitivity of the tool to several of the model inputs. The accuracy is extremely sensitive to geometry and the number of receivers available. By *geometry*, I am referring to the positioning and speed of the receivers relative to the target. The receivers must be located such that there are time differences between the arrivals of the signal. The receivers must also be traveling with different velocities with respect to the targeted emitter so that there are calculable frequency differences of arrivals. The measurement errors can also significantly impact the accuracy of geolocation.

Example: Impact of Geometry

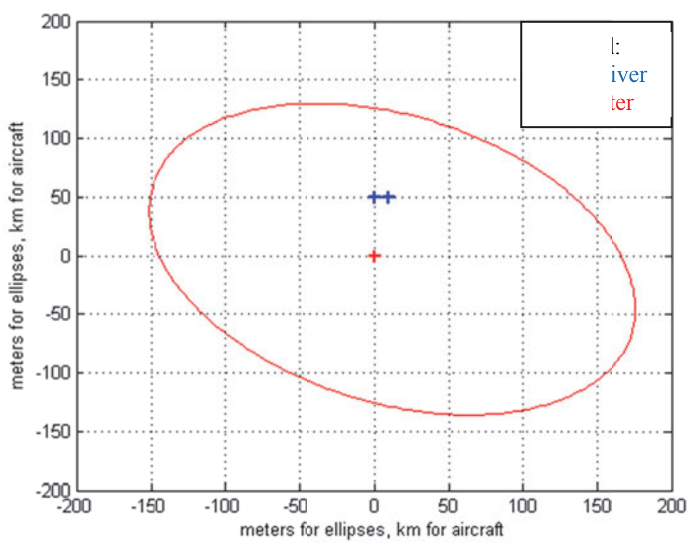
In this scenario, there are two receivers positioned around the emitter. The emitter has a 164 MHz signal that lasts for 30 seconds with a 25 MHz bandwidth, and 5W EIRP, a typical power for a VHF push-to-talk radio. There is a 190°K noise temperature at the receivers with a 4dB noise figure. The receivers are both headed east at 100 m/sec. Figure 2.3 shows the scenario and the resultant error ellipse. The receivers are the blue crosses, and the emitter is the red cross. Positions are in units of kilometers. The error ellipse is in units of meters.

Figure 2.3
Two Receiver Example with 1-Sigma Error Ellipse



The error ellipse is about 2210m^2 centered on the emitter. If the position of one of the receiver is changed, keeping all else constant, the size of the error ellipse can increase drastically. Figure 2.4 shows the resultant error ellipse after moving one receiver to be much closer to the other.

Figure 2.4
Moving One Receiver for Poor Geometry

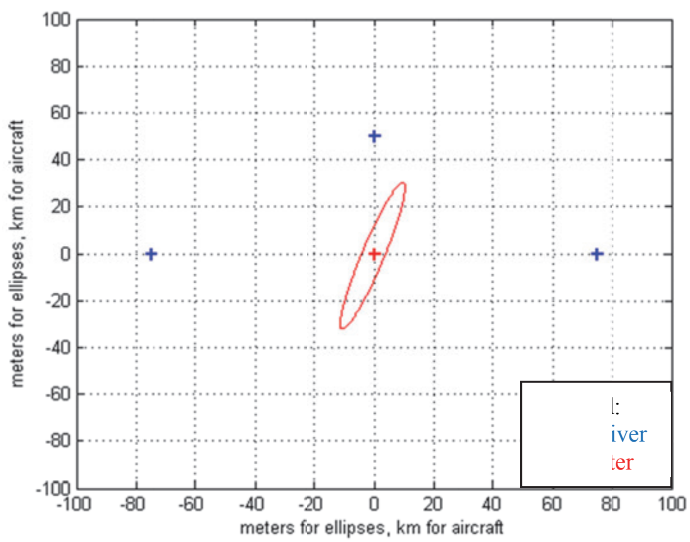


This new ellipse is about 65,000m^2. As the two receivers move closer together, the difference in arrival for both TDOA and FDOA becomes so small that measurement errors and noise dominant the measurement.

Example: Impact of Number of Receivers

The number of receivers is a major determinant of the size of the error ellipse. Returning to the same scenario as the first example with two receivers positioned advantageously, we can add another receiver.

Figure 2.5
Adding a Receiver



The error ellipse is now much smaller, at 392m^2. The number and positioning of the receivers are significant contributors to the estimated error ellipse.

Example: Impact of Measurement Errors

The measurement errors incorporated in the tool are also important contributors to the size of the error ellipse. Again, returning to the same scenario as the first example with two receivers positioned advantageously, we see the impact of the error inherent in a receiver's ability to measure its own position and velocity, σ_p^2 and σ_v^2 respectively. These impacts are shown in Figure 2.6 and Figure 2.7.

Figure 2.6
Ellipse with Reduced Position Error

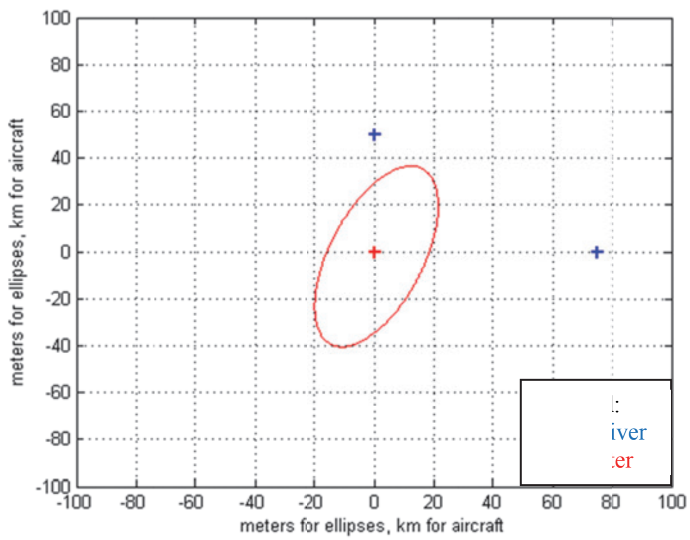
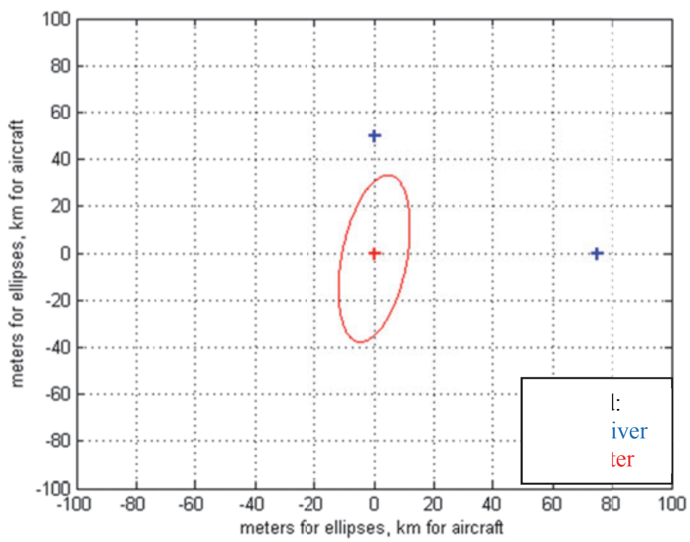
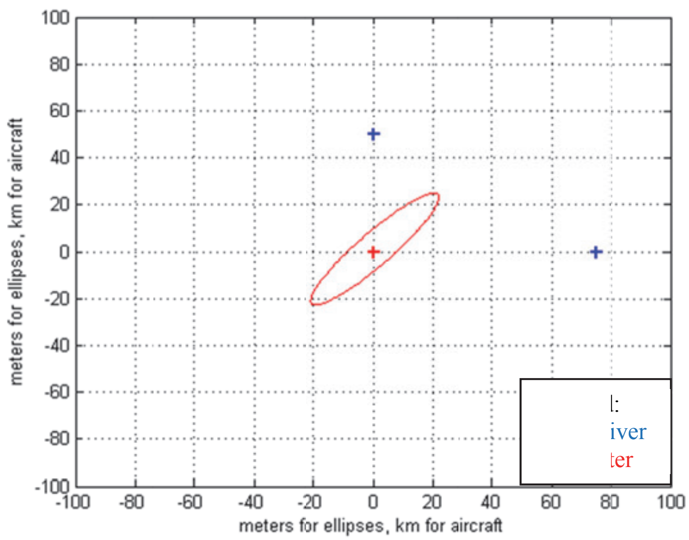


Figure 2.7
Ellipse with Reduced Velocity Error



Reducing the error in the position measurement by half results in a slight reduction of the error ellipse to $2070m^2$. Reducing only the error in velocity measurement by half reduces the error ellipse to $1230m^2$.

Figure 2.8
Ellipse with Reduced Time Synchronization Error



Alternatively, decreasing the time synchronization error between the receivers by a factor of 10 reduces the error ellipse to $615m^2$. The tool is also capable of handling scenarios in three dimensions. The result is an accuracy ellipsoid that incorporates uncertainty in the estimation of the altitude of the emitter.

The T/FDOA Accuracy Estimation Tool can provide useful information across a variety of applications. The tool can be used to predict the T/FDOA geolocation accuracy given a specific application. It can also be leveraged for research, such as the quantitative analysis in this dissertation. For this research, the tool was needed to evaluate the accuracy of T/FDOA as a means of quantifying the benefits of T/FDOA geolocation.

3. When Is T/FDOA Geolocation Useful?

This chapter focuses on whether T/FDOA geolocation would be useful as a capability added to UAS operating today. Specifically, I am interested in whether T/FDOA would fill a gap and be a practical capability on UAS. The accuracy of the geolocation of a signal is dependent on the method of geolocation used, the characteristics of the scenario, and the signal of interest. Direction finding is a common geolocation technique; however, T/FDOA geolocation offers distinct advantages over direction finding. I explore these advantages using a simple model of direction finding to contrast the two techniques. The model is described in Appendix A.

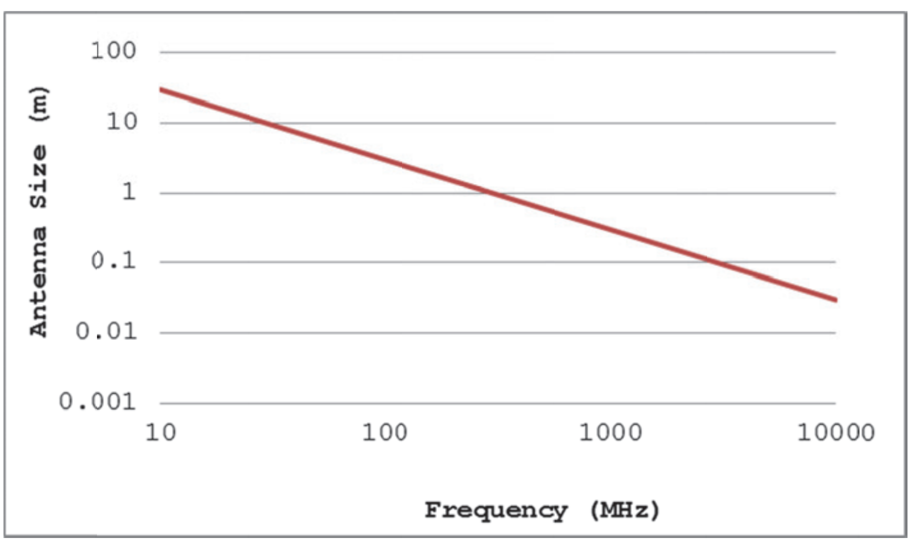
Two major shortcomings of T/FDOA geolocation are the sensitivity of geolocation accuracy to the geometry of the receivers and the target and the requirement for multiple equipped platforms. I explore these two drawbacks in the context of today's operating environment. Today, multi-intelligence capable platforms are tasked with one intelligence priority (e.g., full-motion video-prime), and the orbit flown is optimized for that mission. If T/FDOA were to be added to UAS, I assume that UAS would continue performing their primary mission as tasked today, with geolocation done as a secondary mission. I examine the impact of the orbit geometries dictated by the primary intelligence mission on the expected geolocation accuracy using the T/FDOA Accuracy Estimation Tool. For T/FDOA geolocation, the multiple equipped platforms must be operating within line of sight of the same target. Using a combination of geospatial analysis and the T/FDOA Accuracy Estimation Tool, I analyze the line of sight coverage overlap and the resulting accuracy for specific targets in the current operating environment.

A Contrast of Direction Finding and T/FDOA Geolocation

In the Introduction, some advantages and drawbacks to the traditional geolocation technique of direction finding and T/FDOA geolocation were briefly discussed. T/FDOA and direction finding are difficult to directly compare, because the accuracy of each technique is sensitive to variables that are specific to each application. It is more useful to contrast the techniques. This section goes into more depth on the advantages of T/FDOA geolocation by contrasting the two techniques. I describe the difference in antenna requirements for each technique and the implication for hosting the antenna on an airborne platform. The accuracy of direction finding is in part dependent on the time that the baseline is flown. I then contrast this time element of each technique. The geometry of the specific application impacts the accuracy of either technique; however, the range between the target and the receiver also influences the accuracy for direction finding.

For a system to use direction finding, it must be equipped with a directional antenna. The capability of a directional antenna to capture signals of different frequencies is directly related to its size. A rule of thumb is that the diameter of a circular antenna must be at least the length of the signal wavelength (Elbert 2008). The minimum circular antenna size required as the signal frequency increases is shown in Figure 3.1.

Figure 3.1
Antenna Size vs Frequency



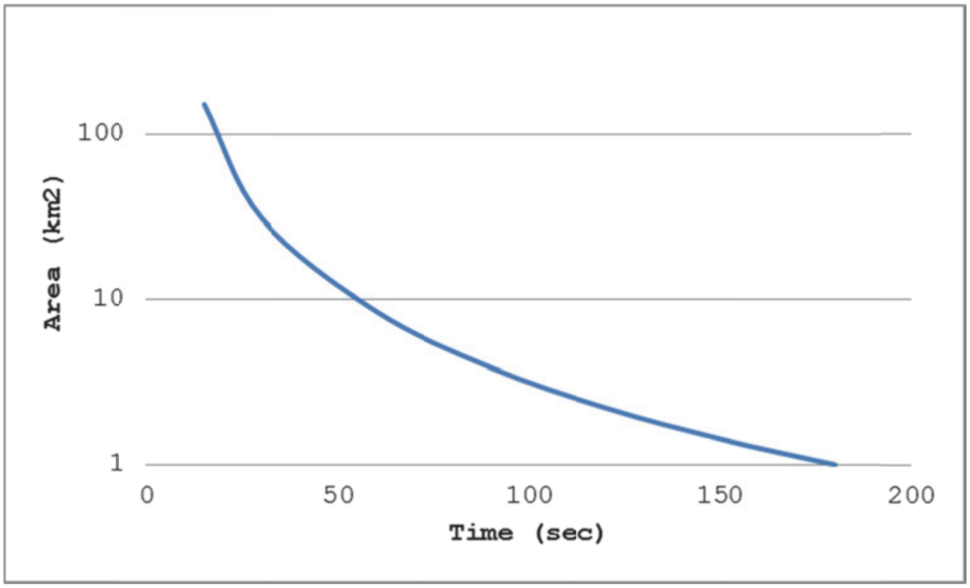
Tactical communications, such as military push-to-talk radios, often operate in the HF and VHF bands, around 10-300MHz. Attempting to geolocate these types of signals using airborne direction finders can result in unwieldy antennas. For example, locating a 35MHz signal would require an antenna with an approximately 8.6m (~28ft) diameter. To target a 300MHz signal, the edge of the VHF band, requires a directional antenna to have a 1m (3ft) diameter. To put this in perspective, the MQ-1 Predator is only 27ft long, with a 55ft wingspan (ACC Public Affairs 2012). Its much larger counterpart, the MQ-9 Reaper, is 33ft long and has a 66ft wingspan (ACC Public Affairs 2012). Placing a directional antenna capable of receiving VHF band frequencies on a UAS is difficult because of the size, weight, and power (SWAP) limitations inherent with an airborne vehicle. In contrast, T/FDOA geolocation does not require a directional antenna. Instead, a smaller non-directional antenna can be used.[12]

To perform direction finding, an aircraft flies a baseline, measures multiple lines of bearing (LOBs), and then correlates those LOBs to determine the position of the target. The accuracy of direction finding is partly dependent on the length of the baseline, which can be thought of as a length of time. As the length of time a baseline is flown increases, the accuracy of direction finding increases. This relationship is shown in Figure 3.2.

---

[12] There are additional benefits to a directional antenna. For example, it provides gain, which improves the signal-to-noise ratio. A non-directional antenna does not have that benefit.

Figure 3.2
Time of Baseline impacts Direction Finding Accuracy

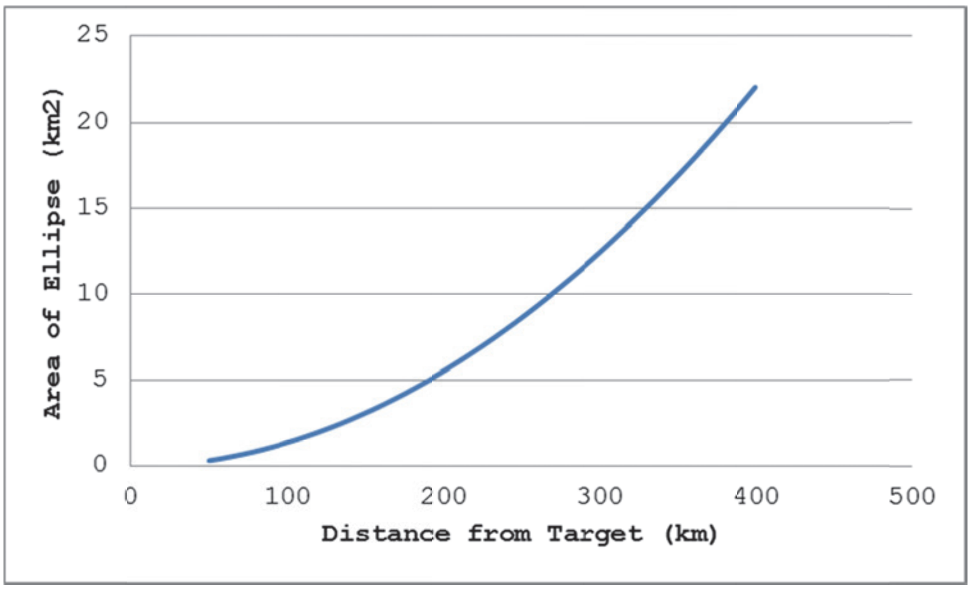


NOTE: Calculations used the DF Model, explained in Appendix A. Assumptions included a range of approximately 125km, an AOA accuracy of 0.08deg, airspeed of 340kts, and a 3sec measurement interval.

In general, accurate direction finding needs a baseline of a few minutes. For a medium accuracy geolocation of $1km^2$, a baseline of approximately three minutes would be needed. The accuracy is therefore dependent on a cooperative target that continues to emit throughout the entire baseline. T/FDOA geolocation is not dependent on the length of time of collection. The collection can be extremely short, because the accuracy of T/FDOA geolocation is impacted by the timing synchronization of the correlated signals and not the length of the emission.

The accuracy of direction finding is more dependent than T/FDOA on the range between the receiver and the target emitter. In general, the closer the receiver is to a target, the better the accuracy of geolocation. Since T/FDOA takes advantage of the differences in time and frequency of arrival, T/FDOA does not suffer the same geometric issue related to range as direction finding. For direction finding, the accuracy degrades in a linear fashion with range. This relationship is shown in Figure 3.3. The ratio of the signal strength to noise level, the signal-to-noise ratio (SNR), impacts the accuracy for both direction finding and T/FDOA. The greater the range to the target, the lower the SNR and the more degraded the accuracy. In T/FDOA, the SNR is part of the error contribution from the Cramér-Rao lower bounds. Bardelli, Haworth, and Smith (1995) found that the Cramér-Rao lower bounds on T/FDOA measurement are typically very small and not the dominate source of error. Provided there is an adequate SNR such that T/FDOA can be calculated, there is little dependence on range, compared with direction finding.

Figure 3.3
Range to Target Impacts Direction Finding Accuracy



Calculations used the DF Model, explained in Appendix A. Assumptions included a baseline of approximately 120sec, an AOA accuracy of 0.08deg, airspeed of 340kts, and a 3sec measurement interval.

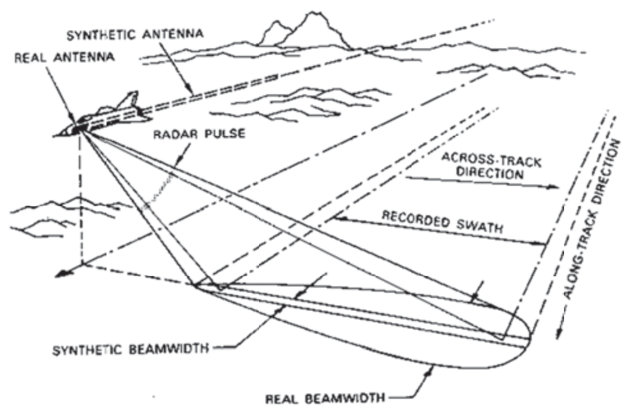
These three advantages—lack of requirement for directional antenna, lack of dependency on emission duration, and lack of dependency on range to target—of T/FDOA geolocation over direction finding make T/FDOA more robust in the types of emitters that can be targeted and less dependent on a cooperative target. A major drawback to T/FDOA is the requirement that multiple platforms receive the same signal and are able to cooperate to geolocate the target. If it were possible to use T/FDOA geolocation in a non-intrusive manner on UAS platforms equipped with other intelligence sensors and continue to achieve highly accurate geolocation, T/FDOA geolocation could greatly expand the geolocation capabilities of the military. The next section investigates the feasibility of using T/FDOA geolocation in a non-intrusive manner on UAS and quantifies the accuracy of geolocation that would be achieved.

Types of Intelligence and Resulting Orbits

The Air Force categorizes ISR into five intelligence disciplines. These are geospatial intelligence (GEOINT), signals intelligence (SIGINT), measurement and signature intelligence (MASINT), human intelligence (HUMINT), and open-source intelligence (OSINT). Geospatial intelligence is the "exploitation and analysis of imagery and geospatial information to describe, assess, and visually depict physical features and geographically referenced activities on the Earth" (U.S. Air Force 2012). Imagery intelligence (IMINT) is a subcomponent of GEOINT that is defined as images that are recorded and stored (U.S. Air Force 2012). IMINT includes radar, infrared, or multispectral imagery, traditional visual photos, and full-motion video. This analysis focused on the various types of IMINT because those are the types of sensors most often hosted on UAS. The next several paragraphs explain intelligence missions that can be accomplished using UAS and the orbit requirements for each particular intelligence type.

Synthetic Aperture Radar. Synthetic aperture radar (SAR) was developed in the 1950s. It is used to image large areas at very high spatial resolution. In radar, an antenna transmits and receives radio waves to illuminate a scene. The range resolution is determined by the bandwidth of the signal transmitted, and the cross-range resolution is determined by the length of the antenna. An airborne antenna provides a good vantage point but physically limits the length of the antenna. For SAR, a small antenna is put in motion, transmitting and receiving signals to synthesize a much larger antenna, for example, an antenna several kilometers long, to achieve good cross-range resolution. SAR depends on specific algorithms to reconstruct the scenes into images. Most of these algorithms assume a straight flight path; any deviations are treated as motion error (Berens 2006).[13] A platform using SAR would fly in straight paths at a constant altitude with the swath width of the sensor as the width between passes.

Figure 3.4
SAR Requires a Straight Flight Path



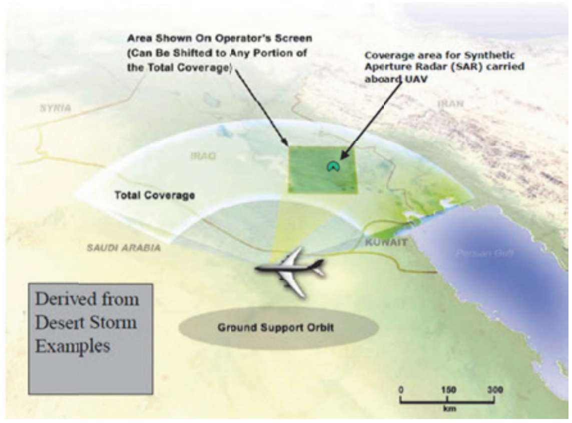
SOURCE: Image from FAO Fisheries and Aquaculture Department (1988).

Ground Moving Target Indicator. Ground moving target indicator (GMTI) is another intelligence collection technique that leverages radar. GMTI detects, locates, and tracks targets that are moving on the surface. For GMTI, the Doppler shift in the frequency of radar returns from a moving target is used to discriminate it from the static surface background (Dunn, Bingham, et al. 2004). GMTI was originally designed to distinguish movements of large objects, such as tanks and trucks, for battle space awareness. When employing GMTI, the platform is typically flown parallel to the area of interest in order to have the most coverage of the area. This results in an elliptical orbit with a small minor axis. A GMTI orbit derived from examples during Desert Storm is shown in Figure 3.5.

---

[13] Algorithms for SAR image formation using alternative flight paths have been developed, but are not commonly used (see Soumekh, 1999).

Figure 3.5
GMTI Is Often an Elliptical Orbit



SOURCE: Dunn, Bingham, et al. (2004).

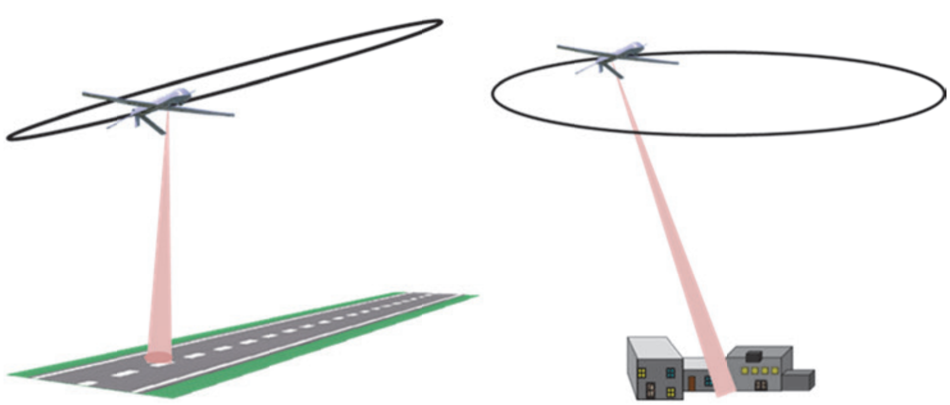
Imagery. By *imagery*, I mean still images generated from an optical sensor. Among other things, imagery is useful in identifying and providing visual information on targets of interest. In airborne applications, aircraft altitude and slant range affect the resolution and image quality. The path or orbit is not prescribed by the intelligence type, but is more dependent on the target deck[14] and efficiently prosecuting all targets. The target deck is likely different each day. A unique scheme of maneuver is developed for each mission; it outlines a track to capture all the requested imagery at the necessary resolution, in the most efficient manner possible. Figure 3.6 shows an example of a scheme of maneuver for imagery.

[14] The target deck or collection deck is a list of all the targets that need to be collected against.

Figure 3.6
IMINT Does Not Dictate an Orbit

Full-Motion Video. The demand for full-motion video (FMV) grew immensely during operations in Iraq and Afghanistan. FMV sensors are typically a turreted pod with dual electro-optical (EO) and infrared (IR) camera systems that permit operation across day and night. FMV is used in many tasks, with the task often determining the orbit flown. This analysis focuses on two common FMV orbits, a racetrack orbit and a circular orbit. A racetrack orbit would be used for a task such as monitoring a road for IED activity. A circular orbit would be used for a task such as providing 360-degree coverage of a compound prior to or during a raid. Figure 3.7 illustrates both of these orbits.

Figure 3.7
Racetrack Orbit for Road Surveillance and Circular Orbit for 360-degree Coverage of Compound



Missions Have a Primary Intelligence Focus

Today, most UAS are tasked as ISR assets through the Combined Air Operations Center (CAOC). The CAOC takes in all the requests for ISR support, prioritizes the requests, and assigns the available air assets to fulfill the requests (U.S. Air Force 2011). Although many UAS are equipped with multiple sensors, when they are tasked by the CAOC, they are usually tasked with one intelligence type as their primary mission, for example, IMINT-prime or SIGINT-prime (AFISRAI-14-153 2009). The mission is planned to maximize the quality of the intelligence gathered. This results in a plan to collect the intelligence targets from an optimum altitude, velocity, distance, or angle to the target. In this way, the intelligence needed drives the orbit the platform will fly when collecting the intelligence.

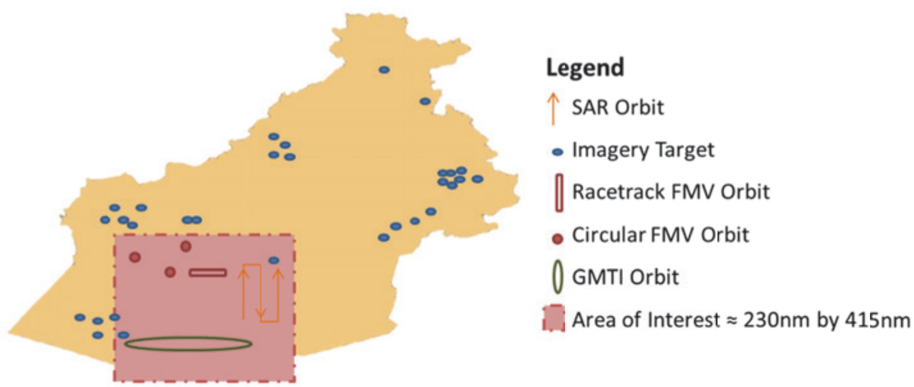
SIGINT is typically provided by manned assets (Thompson 2004). UAS are predominately tasked for their imagery sensors, such as FMV. If a T/FDOA capability was added to UAS, multiple platforms would need to receive the signal in order to determine the probable location using T/FDOA geolocation. Given the high demand for FMV collection and the requirement for multiple platforms, T/FDOA geolocation would likely be accomplished as a secondary mission. The accuracy of T/FDOA geolocation is sensitive to the geometry between the collectors and the target. As discussed above, the different intelligence types dictate specific tracks or orbits that must be followed with different levels of rigorousness. The goal of this section is to show what level of accuracy might be expected if T/FDOA geolocation was included as a secondary mission.

Scenario for Modeling Accuracies

During a day of operations, there will likely be several different intelligence collection missions operating within the same geographic area. Figure 3.8 shows an example of all the different intelligence missions that might be within line of sight of the same targets. There might be a standing target deck for IMINT collections, represented by the blue dots, from a manned or unmanned platform. JSTARS (the joint surveillance and target attack radar system) might be tasked to use its

GMTI radar for border surveillance, shown as the green ellipse. Several MQ-1/MQ-9s might be using FMV to provide over-watch of a house raid, follow a high-value target, or cover a stretch of road to monitor for IED activity, as represented by the red circles and red ellipse. An MQ-9 equipped with SAR might be collecting high-quality terrain data or doing coherent change detection, shown by the orange track. All of these platforms might be operating within line of sight of a target emitter and capable of opportunistic collection on this target emitter, represented by the red box.

Figure 3.8
Operations Might Be in the same Area



For this analysis, I assumed that the T/FDOA system is capable of operating out to the radar horizon.[15] The radar horizon is dependent on the altitude of the platform. The altitudes that were used in these scenarios and the resulting geometric and radar horizon are listed in Table 3.1.

---

[15] If externals are collected, a system is theoretically capable of detecting signals out to the radar horizon.

Table 3.1
Line of Sight Limitations

Altitude[16] (kft/km)	Geometric Horizon (nm/km)	Radar Horizon (nm/km)
15 (4.572)	130 (241)	151 (280)
20 (6.096)	151 (280)	174 (322)
25 (7.620)	168 (311)	194 (359)
30 (9.144)	184 (341)	213 (394)

This analysis used five scenarios, with four different orbit geometries modeled: Circular FMV, Racetrack FMV, SAR, and GMTI. The focus was on intelligence types where the orbit is repetitive and must be followed with some level of rigorousness. For this reason, still imagery was not included in this analysis. As discussed above, the track an imagery mission uses is dependent on the collection target deck for that specific mission. It therefore does not require a repetitive orbit, and could be altered to participate in a T/FDOA collection. The scenarios featured two platforms flying to conduct their primary mission. The five scenarios that were modeled are summarized in Table 3.2.

Table 3.2
Scenarios for Orbit Geometries

Scenario	Orbit of #1	Orbit of #2
1	Circular FMV	Circular FMV
2	SAR	Circular FMV
3	SAR	Racetrack FMV
4	GMTI	Circular FMV
5	GMTI	Racetrack FMV

I varied the type of orbit flown, according to the above scenarios, and the parameters of the orbit. These parameters were meant to exemplify a few typical orbits.[17] The inputs for the orbits are summarized in Table 3.3.

---

[16] Calculated as slant range based on spherical earth, with 0 deg elevation angle.

[17] These parameters were developed in conjunction with members of the dissertation committee. The purpose was not to outline specific tasks and targets for each orbit, but to provide a few notional but practical examples of orbit geometries.

Table 3.3
Orbit Inputs

	GMTI	SAR	Racetrack FMV	Circular FMV
Altitude	30k, 25k, 20k	30k, 25k, 20k, 15k	30k, 25k, 20k, 15k	30k, 25k, 20k, 15k
Speed*	200kts	200kts	200kts	200kts
Orbit Type	Ellipse	Up and Back Track	Racetrack (ellipse)	Circle
Parameters	100-150km, 20-50km	150km path, 2km turn	40-50km, 5-10km	20km or 10km radius

*Speed is constant; however, velocity is calculated based up the orbit.

The other parameters for the T/FDOA Accuracy Estimation Model were held constant throughout this analysis. In preliminary analysis, these parameter values were chosen as a representative case.[18] These parameters, values, and an explanation are listed in Table 3.4.

Table 3.4
Other Model Parameters held Constant

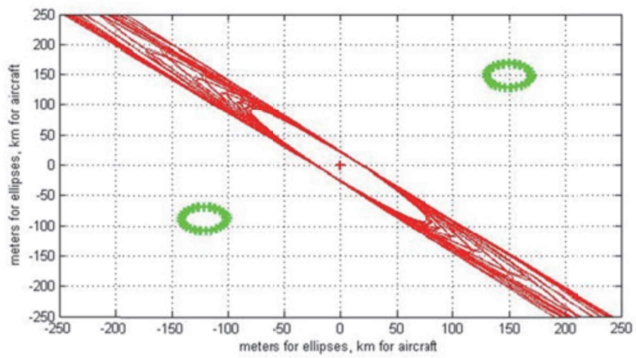
Parameter	Value	Explanation
Target Location	[0,0,0]	Orbits were rotated around target to account for geometric differences in target location
Number of T/FDOAs	1 TDOA, 1 FDOA	This represents a lower bound on the expected accuracy. At least 1 TDOA and 1 FDOA is required for T/FDOA geolocation.
Frequency of Signal	164 MHz	A representative VHF signal
Bandwidth of signal	25 kHz	A representative noise bandwidth
Integration Time	30 sec	Time for integration of signals
Power	7 dBW	5W EIRP, a typical power for a VHF push-to-talk radio
Sigma P	10.2m	Based on GPS P(Y) code error
Sigma V	5cm/sec	Based on typical error for GPS or low grade IMU
Sigma T	100×10^{-9} sec	10 times the worst case GPS clock synchronization error
Two D	1	Indicator for if third dimension (altitude) is known

For each scenario, I modeled 10 cases in which the orbit parameters and orbit distances to the target were varied. Each case was run 50 times with a randomized starting point on the orbit for both

[18] There is a discussion of the impacts of parameters/errors in Chapter Two.

platforms. Within each run, one orbit was rotated around the target to account for differences in geometric orientation and velocity relative to the target. At each rotation point, the orbits were run for 25 position steps, resulting in 200,000 model runs for each scenario. The full results for each scenario are included in Appendix B. An example from Scenario 1: Two Circular FMV Orbits is shown in Figure 3.9.

Figure 3.9
Example of Geolocation Accuracies from Scenario 1



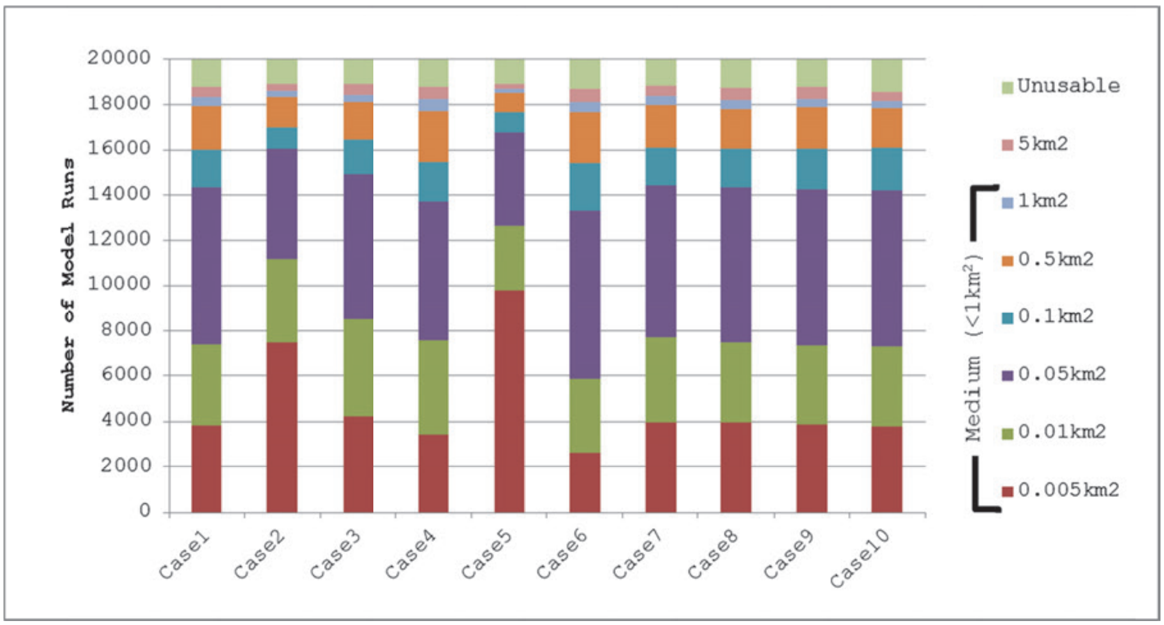
In this example, the target is represented by the red cross. The two UAS orbits, represented in green, are circular orbits centered at (150km, 150km) and (-75km, -125km), respectively. Each red ellipse represents a T/FDOA geolocation in square meters resulting from those orbits. The geolocation is very sensitive to geometry.

Results from Orbit Geometries

The results from Scenario 1: 2 Circular FMV Orbits indicate that, in most instances, very good accuracies can be achieved with this orbit configuration. A histogram of the area of the ellipses for each case is shown below in Figure 3.10. However, even when the primary mission orbits are placed closely together, there is still enough diversity in the geometry to result in a majority of medium accuracy geolocations.

Some configurations achieved overall better accuracies than others, for example, Case 5. The number of low and extremely low accuracies, those with an area greater than $1km^2$, was fairly consistent and low across all the cases. However, examining only those geolocations within at least medium accuracy (<1km^2), there is not much stability between the cases. The placement of the orbits in relation to each other drives some areas to be significantly better than others. However, even when the primary mission orbits are placed closely together, there is still enough diversity in the geometry to result in a majority of medium accuracy geolocations.

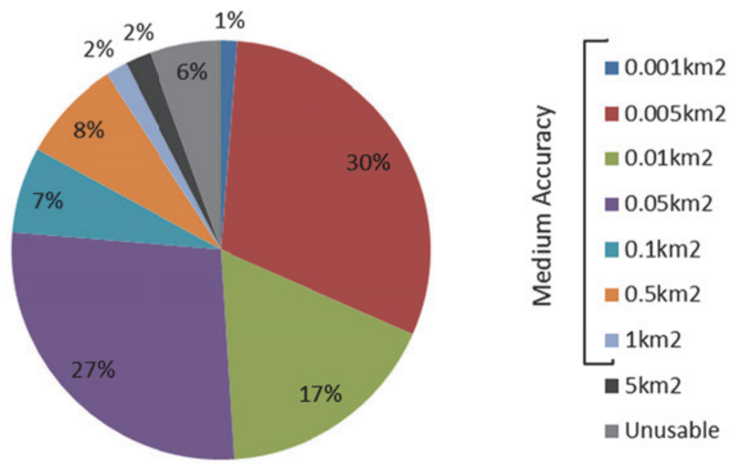
Figure 3.10
Histogram of Areas from Scenario 1



Examining these results categorized only by the area of the ellipse shows that over 90 percent of the geolocations resulted in medium (<1km^2) accuracy. Almost 75 percent of the geolocations had an area less than 0.05km^2, and a little under a quarter were actually within 0.005km^2. Of the approximately 8 percent of geolocations greater than medium accuracy, about 2 percent were of low accuracy (<5km^2), and 6 percent were unusable, resulting in no solution. The situations that did not result in a geolocation were the result of poor geometry.

The results from Scenario 1 indicate that, in most cases, the geometry created by the orbits optimized for FMV intelligence collection will still yield acceptable accuracies. Individually, the other scenarios had similar results. Results for all the scenarios are included in Appendix B. Tabulating the data across all the scenarios, the outcomes remain consistent.

Figure 3.11
Results for 5 Scenarios: Percent Distribution of Error Ellipse Areas



The analysis shows that T/FDOA geolocation is robust to the various orbit combinations. In these partly random, non-optimized scenarios, medium-level accuracy geolocations were achieved consistently. Approximately 90 percent of the geolocations were medium accuracy. Occasionally, the geometry will be poor enough to cause geolocation to fail. The geolocation failures were spread fairly evenly across each scenario, and amounted to approximately 6 percent of the total geolocations. In the instances of poor geometry, the two orbits were usually very close to each other, causing small differences in both the timing and the frequency. Infrequently, the geolocation resulted in high accuracy ellipses of less than $100m^2$. Ideally, high-accuracy geolocation would be preferred each time; however, these results can be thought of as an upper bound. For this analysis, I used only two aircraft, the minimum required for T/FDOA geolocation. More sensors would, in general, improve the accuracies. This analysis shows that as a secondary mission, on a completely non-interference basis, T/FDOA geolocation could be expected to provide at least medium-level accuracy in most instances. This level of accuracy could likely be improved with the addition of more sensors or including minimal planning for T/FDOA geolocation to coordinate orbit start times, orbit locations, etc.

Would UAS Operate Close Enough to Leverage T/FDOA?

To use T/FDOA geolocation, we need at least two platforms with line of sight to the target emitter. I used a model to characterize whether UAS fly close enough to use T/FDOA geolocation in Afghanistan. By FY13, the Air Force plans to have 65 available combat air patrols (CAPs) of MQ-1/9s (Schanz 2011). I used the ArcGIS software to model the CAPs and their line of sight ranges. The model randomly distributes the CAPs throughout the area of interest. It first determines the areas that are within line of sight of each CAP. These areas represent the potential coverage area for SIGINT. Then, it finds the areas that can be seen by multiple CAPs. These areas represent the potential regions for T/FDOA geolocation. The model does not taken into consideration limitations on line of sight caused by terrain. The model is explained in Appendix C. Air assets are typically apportioned according to a weight of effort (Joint Chiefs of Staff 1994). A weight of effort during the height of Operation Enduring Freedom and Operation New Dawn might have been 60 percent Afghanistan, 30 percent Iraq, and 10 percent for the rest of the world. I focused on Afghanistan as the bounding geometry.[19] I modeled the presence of 5, 10, 15, and 20 CAPs in the air simultaneously at four different altitude levels.[20]

As mentioned above, T/FDOA geolocation requires at least two aircraft. I first examined the potential T/FDOA geolocation areas or those areas covered by at least two CAPs. An example of the coverage available with 10 CAPs is shown in Figure 3.12, with green representing areas that are covered by at least two CAPs, red representing areas

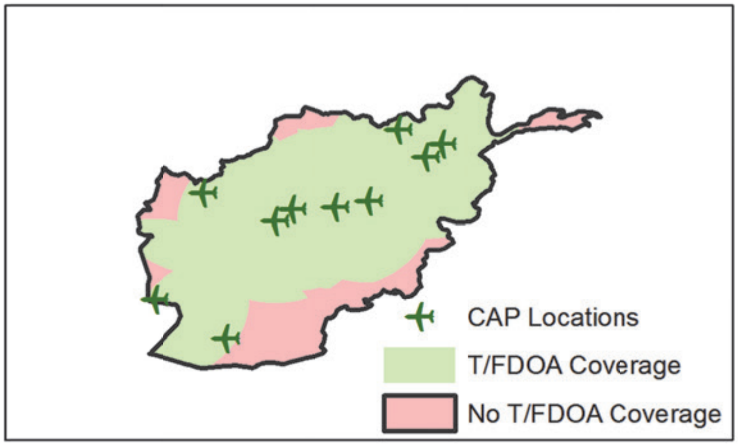
---

[19] I use Afghanistan for the bounding geometry, however I ignore the line of sight limitation of terrain. The results would be similar for any country or area of interest of similar size to Afghanistan.

[20] By FY13, the Air Force plans to have 65 available combat air patrols (CAPs) of MQ-1/9s (Schanz, 2011). These would be simultaneously available.

that are covered by only one CAP, and white representing areas with no coverage.

Figure 3.12
Example Coverage with 10 CAPS



Coverage improves as either altitude or the number of CAPs is increased. For example, the line of sight from five CAPs at 30,000ft would be able to cover almost the same area of Afghanistan as 10 CAPs at 15,000ft. These relationships are shown in Figure 3.13 and Figure 3.14.

Figure 3.13
Area Covered by Line of Sight as Altitude Increases

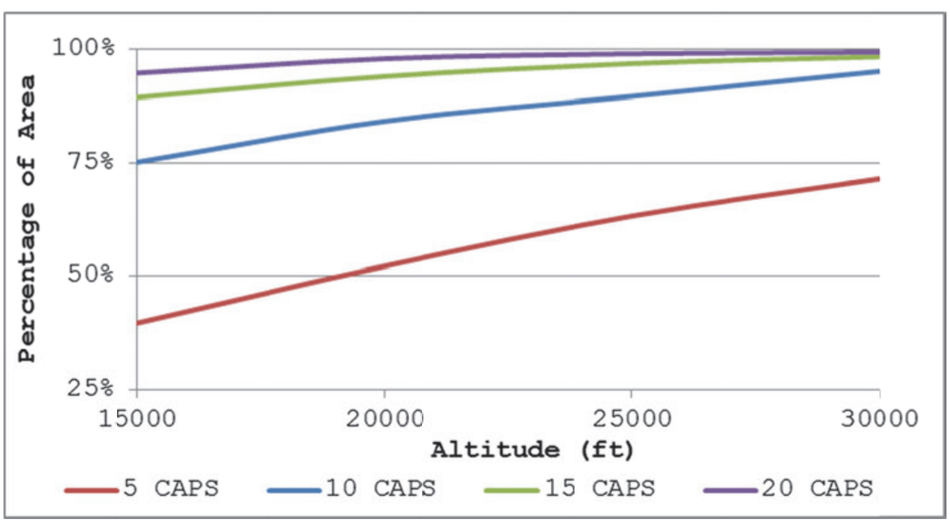
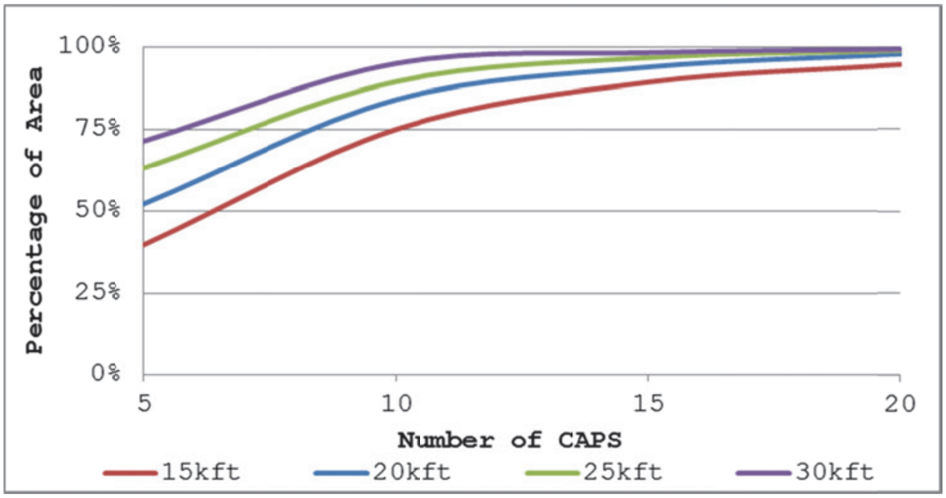


Figure 3.14
Area Covered as CAPs Increase



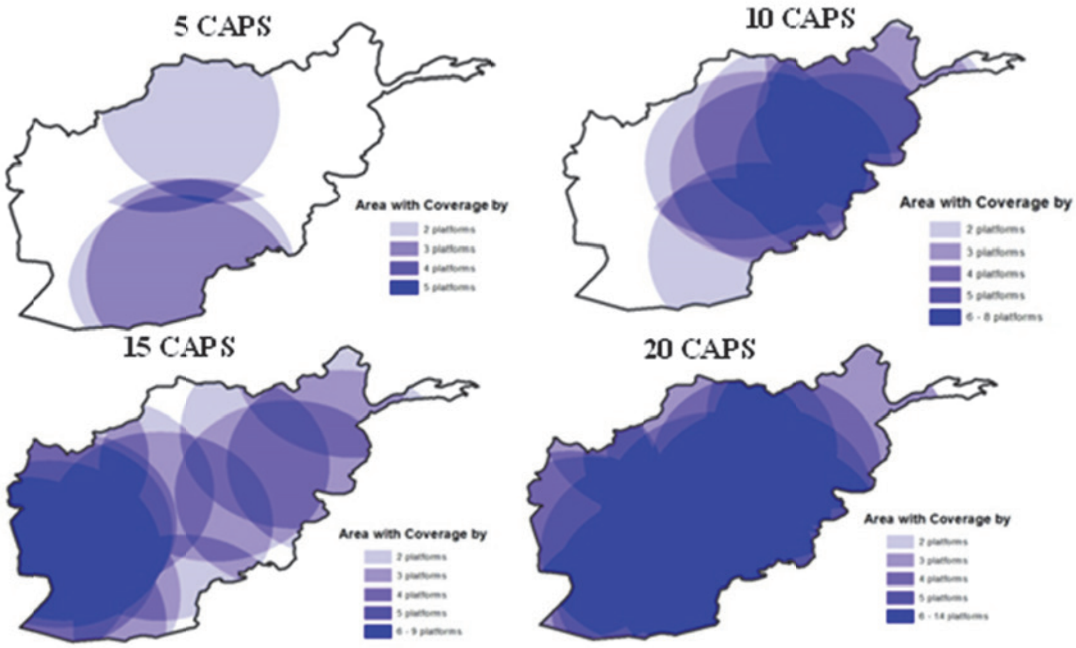
This analysis shows that a small number of UAS CAPs can provide T/FDOA coverage throughout most of an area the size of Afghanistan. Small increases in the number of CAPs and increasing the altitude significantly improves the amount of area covered.

In general, the accuracy of T/FDOA increases as the number of platforms participating in the geolocation increases. Though the accuracy is good when there are collections from two to three platforms, it can be remarkably better if more platforms are involved.[21] We can use the ArcGIS model to further determine exactly how many CAPs cover the area. Figure 3.15 below shows an example of the overlapping areas geographically for one example of 5, 10, 15, and 20 CAPs at an altitude of 20,000ft.

---

[21] Each new platform increases the number of TDOAs and FDOAs that are available for geolocation.

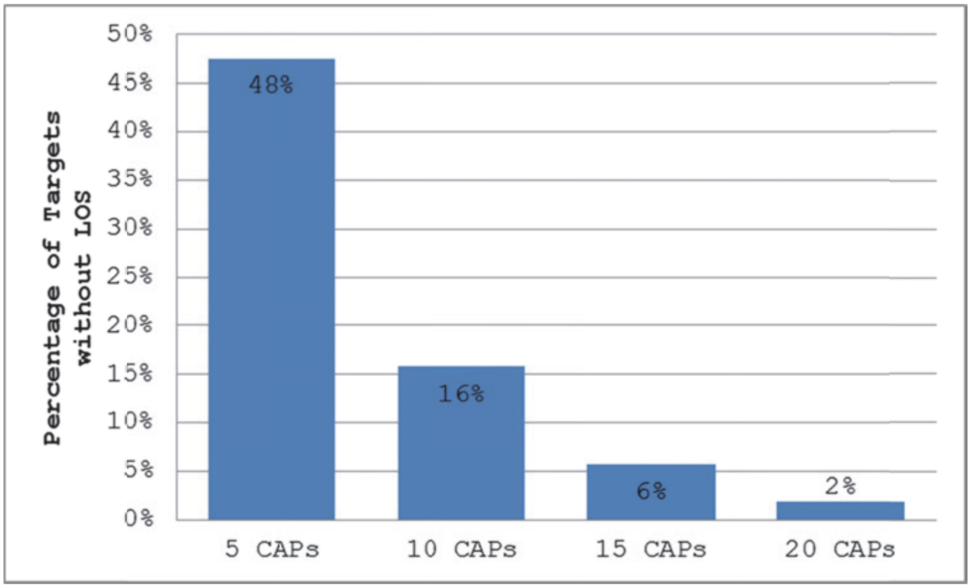
Figure 3.15
Coverage for 5, 10, 15, and 20 CAPs at 20,000ft



Increasing the number of CAPs available greatly increases the amount of area seen by more than two aircraft. As the area seen by four and five or more aircraft increases, the geolocation accuracy will also significantly increase. T/FDOA geolocation could be performed throughout most of an area the size of Afghanistan using only 20 CAPs; however would the accuracy of geolocations from these small numbers of CAPs be useable?

To test this, I used a combination of geospatial analysis with the T/FDOA Accuracy Estimation Model. I randomly distributed 20 targets throughout Afghanistan. The random location of CAPs from the previous analysis and the layer of random targets were used as inputs in the T/FDOA Accuracy Estimation Model. First, I examined the number of targets that were not within line of sight of at least two CAPs. These targets could not be found using T/FDOA geolocation. The number of targets without line of sight decreases as the number of CAPs increases, as shown in Figure 3.16. At 20 CAPs, the average number of targets that were unavailable was less than one.

Figure 3.16
Average Percentage of Targets Without Line of Sight at 20,000ft



Next, I examined the accuracies for the targets that were within line of sight using the T/FDOA Accuracy estimation tool.[22] With only five CAPs, only a handful of targets are found with medium or high accuracy. With 10 CAPs at 15,000ft, approximately 25 percent of the targets were located with medium or high accuracy. As the number of CAPs increases or as the altitude increases the number of targets found with medium or high accuracy also increases. With 20 CAPs at 30,000ft, just under 95 percent of the targets can be found with medium or high accuracy. The number of targets found with high accuracies increases more than the number found with medium accuracy. Figure 3.17 and Figure 3.18 below show these relationships for geolocations at both 15,000ft and 30,000ft.

---

[22] I used the same parameters for the other model inputs as listed in Table 3.4.

Figure 3.17
Results of Geolocations from 15kft

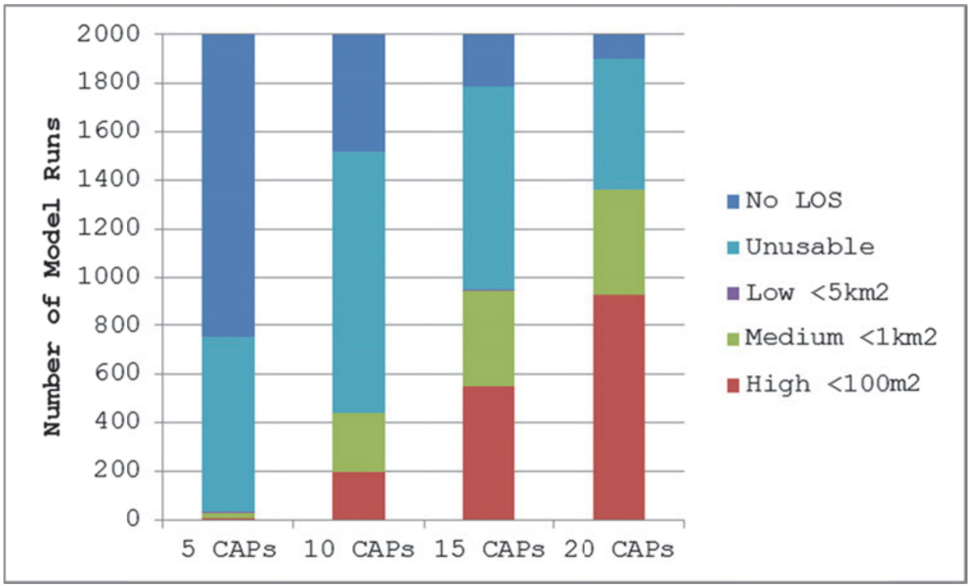
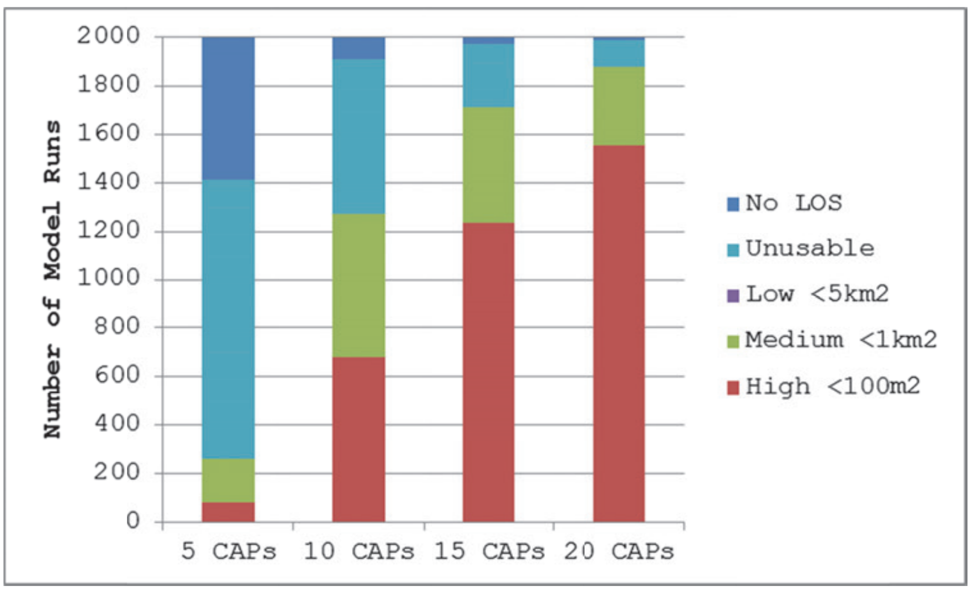


Figure 3.18
Results of Geolocations from 30kft



The results from the analysis indicate that UAS operating in Afghanistan or another similar sized area would be close enough to use T/FDOA throughout most of the area. The geolocations from these UAS have the potential to be very accurate. A few additional UAS CAPs greatly increases the likelihood of successful, accurate geolocation. Increasing the altitude at which the UAS are flown also has a significant impact on the amount of medium and high accuracy geolocations. In practice, there would be a trade-off between increasing the altitude for geolocation and impacting the spatial resolution of the primary intelligence.

Conclusion

The analysis shows that T/FDOA geolocation would be a very useful capability on UAS. When contrasted with direction finding, T/FDOA is more robust in several key ways that make geolocation of signals like push-to-talk radios less challenging. T/FDOA needs only a non-directional antenna, which is less SWAP restricting. T/FDOA is nearly instantaneous, and the accuracy degrades less with range. I explored the two major limitations of T/FDOA geolocation, sensitivity to the geometry of the receivers and the requirement for multiple equipped platforms, using geospatial analysis and the T/FDOA Accuracy Estimation Tool. The results indicate that T/FDOA would provide high-quality geolocation accuracy even as a secondary mission. The different orbit geometries have only minor impacts on the geolocation accuracy. In all of the orbit combinations, medium-accuracy geolocations accounted for nearly 90 percent of all the geolocations. Many of these medium-accuracy geolocations were closer to the high accuracy threshold.

I can conclude that the geometries created by the different orbit combinations are sufficient for quality T/FDOA geolocations. For T/FDOA geolocation to be possible, the participating platforms must be within line of sight of the same target. I explored this question and determined that with a fraction of today's available UAS CAPs, there would be enough T/FDOA coverage to cover most of an area the size of Afghanistan. The accuracies available from these UAS CAPs were of extremely high quality. With only 20 UAS CAPs at 30,000ft, almost 95 percent of the targets were found with high or medium accuracy.

This research used Afghanistan as the bounding geometry. The results would hold for countries of similar size. Modeling the impact of line of sight limitations caused by terrain features was not the point of this research. In general, terrain can impact the line of sight for emissions. Some areas that would be seen with a flat earth would be blocked from view. These blockages would reduce the area for T/FDOA coverage and could impact the number of targets found.

T/FDOA geolocation would be useful addition that would provide supplementary geolocation capability and capacity, while still enabling the UAS assets to continue to conduct their current missions.

4. What Is Needed to Use T/FDOA Geolocation?

This chapter focuses on what would be needed for T/FDOA geolocation to be implemented on UAS. To be T/FDOA-geolocation-capable, the UAS will need to be equipped with a SIGINT system. I first outline specific requirements for a SIGINT system capable of T/FDOA. Then, I investigate the first T/FDOA capable system, AT3, to uncover technological and design challenges. Using AT3 as a guide, I detail integration on UAS and explain some challenges. An analysis of the costs of the SIGINT system is outside the scope of this work. A SIGINT sensor system on UAS will bring additional data that needs to be processed, exploited, and disseminated (PED) as intelligence. PED is often very manpower-intensive. I estimate the manpower needed for T/FDOA PED and the cost implications of the new manpower.

Equipment for Platforms to Be Capable of T/FDOA Geolocation

Two key choices to be made in designing a SIGINT system are the antenna and the receiver(s) to be used. These two choices drive the capabilities of the system. The system is usually described by several parameters, which are listed in the Table 4.1.

Table 4.1
System Parameters

Term	Definition
Gain	The increase in signal strength (dB) as the signal is processed.
Frequency coverage	The frequency range over which the system can transmit or receive signals.
Polarization	The orientation of the electric field of the radio wave.
Beamwidth	The angular coverage of the antenna (degrees).
Efficiency	Ratio of power radiated by the signal to power absorbed by the system.
Bandwidth	The instantaneous bandwidth of a signal that can be collected.

SOURCE: Adapted from Adamy (2001), p. 32.

For SIGINT tasks, the antenna choices are dominated by the ability to provide the required angular coverage (directional vs. non-directional), polarization, and frequency coverage. The receiver choice can be influenced by the information required for the task.

Channelized and digital receivers are the state of the art and the most capable. In previous years, they were considered too expensive and too SWAP-restrictive (Adamy 2001). Digital receivers offer several benefits over analog receivers that are important for a T/FDOA system. Additional channels are low-cost due to economies of scale (Hosking 2006). Digital receivers are low-powered with improved stability and accuracy and high reliability compared with analog receivers. In addition, the programmable nature of digital receivers means that often a software update is all that is needed to upgrade the receiver.

Requirements for T/FDOA

For a system to be capable of T/FDOA, it must first receive the signals. The antenna choice will be primarily driven by the signals of interest. For example, if the targets of interest are push-to-talk radios, then the antenna should provide the requisite frequency coverage of the UHF/VHF bands. A T/FDOA system must also be able to measure both the time of arrival and the RF frequency, so a simple receiver is not enough. Besides geometry, the largest drivers of T/FDOA accuracy are usually the timing synchronization error and the position errors. A T/FDOA system therefore needs the highest-quality timing and position inputs. T/FDOA requires coherent sensors. In this context, *coherent* has a broader definition than the traditional use of the term. A coherent sensor must "provide precise control of amplitude, frequency, and carrier-phase offsets, and must also take into account propagation delays" (Kosinski 2003). It must also provide precise location, timing, and axial orientation to every other sensor that will participate in the T/FDOA calculation. Since T/FDOA is a cooperative technique with geographically separated receivers, a data link is required to pass the data needed to calculate each T/FDOA.

AT3 System

The AT3 system is the first T/FDOA capable system designed from scratch. It was designed to be functional on any tactical platform. It leveraged and created new technology to create an affordable package with minimal SWAP burden. The goal for AT3 was an accuracy of at least 50m circular error probable (CEP) at distances greater than 50nm in less than 10secs (Highnam 2001). The T/FDOA techniques require precise measurement of time and frequency as well as transferring that information between participating collectors and conductors of the requisite PED. The precision requirements drive the system components used in AT3. Table 4.2 shows the key components of AT3 needed to accomplish T/FDOA and their functions within the system.

Table 4.2
AT3 Sensor System

Component	Function	Key Features
Radome	Protect antennas from weather, reduce drag on aircraft	Broad band
Antennas	Transduce RF energy into system	Broad band, wide field of view
RF Down Converter	Translate RF signals to an intermediate frequency	Broad band, low noise, wide IF bandwidth
Digital Receiver	Extract signal information from IF	Wide band, high-speed ADC, high sensitivity
Local Oscillator	Provide reference signals for system and RF down-conversion	Low phase noise, narrow phase lock bandwidth
GPS	Provide time, frequency and position information	All-in-view receiver
Frequency and Time Board	Synchronize AT3 with GPS	System clock, GPS time and frequency transfer
Signal Processing	High sensitivity	High-resolution channelizer, many narrow band detectors
	Precision Time	Leading edge measurement

	Measurement Precision Frequency Measurement Geolocation	Phase measurement TDOA, FDOA, hybrid, derivative of GPS equation, erroneous measurement filtering
Data Link	Exchange data between aircraft	JTIDS, efficient slot utilization
	AT3 INSTRUMENTATION SYSTEM	
Cesium Clock	Time and frequency reference	Primary standard
Time Interval Analyzer	Time benchmark between system clock and Cs Clock	
Frequency Measurement System	Short time frequency measurement	Hybrid phase noise/TIA, short time frequency benchmark between reference LO and Cs
Secondary GPS	Time Space Position Information (TSPI)	Commercial survey quality, support kinematic survey of aircraft

SOURCE: adapted from Raytheon (2004), p. 18.

In designing the AT3 system, DARPA encountered several technical challenges that needed to be overcome. The long-range goal of at least 50nm meant that an extremely sensitive receiver was needed. To provide this sensitivity, a digital receiver with a low noise multi-octave RF down converter was used (Raytheon 2004). As mentioned above, T/FDOA requires extremely precise knowledge of position and velocity. DARPA integrated an inertial navigation system (INS) with GPS to determine the precise aircraft state vector (Highnam 2001).

There were also issues with meeting the time and frequency transfer requirements. A Kalman filter was used to help align the data from the analog-to-digital converter into GPS time reference (Raytheon 2004). To verify the accuracy of time and frequency transfer, AT3 employed cesium clocks on each platform that were calibrated before and after each flight (Raytheon 2004). There were no algorithms for tagging time of arrival and frequency of arrival at the low SNR levels that would be encountered. The engineers designed a hybrid algorithm that accurately tagged the leading edge as well as identified potential issues within the pulse (Raytheon 2004). Finally, AT3 was required to use the existing Joint Tactical Information Distribution System (JTIDS) as the data link to pass information. JTIDS is a widely used system with limited available bandwidth. The solution was to reduce the data transferred by limiting the number of platforms involved (Raytheon 2004). Only two collectors passed data to a third master platform for each geolocation, reducing the bandwidth needed for T/FDOA. The AT3 system resolved many key challenges for a T/FDOA system.

UAS Integration

T/FDOA can be accomplished with a non-directional antenna. UAS are already equipped with several non-directional antennas for communications purposes that could be leverage by a T/FDOA system. For example, the MQ-1B Predator is equipped with an AN/ARC-210 digital communication system that has a frequency range of 30-941MHz, which includes a UHF/VHF antenna on the top side and under side of the platform (ACC Public Affairs 2012; Rockwell Collins 2012). The presence of a UHF/VHF antenna would allow the UAS to host a T/FDOA system without any external modification to the platform. Following the path set by AT3, a digital receiver would be the best choice because of its performance capabilities. The system would need to be integrated with GPS/INS to provide the needed precision for the aircraft state vector.

The reliance of T/FDOA on precise measurements means the design of the system can have significant influence on the accuracy of geolocation. The location of the system in relation to the GPS receiver can potentially impact the accuracy, especially if the platform will be turning or banking frequently. For example, if a system was located on the wing of the aircraft while the GPS receiver was located centrally on the body of the aircraft, the input of the receiver positions will be inaccurate. If the aircraft flew straight, this difference could be easily factored into the T/FDOA calculation. However, if the aircraft is turning or banking, there could be a difference in all three coordinates (x,y,z) that could not be easily corrected. The inaccuracy with which the receiver position is known can create geolocation ellipses that misstate the accuracy. The severity of these misstatements increases as the geometry degrades.

Figure 4.1
Geolocation Error Ellipse Can Be Influenced by Location of GPS in Relation to Receiver

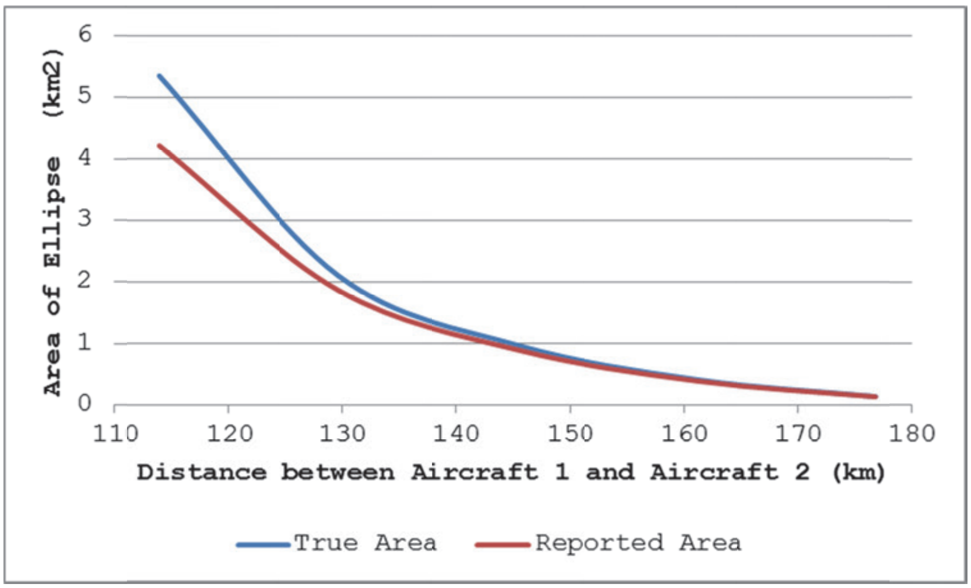


Figure 4.1 shows an example how the area of the ellipse can be misstated due to the position of the receiver in relation to the GPS receiver. In this example, two aircraft are used for the geolocation. One aircraft is in a simulated 30 deg bank. The banking aircraft is moved closer to the second receiver along a diagonal from the target location. Initially, the reported area overstates the true accuracy. However, as the geometry degrades, the reported area begins to understate the true accuracy.

The time interval for the reporting of the aircraft state vector can also influence the geolocation accuracy. These aircraft are moving at a typical speed of 200 knots, or about 100m/s in any given direction. The reporting frequency of the aircraft state vector can influence the accuracy of the state vector data, which in turn impacts the accuracy of geolocation. We can represent the impact of the reporting frequency as a change in the error terms for position and velocity. Figure 4.2 and Figure 4.3 show the impact of each error as it is increased and all other inputs are held constant.

Figure 4.2
Size of Error Ellipse Increases as Position Error Increases

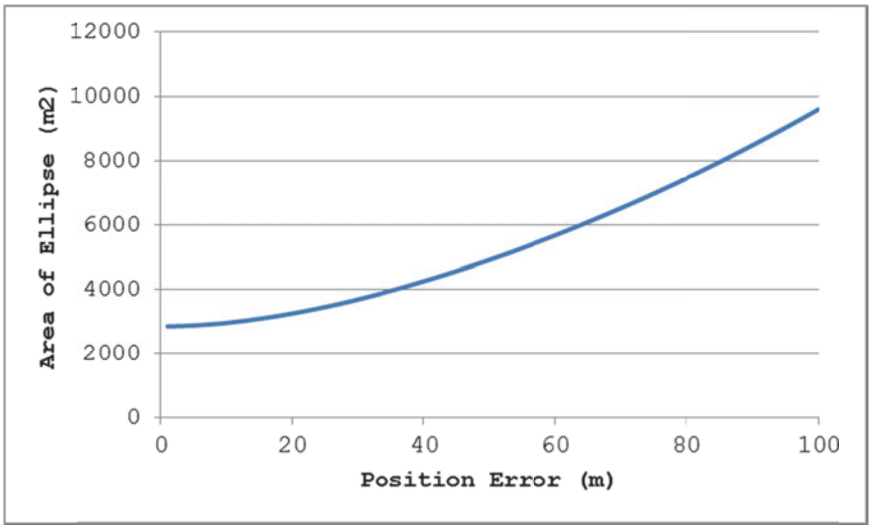
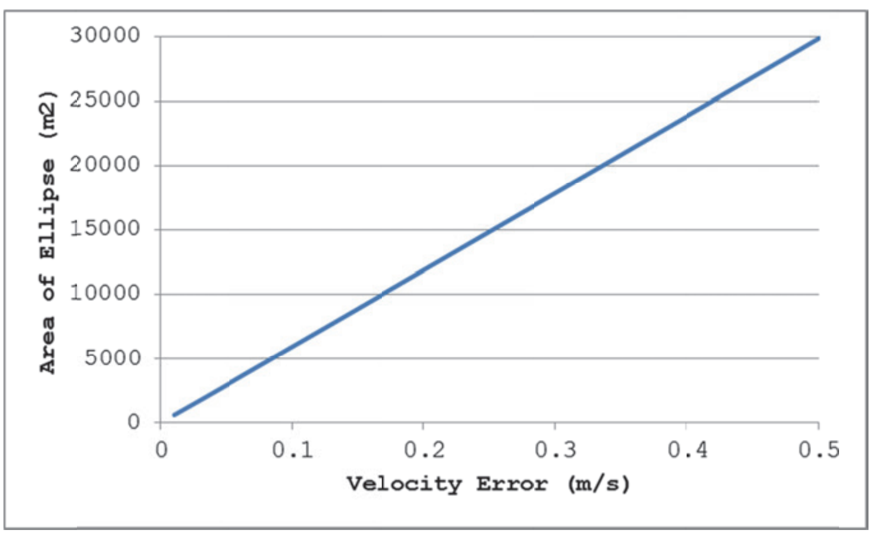


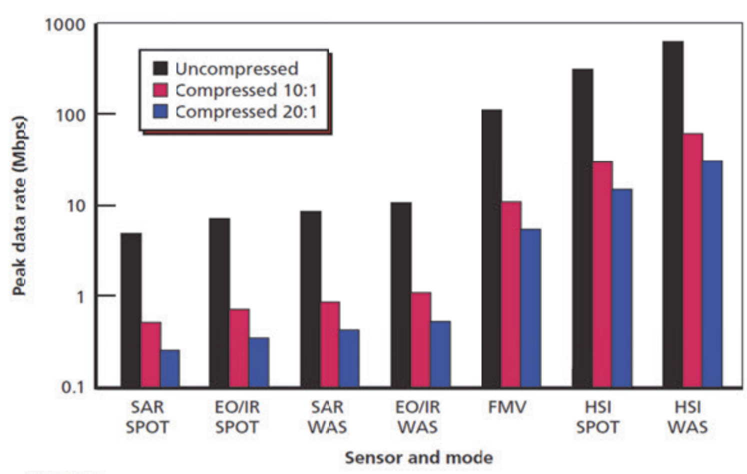
Figure 4.3
Size of Error Ellipse Increases as Velocity Error Increases



Small inaccuracies in the velocity and position measurement can lead to significant increases in the ellipse size. It is important to minimize the error contribution with quality system design.

The constraint for using JTIDS data link forced AT3 to severely limit the number of collectors involved in the geolocation to reduce the bandwidth needed. A T/FDOA system on UAS would not be restricted to a similar solution because off-board geolocation calculation could take place at a PED center. For data dissemination and C2, UAS are currently operated with a constant data link. Two types of links are primarily used, a line-of-sight link or a beyond-line-of-sight link using satellite communication (SATCOM). The Army uses a line of sight data link with its RQ-7 Shadow that uses a C-band link to send data to the ground control station and then forward to users. A line of sight data link is a tether, restricting operations to within line of sight of the ground control station. The Air Force uses satellite communication (SATCOM) to send data back from its MQ-1s and MQ-9s (FY09-40 UAS Roadmap Undersecretary of Defense for AT&L 2009). The Reaper and Predator transfer data back to the PED centers using Ku-band SATCOM. The data from T/FDOA would piggyback on the intelligence data collected from the primary mission. Typical data rates for IMINT sensors are shown in Figure 4.4.

Figure 4.4
Typical Peak Data Rates for IMINT Sensors



SOURCE: Alkire, Kallimani, et al. (2010).

I evaluated the data rate that might be created from a T/FDOA system on UAS. A number of factors influence the data rate, including the bandwidth monitored, the duration of the emissions, and the periodicity of emissions on each channel. For this analysis, I assumed an emission lasts for 20 seconds, with one emission every ten minutes.[23] A typical VHF push-to-talk radio would have a 25kHz bandwidth per channel.[24] A storage buffer would be required to record the signals until an analyst determined that a geolocation was needed. I assume that the buffer would need to be at least large enough to hold one period's worth of emissions and that thresholding is used.[25] For each 25kHz increase in the bandwidth monitored, the buffer size increases 16Mb. The peak data rate is influenced by the speed with which the data is needed; I call this the urgency. Examining the peak data rate as the urgency changes shows that a quick time requirement can drive the date rate. Figure 4.5 shows the relationship between urgency and the peak data rate. I use an urgency of 90 seconds for the remainder of the analysis.

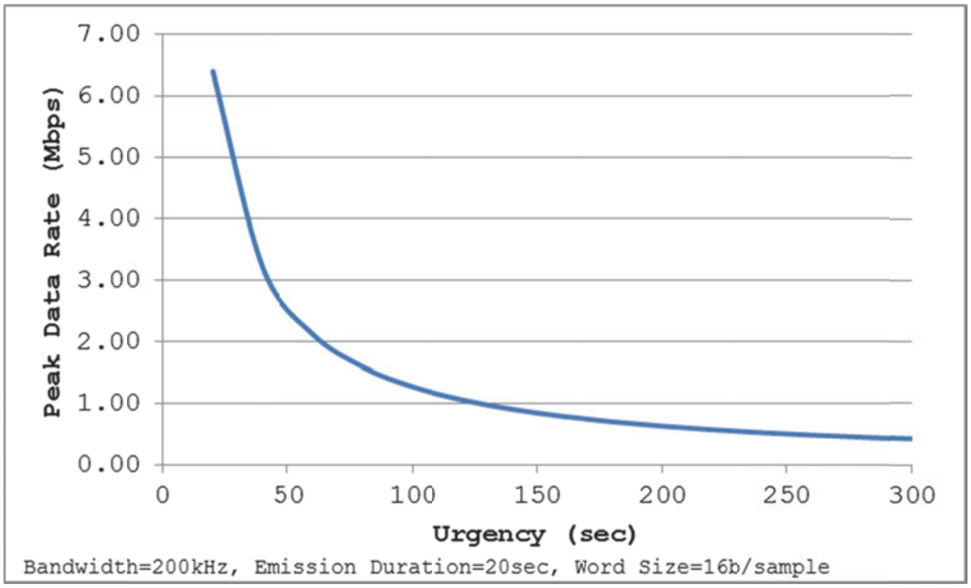
---

[23] The emission may last longer than 20 seconds. The entire emission is not needed to calculate a T/FDOA. Twenty seconds is more than adequate for the calculation in typical applications.

[24] VHF/UHF radios can be narrowband-capable with 12.5kHz channels. Narrower channels decreases the sampling rate, which in turn decreases the storage needed for one period of emissions and the peak data rate.

[25] Recording only occurs when a signal has been detected. Therefore, silence is not recorded.

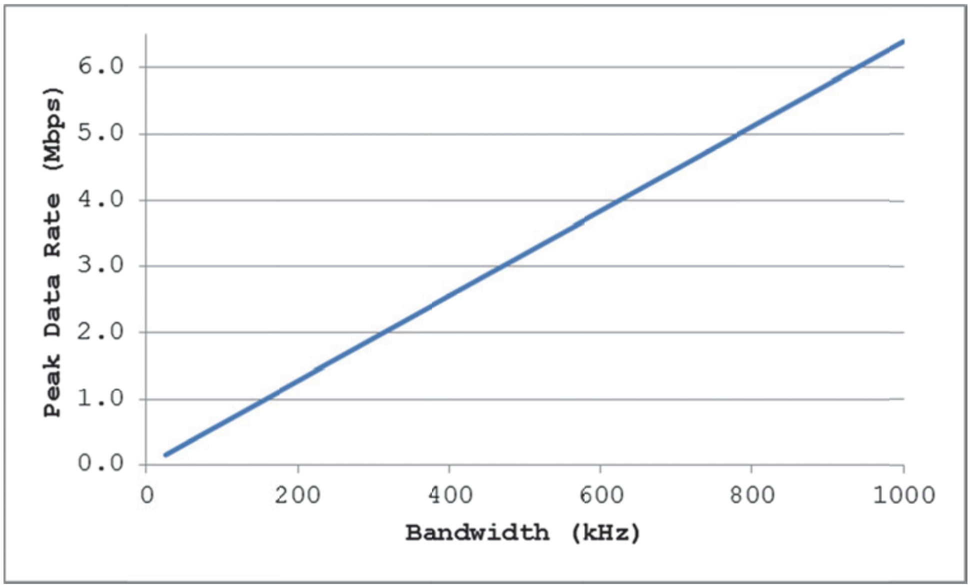
Figure 4.5
Peak Data Rate as Urgency Requirement Changes



The peak data rate requirement as the bandwidth monitored increases is shown in Figure 4.6. Compared with the typical data rates for IMINT sensors, a T/FDOA system would add a small data rate burden. For forensic analysis, storage on-board the aircraft of all the emissions over the entire mission would be necessary.[26] Using a mission length of 16 hours, each additional 25kHz of bandwidth monitored increases the on-board mission storage requirement by 1.5 gigabits.

[26] This data would be transferred at the end of each mission to a more permanent storage. I expect that data would not be kept more than 30 days in the permanent storage. I do not estimate the capacity needed for more permanent storage.

Figure 4.6
Peak Data Rate as Bandwidth Monitored Increases



Today, the United States purchases nearly all the SATCOM used for UAS from commercial sources. Since it is contracted, there is some flexibility in the availability of SATCOM. However, there would likely be some additional cost for providing the additional SATCOM for T/FDOA, even if the data rate burden is small. I did not estimate the additional cost of the SATCOM.

An analysis of the cost and SWAP implications of integrating a T/FDOA capable SIGINT system on UAS are outside the scope of this research; however, we can use the Harm Targeting System Revision 7(HTS R7) as an upper bound. The HTS R7 is a T/FDOA capable system that grew out of DARPA's AT3 program. Hosted on F-16 Block 50/52s, the HTS R7 enables these aircraft to cooperate to quickly locate and target surface-to-air missiles (SAMs). Each HTS R7 pod is approximately 1.2m long, with a diameter of 0.2m, and weighs 100lbs (ACC Public Affairs 2012). I estimate that the equipment for T/FDOA capability weighs approximately 20lbs.[27] I estimate that the power of a T/FDOA capable

---

[27] HTS R7 is an upgrade to the HTS R6. Primarily, the upgrade added the T/FDOA capability, including a digital receiver, GPS hardware, and Link 16 connectivity. The change in weight between HTS R7 and HTS R6

system would range from 1 to 1.5kW.[28] The HTS R7 was procured for several years starting in 2006 at an approximate cost of $750,000 each (U.S. Air Force SAF/FM 2007).[29] The HTS R7 is much more complex and capable system than would be need to use T/FDOA geolocation on UAS. As such, I can consider it an upper bound on both the cost and SWAP implications of a T/FDOA-capable SIGINT system.

The technology for incorporating T/FDOA geolocation on UAS exists. Improvements have been made in digital receiver technology that reduce the cost and SWAP prohibitions. Many UAS are already equipped with antennas that could be used—for example, the UHF/VHF antenna on the MQ-1B. DARPA’s AT3 program laid out many of the technical challenges. There are considerations for UAS that need to be explored, such as the placement of the receiver. The data rate, a limiting factor for AT3, is less of an issue for UAS because of the necessity of a large data link for transferring back other intelligence types, such as FMV. The peak data rate for T/FDOA geolocation would often be less than the data rates of typical IMINT sensors. The peak data rate could also be manipulated as shown in the analysis above to fit the mission demands.

MANPOWER FOR PED

Incorporating new sensors on UAS creates a new source of data that need to be turned into intelligence through processing, exploitation, and dissemination (PED). One of the largest drivers of manpower for UAS is PED. The Air Force’s RPA Task Force estimated that for FY2011, approximately 4,750 personnel were dedicated to UAS PED alone (Menthe, Cordova et al. 2012). Each FMV CAP requires about 63 personnel for PED (Gear 2011). In this section, I estimate the manpower and cost implications of the PED for T/FDOA geolocation. I begin by outlining a potential CONOPs and organizational construct using the Air Force PED

---

was about 20lbs. Information from ACC Public Affairs (2012). Fact Sheet: High-Speed Anti-Radiation Missile Targeting System.

[28] Estimate based of ASIP-2C power requirements. For more information see Penn, B. (2008).

[29] FY 2006 funds procured 22 HTS R7 pods for $16.917 million. Additionally, an FY08 GWOT submission for $25 million was requested to procure an additional 35 HTS R7 pods. For more information see U.S. Air Force SAF/FM (2007, 2008).

enterprise, the Distributed Common Ground System. I examine the manpower needs for two organizational constructs, one where a single operator is capable of controlling a single sensor and one where a single operator could control multiple sensors. I then estimate the cost implications of these manpower requirements.

CONOPs, Organization, and Tasks

I assume all Class IV/V UAS would be equipped for T/FDOA. Since the Air Force has majority of these assets, I use the Air Force's PED structure to investigate what the manpower requirements for T/FDOA PED might be. The Air Force operates its large UAS under the remote-split operations concept. In this concept, the aircraft are forward deployed to the operating area with a small crew. The forward crew controls the takeoff of the aircraft with a line of sight data link, then switches to a SATCOM data link and passes control to a stateside crew. The bandwidth and coverage of SATCOM also allows the PED components of the mission to remain stateside.

For the Air Force, intelligence data such as FMV collected by UAS travels through SATCOM to different PED sites in the Distributed Common Ground System (DCGS). The DCGS provides the "capability to conduct multiple, simultaneous multi-intelligence (Imagery, Signals, and Measurements and Signatures) ISR missions worldwide through distributive and collaborative operations" (AFISRAI-14-153 2009). In some cases, DCGS has the capability to control the sensors (AFISRAI-14-153 2009). I would expect that the set up for T/FDOA would be similar. The DCGS would control the SIGINT sensors for T/FDOA. All of the data gathered from these sensors would be processed within the DCGS enterprise. The geolocation from T/FDOA would be calculated at the DCGS, and the DCGS would be responsible for disseminating the intelligence. T/FDOA is a multi-platform technique. Consequently, the systems would need to be setup as "master/slaves." The operator would initiate a T/FDOA on one system, the master, and all other systems in the area would automatically tune to the frequency, the slaves.

I considered two different organizations, one where a single T/FDOA operator controls one sensor (one-to-one) and one where a single

T/FDOA operator controls multiple sensors (one-to-many). I placed the T/FDOA PED in different settings within the DCGS. For the one-to-one construct, it makes the most sense to place T/FDOA PED with the platform PED crew. Today, the PED crew is tied to the platform it is supporting. Placing the PED for T/FDOA within the crew would keep with the focus on the crew. T/FDOA would be employed in a supporting manner to other intelligence types, and so having close contact with other crew members might facilitate employment. In the one-to-many construct, the T/FDOA PED would be done within the DCGS Analysis and Reporting Team (DART). The DART is a regionally focused fusion cell designed to correlate and synthesize the intelligence data collected from the platforms/sensors that the DCGS manages or exploits and fuse this data with external sources of intelligence. The multi-platform nature of T/FDOA and the multi-intelligence correlation for PED fits nicely with the mission of the DART. Placing the PED for T/FDOA within the DART would leverage the area focus of the DART.

Regardless of how many sensors the operator can control and where the operator is located, there are certain tasks that he or she would do. First, the operator would need to work with the contact from the ground forces to determine the frequencies of interest. In most missions, T/FDOA geolocation should be employed using prior information, as opposed to a means to discover new adversary frequencies. The operator would be in control of the receiver(s) and initiate the geolocations.[30] For example, if a known frequency became active, the operator might choose to create a new T/FDOA geolocation every time the frequency is active for more than 10secs. The operator would actively work to cross-cue with other intelligence types, including intelligence gathered from the same platform and intelligence gathered from nearby platforms. The operator would report the geolocation intelligence. For example, he or she might create a short document that shows the error ellipse, the frequency, and any other information known about the target. Finally, the operator would be

[30] It is likely possible to automate the initiation of geolocation; however, an operator would likely still verify the results before reporting the intelligence.

responsible for sending the document to the supported unit and informing the DART for correlation with other area intelligence. Given these tasks, the operator would most likely be at least a SrA with an all-source (1N0XX), electronic signals exploitation (1N5XX), or cryptologic linguist (1N3XX) background.

PED Within Platform Crew

Today, a typical FMV crew for UAS is composed primarily of imagery specialists. The crew positions, specialties, and minimum ranks are shown in Table 4.3.

Table 4.3
UAS FMV Mission Crew Positions

Crew Position	AFSC	Rank	Previous Qualification
Mission Operations Commander (MOC)	14N	2Lt	
Imagery Mission Supervisor (IMS)	1N1 (imagery)	SSgt	IRE
Mission Planner (MP)	1N1 (imagery)	SrA	IA
Imagery Report Editor (IRE)	1N1 (imagery)	A1C	IA
Imagery Analyst (IA)	1N1 (imagery)	AMN	
Multi-Source Analyst (MSA)	1N0 (all-source)	A1C	
Screener	1N1 (imagery)	A1C	IA
TACOM	1N4 (networks)	AMN	

SOURCE: Adapted from AFISRAI-14-153V3 (2009).

The MOC and MSA are the only crew positions with defined multi-intelligence responsibilities.[31] The MOC is the overall supervisor, responsible for the direction of the ISR mission. As such, the MOC manages all SIGINT, IMINT, and/or MASINT collection. The MOC is also responsible for facilitating cross-cues in conjunction with the MSA.

---

[31] Both positions have additional responsibilities. For full description of roles and responsibilities see the Air Force Distributed Common Ground System Operations (AFISRA 14-153V3 2009) Attachment 2.

The MSA is responsible for collecting and maintaining the target research necessary to complete the IMINT, SIGNINT, and MASINT tasking. The MSA also coordinates with the MOC on cross-cues. In contrast, the PED crew positions for other assets with both SIGINT and IMINT missions include a position dedicated to correlating the various intelligence data collected by the platform, the correlation analyst (CAN), and several other positions with some multi-intelligence responsibilities in addition to a MOC and MSA.

The CAN is considered the focal point for multi-intelligence correlation. One of his or her responsibilities is to monitor all of the SIGINT, MASINT, and IMINT reporting and identify potential for cross-cueing and dynamic sensor re-taskings. The CAN is also responsible for coordinating with the different intelligence mission supervisors during cross-cue opportunities. The CAN has an all-source or networks intelligence background, is at least a SrA, and previously performed duties as the TACOM or MSA.

Given the tasks required for T/FDOA geolocation and the imagery expertise of current crew positions, a new position for T/FDOA PED would likely be needed. This position would be similar to the CAN position for the SIGINT crews. He or she would be responsible for the tasks outlined above for T/FDOA geolocation as well as the focal point for multi-intelligence synthesis for the crew.

PED Within DART

The DART is a relatively new concept created to add flexibility and responsiveness into the DCGS for the COIN/counterterrorism missions encountered in Operations Enduring Freedom and Iraqi Freedom. The DART construct includes five DARTs at each of the five core distributed ground station sites and additional specialized DARTs. The core distributed ground station cells are regionally focused, supporting specific theater(s). The DARTs are responsible for maintaining an overall picture of all DCGS platforms/sensors and a status of mission execution to enable ad-hoc taskings. The DARTs are also tasked to continuously monitor the overall adversary situational awareness picture for their specific area. Beyond providing situational awareness, the DARTs rapidly correlate data from the various intelligence sources and create integrated products for the supported units. As part of this analysis, the DART is expected to identify developing targets from the association of the disparate intelligence sources.

There is no specific guidance on positions within the DART. It is difficult to say whether the DART already has the expertise and available personnel to incorporate the T/FDOA PED tasks into the workload of an existing position; therefore, I will assume that a new position is necessary. This assumption will provide an upper bound for the manpower estimation. It is also difficult to say how many sensors a T/FDOA CAN could manage. I will analyze the manpower where control of 2-4 sensors is possible.

Manpower and Costs Implications for Approaches

The DCGS operates 24 hours, seven days a week to conduct PED for missions flown around the world. There are therefore limitations on the length of a crew duty period. A PED crew member may work a maximum crew duty of 12 hours. Crew duties are those that directly support the mission. For example, time spent preparing, planning, executing, and post-mission recordkeeping are all included. General military training and general squadron duties and tasks are not considered crew-related duties. For each CAP supported with T/FDOA PED embedded with the platform crew, we need five people to fill the one position.[32] The number of CAPs that we wish to support heavily influences the total minimum manpower requirement.

Table 4.4
Manpower for T/FDOA PED

	With Crew	**With DART**		
		2 Sensors	**3 Sensors**	**4 Sensors**
35 CAPs	157	79	53	40
50 CAPs	224	112	75	55
65 CAPs	291	146	97	73

[32] See Appendix D for the minimum manpower factor calculation.

Table 4.4 shows the minimum manpower requirement at several different CAP levels. These manpower requirements are relatively small when compared with the requirements for other aspects of the PED. There are significant manpower savings if an operator is capable of controlling multiple sensors.

I can estimate the cost implications for the minimum manpower requirements. I calculated the cost implications using the FY2011 Total Annual Composite Rates from the Military Annual Standard Composite Pay based on the President’s Budget. The rate includes costs for basic pay, health care, retired pay, allowances and incentive pays, etc. Since I expect the operator to be at least a SrA (E-4), I averaged the rate for E-4 to E-6. The resulting rate was $76,680.

The cost implication per CAP is $383,400 annually for T/FDOA PED with the crew. Table 4.5 shows the estimated cost implications for T/FDOA PED at several different numbers of CAPs. Again, there are significant savings if an operator is capable of controlling multiple sensors. I estimate the maximum cost implication of T/FDOA PED to be $20.6 million for the Air Force annually. This cost would be for using T/FDOA on all planned Air Force UAS with T/FDOA PED done by a new position with one-to-one positions per CAP.

Table 4.5
Costs for Manpower for T/FDOA PED in $100,000

	With Crew	With DART		
		2 Sensors	3 Sensors	4 Sensors
35 CAPs	$12,038	$6,058	$4,064	$3,067
50 CAPs	$17,176	$8,588	$5,751	$4,294
65 CAPs	$20,626	$10,352	$6,901	$5,214

The manpower and cost implications for T/FDOA PED are minimal compared with the rest of the manpower dedicated for UAS PED. The minimum manpower requirements can be reduced by enabling one operator to control multiple sensors.

Conclusion

The analysis shows that small changes are needed for T/FDOA geolocation to be implemented on UAS. Each UAS would need to be equipped with a SIGINT system; however, the technology for T/FDOA already exists, and many of the pieces are already in place. For example, most UAS are already equipped with several different antennas that could provide frequency coverage of communication bands like UHF/VHF. AT3 broke through many of the technical barriers to T/FDOA. There will be unique design considerations for implementation on UAS, but these can be positive. For example, the data transfer issues would be easier on UAS because of the use of large data pipes for other intelligence distribution and C2. I caveat this research by acknowledging the difficulties that can be faced when integrating new technologies on aircraft.

Additional collection of intelligence data requires additional manpower to process, exploit, and disseminate that data as usable information. For the Air Force, T/FDOA PED would likely be done within the DCGS, similar to PED of other intelligence data. The CONOPs and tasks needed for T/FDOA PED influence the estimate of the manpower required. I let the number of sensors the operator can control vary and determine the minimum manpower required to sustain 24/7 operations. This manpower ranges from 40 to 291 people, depending on the number of sensors an operator can control and the number of CAPs of T/FDOA PED used. The cost implications of these manpower requirements range from $3 million to $20.6 million annually. The manpower and cost implications for T/FDOA PED are minimal compared with the rest of the manpower dedicated for UAS PED.

5. How Can T/FDOA Be Leveraged in Multi-Intelligence Operations?

This chapter focuses on how T/FDOA can be leveraged in multi-intelligence operations. I first provide some background on why multi-intelligence operations are useful. I then present an example to show how T/FDOA geolocation can improve multi-intelligence operations. Finally, I investigate the command, control, and communication (C3) that would be needed for these complex operations to be successful.

Background for Multi-Intelligence Operations

There are tradeoffs between the intelligence type used and the information that can be provided. For example, IMINT can provide some identification and location, but not necessarily intent. FMV can provide identification, location, tracking, and intent, but has a very limited field of view. As targets improve their concealment, mobility, and dispersion it becomes more difficult to generate the intelligence necessary to prosecute the targets (Isherwood 2011). Fusing intelligence gathered from multiple sources provides a much more complete picture.

Table 5.1
Intelligence Types Provide Different Information About the Target

	Who	**What**	**Where**	**When**	**Why**	**Field of View**
SIGINT	Yes	Yes	Yes	Yes	Yes	Wide
GMTI	No	Yes	Yes	Yes	No	Wide
IMINT	No	Yes	Yes	Yes	No	Medium
FMV	No	Yes	Yes	Yes	No	Narrow

SOURCE: Adapted from Isherwood (2011), p. 20.

Layering ISR by positioning ISR assets over the same geographic areas at the same time is one way to generate intelligence that can be fused. Layering complementing ISR can provide more information about each target. For example, by fusing IMINT and SIGINT, we might be able to identify a decoy SAM from an actual SAM. Layering ISR can also improve the accuracy of information. For example, suspicious movement characterized by GMTI and paired with FMV could show that the movement is an illegal checkpoint set up by the enemy. These improvements in quantity and quality enhance operational decisionmaking and the ability to respond. Using SIGINT with T/FDOA geolocation on UAS would help layer at least two intelligence types for nearly every UAS mission.

Cross-cueing is defined as an exchange of intelligence data between units intended to generate additional collection on the same target/activity to create higher confidence, more accurate, or more complete reporting (480th ISR Wing 2010). It is also known as a tip-off, intended to increase situational awareness (480th ISR Wing 2010). Cross-cueing is typically thought of as cueing between the different intelligence types or assets to provide additional information. It is an important force-multiplier, allowing the complementing capabilities of each intelligence type to be focused on one target. In today's war, multiple sources of intelligence are often needed to find and locate the enemy (Isherwood 2011). One example of cross-cueing would be using the GMTI to track a target that has been geolocated from SIGINT.

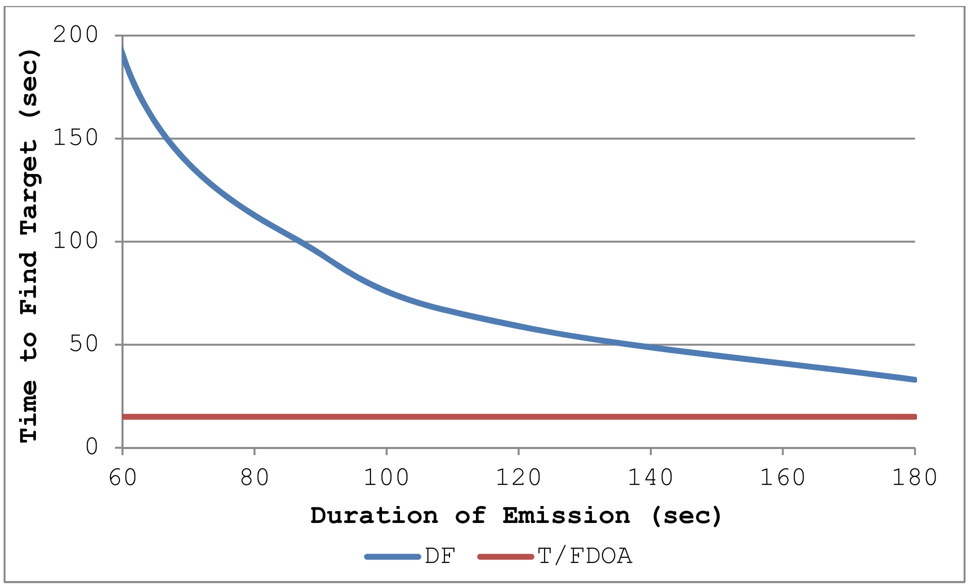
Impact of T/FDOA Geolocation

Two of the advantages of T/FDOA, speed and accuracy, could significantly improve our ability to conduct multi-intelligence operations and use cross-cueing. In a cross-cue, the second intelligence type often must search a particular location to find the target of interest. For example, if trying to cue FMV from a SIGINT hit, an analyst might have to search throughout the ellipse to find the target. Therefore, the accuracy of the geolocation is a large driver of the time it can take to find the target.

Operation with Direction Finding versus T/FDOA Geolocation

I compared the time it would take to find a target using FMV if the geolocation of the SIGINT cue was accomplished using direction finding or T/FDOA. I use two UAS each equipped with FMV to search the error ellipses resulting from the geolocations. For direction finding, the length of the baseline severely impacts the accuracy of geolocation. I assume the baseline is as long as the duration of the emission. As the emission duration increases, the error ellipse shrinks, and so the time to find the target using direction finding decreases. However, as Figure 5.1 shows, using T/FDOA geolocation is better than even a baseline of more than three minutes.

Figure 5.1
Size of SIGINT Ellipse Impacts Time Needed to Find Target



NOTES: The analysis assumes a static target with the SIGINT platform in close proximity (50km) to the target. I use a report time of 10sec for the SIGINT to FMV cue. For FMV, a resolution of 0.3 meters is required. An FMV platform at 25 km range, 12.4kft altitude, equipped with a 0.16 meter diameter optic with 8 meter focal length at 0.8 micrometer (near IR) wavelength with 0.02 by 0.02 meter detector array will have a resolution of 0.3 meters (diffraction limited). The spot size would be 62.5 by 413 meters (0.02582 km2). I use a dwell time of 5sec for each FMV spot and slew time of 2sec to move the spot to a new location.

The longer FMV must search for a target, the higher the chance that the target will be lost. The accuracy of T/FDOA geolocation can greatly reduce the search time for an emitter.

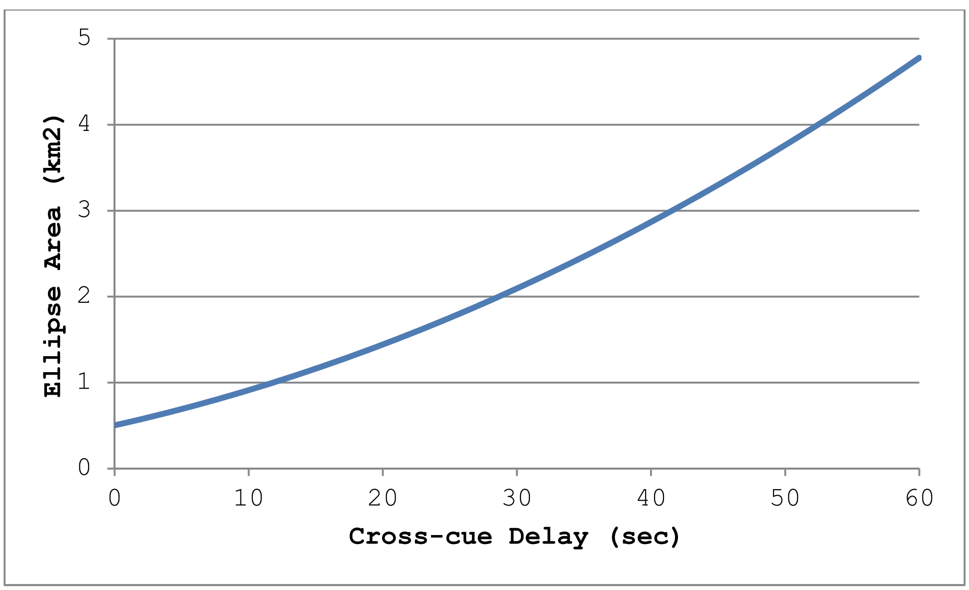
In this example, the FMV platform did not need to travel a great distance to arrive at the geolocation error ellipse. Although T/FDOA geolocation can be nearly instantaneous, and therefore reduce the time to search the area, the same limitations on aircraft movement exist.

For example, a UAS traveling at 100m/s would take over 16 minutes to travel 100km. The limitations on aircraft movement mean that the second intelligence collector must be relatively close to the target to cross-cue.

Importance of Timing

The timing of target handoffs is crucial to the success of cross-cueing. The passing of the target from one sensor/platform to another must happen very quickly, or the area that needs to be searched can grow very large. In some cases, the area grows so much that the target will be lost. Figure 5.2 shows an example of how the cross-cue delay impacts the error ellipse for SIGINT to FMV cross-cue with a moving target.

Figure 5.2
Delay in Cross-cue Increases the Area Needed to Search



NOTES: Analysis uses an initial ellipse of .50km2. Target is travelling 50 km/hr in an open area unconstrained by travelling on roads or terrain limitations.

The cross-cue delay can cause a medium accuracy error ellipse to become unusable. Cross-cueing of a challenging target, like a moving target, must happen within a minute for the cross-cue to be successful. T/FDOA geolocation meets this quickness standard. The speed of T/FDOA reduces the time from initial SIGINT hit to geolocation ellipse without degrading the accuracy. The near-real-time geolocation from T/FDOA can reduce the cross-cue delay in a multi-intelligence operation.

Command, Control, and Communication

Cross-cueing between intelligence types becomes more difficult and less fruitful the longer the delay between target handoff. This section examines what C3 would be required for successful multi-intelligence operations with T/FDOA and how that C3 can be provided using the emerging ISR Mission Type Orders (MTOs) concept.

What C3 Is Needed for Multi-Intelligence Operations with T/FDOA?

Cross-cueing can be very complicated. Someone needs access to the multiple streams of intelligence (HUMINT, SIGINT, IMINT, etc.) in order to determine the potential for a cross-cue. If SIGINT geolocated a target signal, but was unaware of the presence of the FMV, the cross-cue will not happen. To effectively cross-cue, the supporting unit, for example the UAS and relevant PED, should have an understanding of the situation on the ground. Knowing the commander’s intent, the purpose of the operation, and other pertinent background information allows the UAS operators and PED analysts to leverage their expertise.

When responsibility is passed, the units try to avoid a “blink” where the target is lost. Latency and incompatible or incomplete data can cause a cross-cue to fail. As discussed above, the timing of target handoffs is crucial to the success of cross-cueing. The passing of the target from one sensor/platform to another must happen very quickly, or the target is easily lost.

The dynamic tasking and targeting needs to be flexible in order to deviate from the planned collection and enable collection on a cross-cue. The receiving sensor (the second or third, etc., participating in the cue) likely has some intelligence request that it is currently fulfilling. Once there is potential for a cross-cue, the authority to change the tasking for the receiving sensor needs to be immediate. This authorization needs to have prioritized the time sensitivity of this cross-cue with other requests, decided which other requests can be delayed or dropped, and done this within seconds. For a multi-intelligence equipped asset cueing to a second sensor on the same asset, this authorization process would likely be simpler, since they still continue supporting their primary task.[33]

Quick and clear coordination with other assets is essential to cross-cueing. Often, these assets are owned by different components and supporting different units. For these multi-intelligence operations, those involved must communicate closely with ground forces and other supporting assets. Cross-cues depend on quickly and accurately conveying information. Standardized communication practices, similar to a 9-line, would enable clear communication.

Using ISR MTOs

ISR MTOs grew out of a desire to deviate from the preplanned, rigid taskings and target decks. Joint Publication 3-50 defines MTOs as "an order to a unit to perform a mission without specifying how it is to be accomplished." An ISR MTO is typically a more narrative tasking that provides background information on the supported unit's commander's intent (Green 2011). ISR MTOs can also introduce more flexibility in the planning and integration process (Green 2011). A major difference between ISR MTOs and the traditional tasking is the establishment of direct liaison authority (DIRLAUTH), which allows the collectors and the units they are supporting to communicate and work together directly to accomplish the mission (Green 2011). DIRLAUTH encourages the collectors, the supporting unit, and the PED unit to coordinate in initial planning and C2 methods (Green 2011). Through this pre-coordination, the DIRLAUTH established by ISR MTOs fosters dynamic changes within a complex operational environment.

Using ISR MTOs meets most of the C3 demands for leveraging T/FDOA geolocation through cross-cueing. Establishing DIRLAUTH promotes pre-coordination with the ground unit, enabling communication and understanding during the mission. MTOs can also be written so that

[33] Today though, these assets are tasked with only one of their sensors as prime. Oftentimes, the other sensors are unsupported and so not available (Green 2011).

there is flexibility with the target deck. In an MTO, the authorization to cue would be from the ground unit. Since constant communication is established, that authorization would likely be very quick.

Conclusion

The analysis shows that using T/FDOA on UAS would strengthen our multi-intelligence capabilities. Adding SIGINT with T/FDOA geolocation on UAS immediately creates the potential to layer complementing sensors. Since these sensors provide different information, fusing the data from layer sensors offers much more intelligence on the target. T/FDOA would improve our abilities to cross-cue. The accuracy advantages of T/FDOA with short duration emissions reduce the time needed to search for a target with a SIGINT to FMV cross-cue. Time is extremely important for a cross-cue. A cross-cue delay of more than seconds can cause the cross-cue to fail, especially with a moving target.

Multi-intelligence operations are complex and place unique demands on the command, control, and communication of airborne ISR. The new ISR MTO construct provides a unique way to support cross-cueing with T/FDOA geolocation. The establishment of DIRLAUTH enables quick communication between all the units in the operation, which is key to these operations.

6. Conclusions and Recommendations

This research shows that DoD can better leverage UAS and improve multi-intelligence capabilities by expanding its geolocation capacity through the use of T/FDOA geolocation on UAS. I demonstrated that a T/FDOA geolocation would be useful in the context of today's operations. I outlined some requirements needed to implement T/FDOA geolocation, both on the platform and for the PED. Finally, I showed how the speed and accuracy of T/FDOA could improve multi-intelligence collection.

T/FDOA geolocation is useful against many targets, particularly those in an IW/COIN environment that are difficult to geolocate using direction finding. These difficult targets include those in lower frequencies (HF/VHF), those that limit the emission duration, and those that are farther from the receiver aircraft. Two of the major drawbacks to T/FDOA are the need for multiple platforms and the sensitivity to geometry. The drawbacks do not hinder employment of T/FDOA as a secondary capability on UAS. The orbits demanded by the primary intelligence collection do not negatively impact the accuracy of geolocation using T/FDOA. Without impacting the primary mission, UAS with T/FDOA capability would likely be within line of sight of the same targets.

Small changes are necessary to implement T/FDOA on UAS. The technology for T/FDOA capable sensors already exists. Many UAS are nearly equipped to be capable. Each UAS would need a SIGINT sensor with certain characteristics. The receiver(s) likely needs to be a digital receiver to meet the demands for precision and sensitivity. The system needs to be integrated with the GPS/INS systems of the UAS to provide the aircraft state vector with high enough precision. The new sensor would need to be integrated on the UAS. Integration issues are beyond the scope of this research. Today, one of the largest drivers of manpower for UAS is the PED needed to turn the data collected into actionable intelligence. The PED for T/FDOA would likely mirror PED for the other intelligence types. Focusing on the Air Force, this means that PED would be conducted within the DCGS. I present two options for organizing the PED based on how many sensors a single operator is capable of controlling. The manpower and cost implications appear to be small compared with the requirements to PED other sensors.

T/FDOA can be leveraged to improve multi-intelligence operations. Adding a SIGINT with T/FDOA capability to UAS instantly increases our ability to provide more information about targets by layering complementing ISR sensors. The accuracy and speed of T/FDOA geolocation can make a large impact in our ability to cross-cue. Cross-cueing must happen within seconds to be successful. T/FDOA geolocation provides high-accuracy geolocation very quickly, reducing the time delay between intelligence types and the area that a second intelligence, such as FMV, would need to search. For C3, the emerging ISR MTO concept meets the C3 needs for T/FDOA geolocation in complex operating environments.

This research was intended as a theoretical "proof of concept" for the use of T/FDOA geolocation on UAS. It shows what we would gain from using T/FDOA geolocation in an opportunistic fashion and as a secondary mission on UAS. There are many questions and analysis beyond the scope of this research that would need to be investigated before realizing a T/FDOA geolocation capability on UAS. This work outlined what would be necessary for a SIGINT system capable of T/FDOA geolocation. There is much more work that would need to be accomplished to create this SIGINT system. Additional sensors on a platform can cause issues with the current sensors, including SWAP trade-offs and issues from emissions on overlapping frequencies. For each platform that would host T/FDOA, the compatibility of a T/FDOA sensor with the other sensors would need to be investigated. In this work, only the cost implications of the manpower for PED were examined. The complete costs of implementation are much broader and range from costs associated with maintenance in the field to potential costs of additional bandwidth. These costs would need to be thoroughly researched. This research points out the importance of quickly transitioning between intelligence types, but does not delve into the tasking and re-tasking of sensors. The best method of tasking of multi-intelligence capable assets to leverage sensors for primary and secondary missions would need to be further investigated.

There are many potential stakeholders for T/FDOA geolocation. At the DoD level, the major stakeholder is the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD AT&L). Within USD AT&L, Unmanned Warfare (UW) is the lead for providing oversight of UAS acquisitions, including all subsystems such as sensors. For each individual service, stakeholders fall into similar groups. There are those that operate the UAS, those that conduct the PED for the intelligence data collected by the UAS, those that use the intelligence, and those that purchase the sensors. Each of these stakeholders will need to work together to create the most useful T/FDOA-capable sensor. Cooperation across services and organizations is important to create the most capable sensor. The accuracy of T/FDOA can be improved by increasing the number of sensors participating in the geolocation. Sensors that are interoperable are essential for T/FDOA geolocation to be the most useful.

There are several next steps that DoD should take to continue pursuing T/FDOA geolocation on UAS. This research shows how T/FDOA geolocation on UAS would complement direction finding and provide an ability to go after difficult targets in a COIN/IW environment. A full gap analysis should be done to illustrate how T/FDOA would fit in DoD’s geolocation portfolio. As stated above, this research touches only on one cost implication for T/FDOA. A complete cost-benefit analysis would be needed to justify the capability. Finally, a technology demonstration would be needed before moving forward.

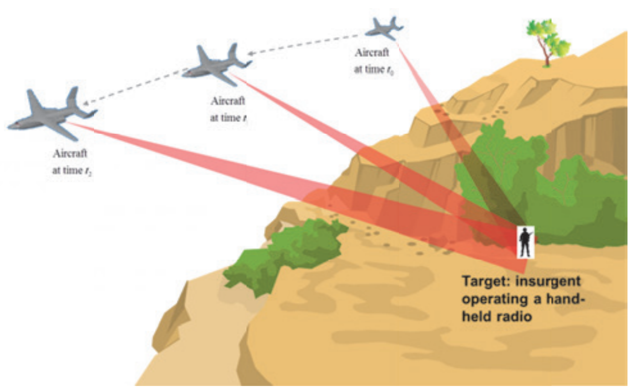
Appendix

A. Direction Finding Model

Direction Finding

The military commonly uses direction finding, also known as triangulation, to fix the position of an emitter. For example, in direction finding, an aircraft would measure the angle of arrival (AOA) at multiple locations along a baseline to create lines of bearing (LOBs) between the receiver and the emitter. Two or more LOBs enable the emitter to be fixed at the intersection of these different LOBs. An example of direction finding is depicted in Figure A.1. Direction finding requires one receiver to measure the signal at one position and then move and re-measure the same signal. There are many algorithms available to calculate the emitter location. These range from plotting lines of bearing on a common map to calculations based on the various statistical techniques such as least-squares error estimation and the discrete probability density method. One of the first and classical techniques is a variant of maximum-likelihood estimation advanced by Stansfield in his "Statistical Theory of D.F. Fixing."

Figure A.1
Aircraft Calculates LOBs Along a Baseline



Theoretical Basis, the Stansfield Estimator

The Stansfield Estimator assumes lines of bearings are measured from multiple locations. In practice, measured bearings include both systematic error and random error. Typically, systematic errors are known and therefore can be accounted for in the implementation. As with successor models, Stansfield assumes that bearings are corrupted only by random errors, which are assumed to be from a Gaussian distribution with a mean of zero.[34] Stansfield uses the following geometry:

$J, K, L, M, N =$ positions of d. f. stations

$n =$ number of d. f. stations

$d =$ semi − distance between two d. f. stations

$D =$ distance of point to be located from d. f. station

$D_j =$ distance from station J, etc.

$\theta =$ station bearing

$\theta_J =$ bearing from station J, etc.

$\psi =$ error in bearing

$\psi_J =$ error in bearing from station J, etc.

$p_J =$ distance from point to be located to line of bearing from station J, etc.

$q_J =$ distance from an arbitrary point to line of bearing from station J, etc.

If the true position of the emitter is unknown, but guessed to be at point S, with coordinates x,y and perpendicular distance q_J from the line of bearing of station J, then:

$$q_J = p_J + x\sin(\theta_J) - y\cos(\theta_J)$$

The equation for the likelihood of the set of position lines is then:

$$P(q_1 \dots q_n)dq_1 \dots dq_n = \frac{1}{(2\pi)^{\frac{n}{2}}\sigma_{p1}\dots\sigma_{p1}} \exp\left[-\frac{1}{2}\sum\frac{\left(p_J + x\sin(\theta_J) - y\cos(\theta_J)\right)^2}{\sigma_{pJ}^2}\right] dp_1 \dots dp_n$$

Using the following substitutions to make the equations easier to write:

---

[34] Stansfield validated the assumption of Gaussian with mean of zero using actual data gathered during World War 2. He removed approximately 1 percent of the bearings that were determined to have egregious errors.

$$\lambda = \sum \left(\frac{\sin\theta_J}{\sigma_{pJ}}\right)^2 = \sum \left(\frac{\sin\theta_J}{\sigma_{\psi J} D_J}\right)^2$$

$$\mu = \sum \left(\frac{\cos\theta_J}{\sigma_{pJ}}\right)^2 = \sum \left(\frac{\cos\theta_J}{\sigma_{\psi J} D_J}\right)^2$$

$$\nu = \sum \left(\frac{\sin\theta_J \cos\theta_J}{\sigma_{pJ}^2}\right) = \sum \left(\frac{\sin\theta_J \cos\theta_J}{\sigma_{\psi J}^2 D_J^2}\right)$$

The $(\hat{x}, \hat{y})$, which maximizes the expression in the exponent above, is the best guess for the fix:

$$\hat{x} = \frac{1}{(\lambda\mu - \nu^2)} \left[\sum p_J \frac{\left(\nu\cos(\theta_J) - \mu\sin(\theta_J)\right)}{\sigma_{pJ}^2}\right]$$

$$\hat{y} = \frac{1}{(\lambda\mu - \nu^2)} \left[\sum p_J \frac{\left(\lambda\cos(\theta_J) - \nu\sin(\theta_J)\right)}{\sigma_{pJ}^2}\right]$$

If this is repeated, the distribution of the "optimal fixes" is:

$$P(x,y)dxdy = \frac{\sqrt{(\lambda\mu - \nu^2)}}{2\pi} \exp\left[-\frac{1}{2}(\lambda x^2 - 2\nu xy + \mu y^2)\right] dxdy$$

This can be transformed into

$$P(X,Y)dXdY = \frac{1}{2\pi ab} \exp\left[-\frac{1}{2}\left(\frac{X^2}{a^2} + \frac{Y^2}{b^2}\right)\right] dXdY$$

where,

$$\frac{2}{a^2}, \frac{2}{b^2} = \lambda + \mu \pm \sqrt{(\lambda - \mu)^2 + 4\nu^2}\,.$$

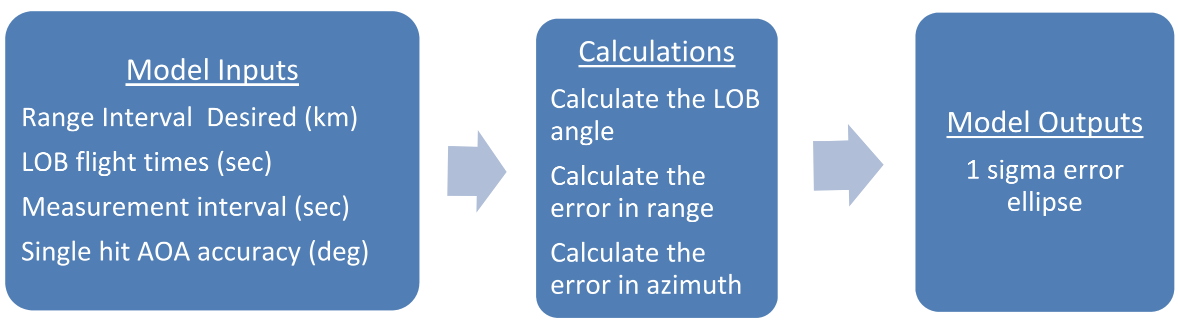
Errors

The errors that impact direction finding include measurement errors, position errors, and random errors. This model focuses on measurement error, particularly the measurement of the angle of arrival. For simplicity, the errors for AOA measurement are determined using a constant LOB angular error. This could be changed to a random draw from a normal distribution, with mean of zero and standard deviation defined by the parameter sigma.

Model Implementation

I adapted a model that had been previously used in work done for RAND's Project AIR FORCE. This model is based on the Stansfield approach described above. A graphical depiction of the model is shown in Figure A.2. The inputs are the range interval between the target and receiver (ex. 50km – 400km), the flight times of the LOBs (ex. 60sec, 120sec, 180sec), the measurement interval for each AOA (ex. 3 sec), and the single-hit AOA accuracy (ex. 0.07 deg). Using those inputs, the true LOB angle is calculated. The error in range and azimuth are then determined for each point along the range interval. These estimates are then used to create a 1-sigma error ellipse for each range increment.

Figure A.2
Graphical Depiction of Direction Finding Model



Stansfield's method is a simple method that will provide a good first cut of the accuracy. There are other, more complex and more accurate methods to estimate the error of direction finding. For the comparisons in this dissertation, Stansfield's method is a good approximation.

B. ORBIT GEOMETRY RESULTS

SCENARIO 1: TWO CIRCULAR FMV ORBITS

In this scenario, there are two UAS each flying circular FMV orbits. The orbit parameters for each case are listed in Table B.1.

Table B.1
Orbit Parameters for Scenario 1

	Aircraft 1: Circular FMV Orbit				Aircraft 2: Circular FMV Orbit			
	X Offset	Y Offset	Altitude	Radius	X Offset	Y Offset	Altitude	Radius
Case 1	150km	150km	20kft	20km	150km	150km	20kft	20km
Case 2	200km	200km	20kft	20km	75km	75km	20kft	20km
Case 3	200km	200km	20kft	20km	125km	125km	20kft	20km
Case 4	300km	100km	25kft	20km	150km	150km	25kft	20km
Case 5	250km	250km	30kft	20km	50km	50km	20kft	20km
Case 6	150km	150km	15kft	20km	250km	250km	30kft	20km
Case 7	150km	150km	15kft	20km	150km	150km	15kft	20km
Case 8	150km	150km	15kft	10km	150km	150km	15kft	20km
Case 9	150km	150km	30kft	10km	150km	150km	30kft	20km
Case 10	150km	150km	20kft	10km	150km	150km	20kft	10km

An example of the output of the model for this scenario is shown in Figures B.1 and B.2.

Figure B.1
Example of Scenario 1: Two Circular FMV Orbits

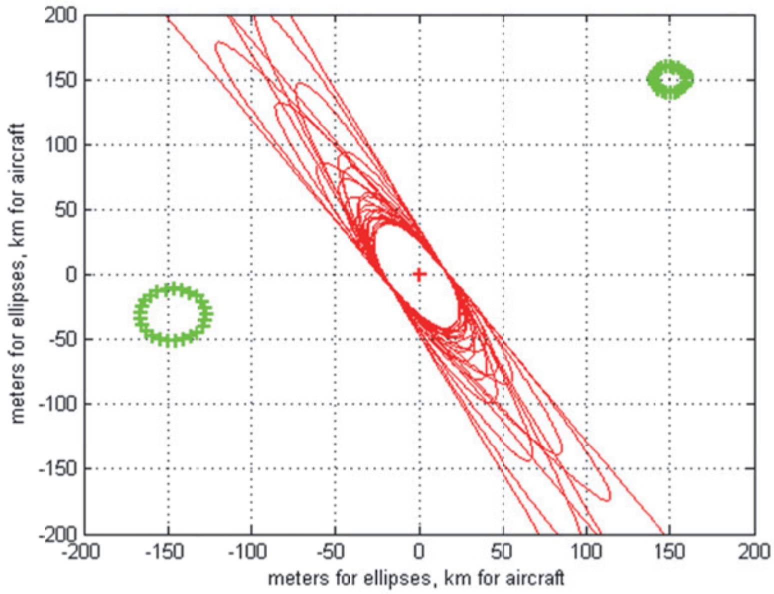
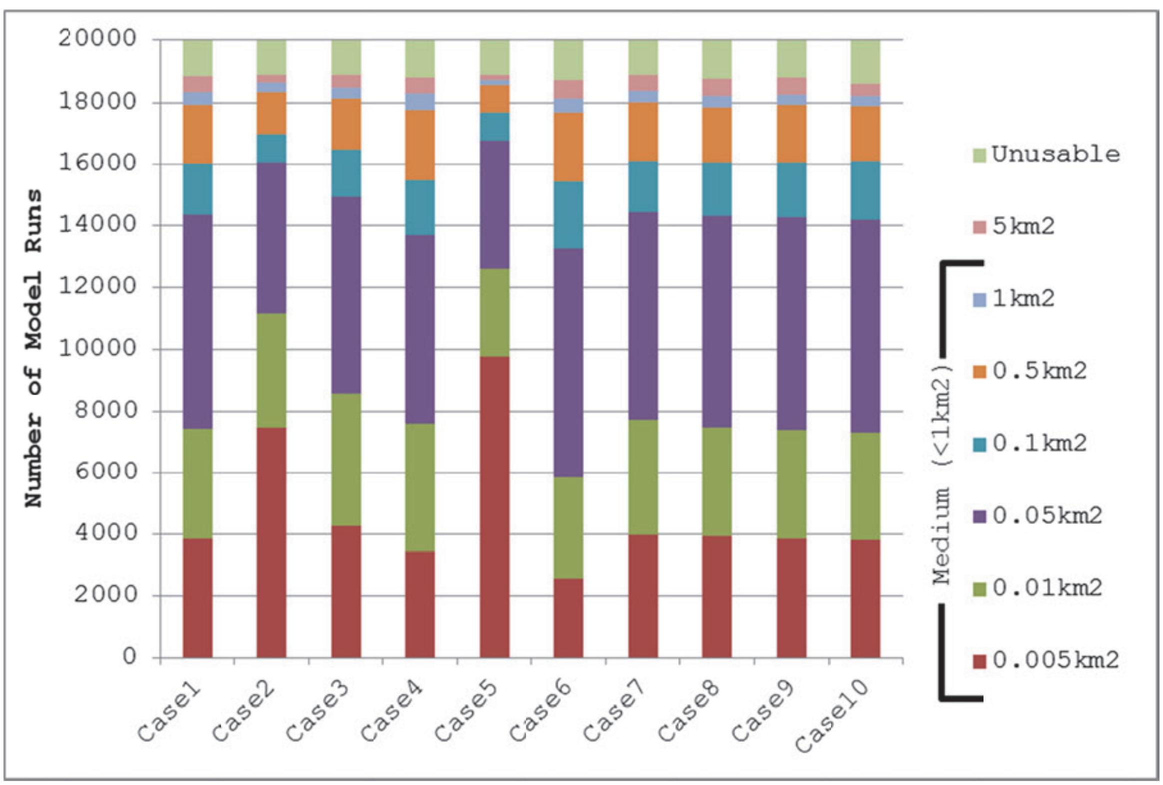


Figure B.2
Histogram of Scenario 1 Error Ellipse Areas



Scenario 2: One SAR, One Racetrack FMV

In this scenario, one of the UAS is collecting SAR imagery and the other is flying a racetrack FMV orbit. The orbit parameters for each case are listed in Table B.2.

Table B.2
Orbit Parameters for Scenario 2

	Aircraft 1: SAR Orbit				Aircraft 2: Racetrack FMV Orbit				
	X Offset	Y Offset	Alt	Axis of Path	X Center	Y Center	Alt	RA	RB
Case 1	50km	150km	20kft	X	150km	150km	20kft	40km	5km
Case 2	75km	100km	20kft	X	150km	150km	20kft	5km	40km
Case 3	150km	200km	30kft	X	250km	250km	30kft	5km	40km
Case 4	150km	75km	25kft	X	250km	250km	30kft	40km	5km
Case 5	200km	50km	30kft	X	75km	125km	15kft	40km	5km
Case 6	100km	75km	25kft	Y	125km	125km	15kft	10km	50km
Case 7	200km	50km	30kft	Y	125km	125km	25kft	50km	10km
Case 8	75km	150km	20kft	Y	50km	250km	25kft	50km	10km
Case 9	100km	100km	15kft	Y	200km	200km	30kft	10km	50km
Case 10	75km	200km	30kft	Y	100km	100km	20kft	10km	50km

An example of the output of the model for this scenario is shown in Figures B.3 and B.4.

Figure B.3
Example of Scenario 2: One SAR, One Racetrack FMV

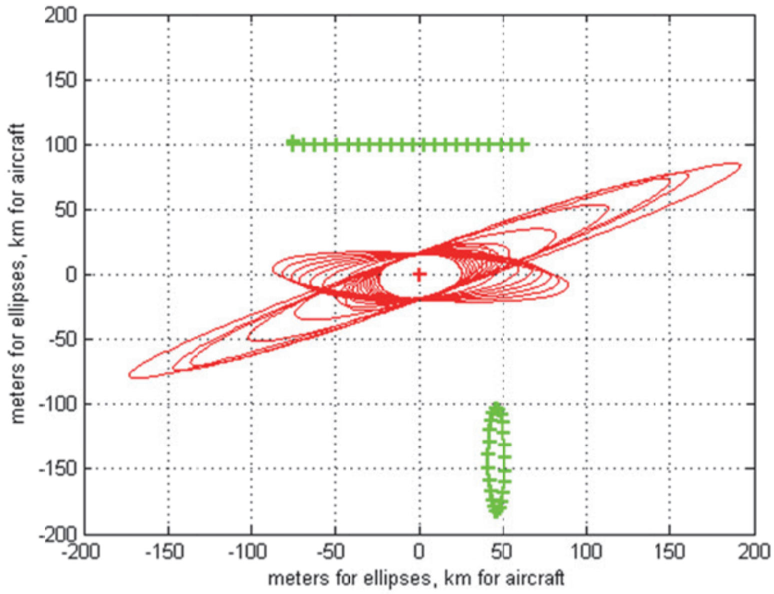
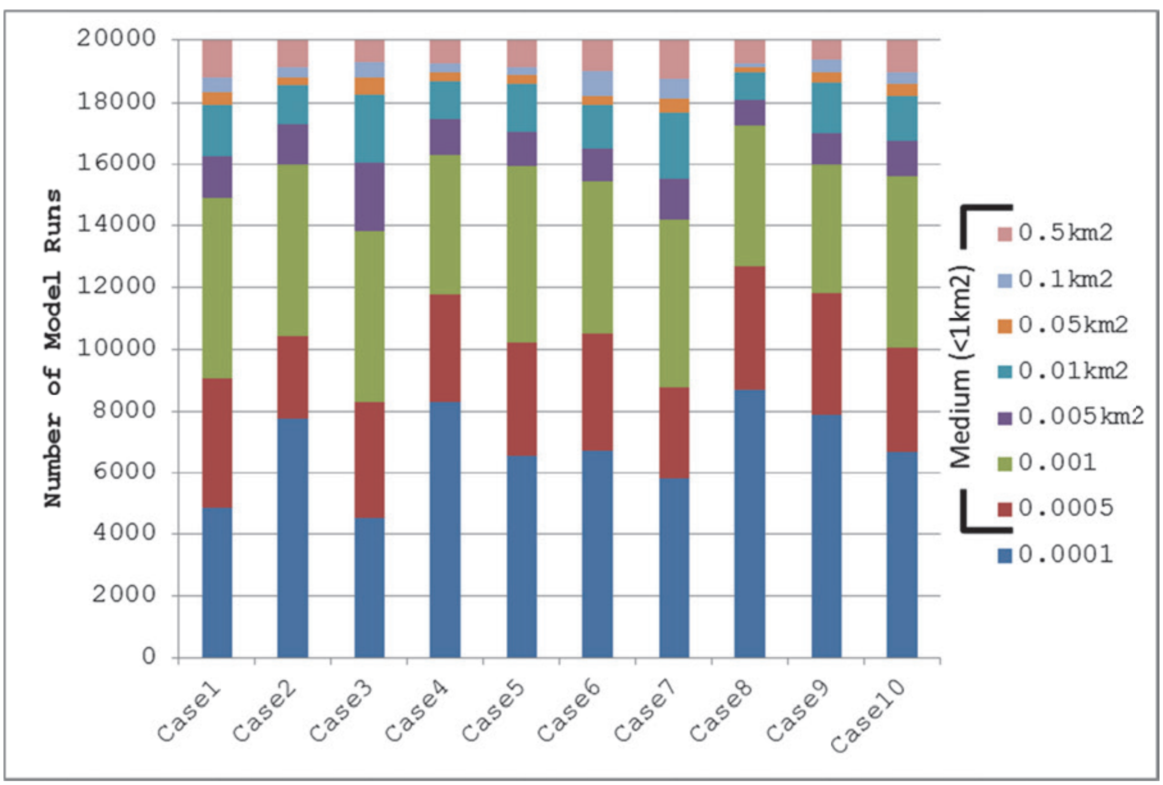


Figure B.4
Histogram of Scenario 2 Error Ellipse Areas



SCENARIO 3: SAR FMV 2 CASES SUMMARY

In this scenario, one of the UAS is collecting SAR imagery and the other is flying a circular FMV orbit. The orbit parameters for each case are listed in the Table B.3.

Table B.3
Orbit Parameters for Scenario 3

	Aircraft 1: SAR FMV				Aircraft 2: Circular FMV Orbit			
	X Offset	Y Offset	Alt	Axis of Path	X Offset	Y Offset	Alt	Radius
Case 1	50km	150km	20kft	X	150km	150km	30kft	20km
Case 2	75km	100km	20kft	X	150km	150km	20kft	20km
Case 3	150km	200km	30kft	X	100km	100km	20kft	20km
Case 4	150km	75km	25kft	X	100km	100km	20kft	10km
Case 5	200km	50km	30kft	X	75km	125km	20kft	10km
Case 6	100km	75km	25kft	Y	100km	100km	20kft	10km
Case 7	200km	50km	30kft	Y	150km	150km	15kft	20km
Case 8	75km	150km	20kft	Y	200km	200km	20kft	20km
Case 9	100km	100km	15kft	Y	75km	150km	20kft	20km
Case 10	75km	200km	30kft	Y	150km	150km	20kft	10km

An example of the output of the model for this scenario is shown Figure B.5 and B.6.

Figure B.5
Example of Scenario 3: One SAR, One Circular FMV

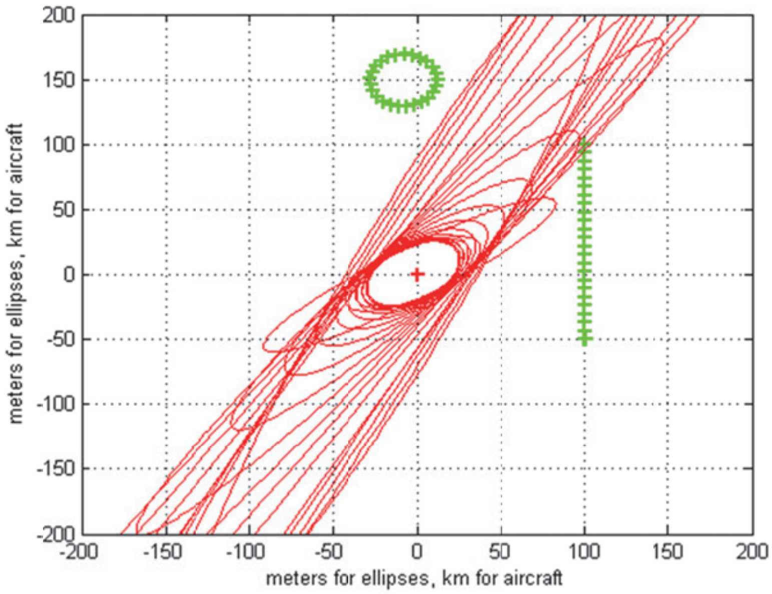
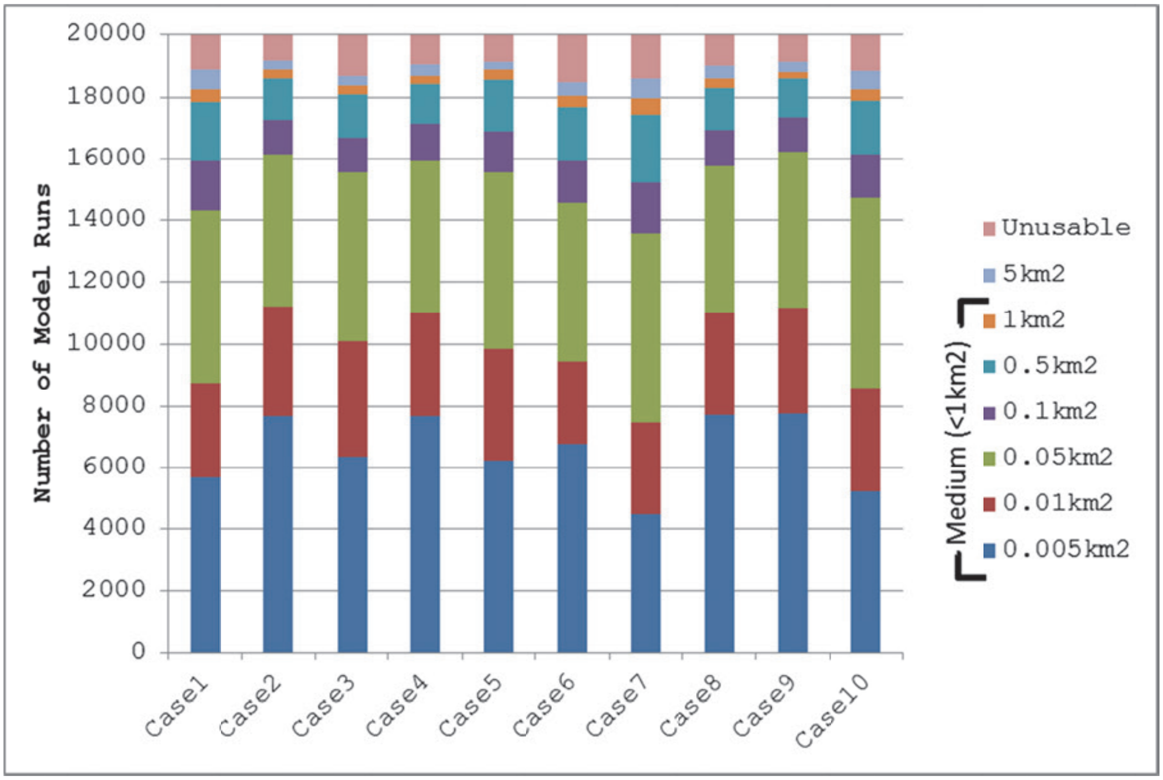


Figure B.6
Histogram of Scenario 3 Error Ellipse Areas



Scenario 4: GMTI-FMV 1 Cases

In this scenario, one of the UAS is flying a GMTI orbit and the other is flying a racetrack FMV orbit. The orbit parameters for each case are listed in Table B.4.

Table B.4
Orbit Parameters for Scenario 4

	Aircraft 1: GMTI Orbit					Aircraft 2: Racetrack FMV Orbit				
	X Center	Y Center	Alt	RA	RB	X Center	Y Center	Alt	RA	RB
Case 1	100km	100km	20kft	100km	20km	150km	150km	20kft	40km	5km
Case 2	100km	100km	20kft	150km	50km	150km	150km	20kft	5km	40km
Case 3	0km	100km	25kft	100km	20km	250km	250km	30kft	5km	40km
Case 4	0km	100km	25kft	150km	0km	250km	250km	30kft	40km	5km

Case 5	100km	0km	30kft	100km	20km	75km	125km	15kft	40km	5km
Case 6	100km	0km	30kft	150km	50km	125km	125km	15kft	10km	50km
Case 7	100km	0km	20kft	100km	20km	125km	125km	25kft	50km	10km
Case 8	0km	100km	20kft	150km	50km	50km	250km	25kft	50km	10km
Case 9	150km	150km	30kft	100km	20km	200km	200km	30kft	10km	50km
Case 10	150km	150km	30kft	150km	50km	100km	100km	20kft	10km	50km

An example of the output of the model for this scenario is shown in Figures B.7 and B.8.

Figure B.7
Example of Scenario 4: One GMTI, One Racetrack FMV

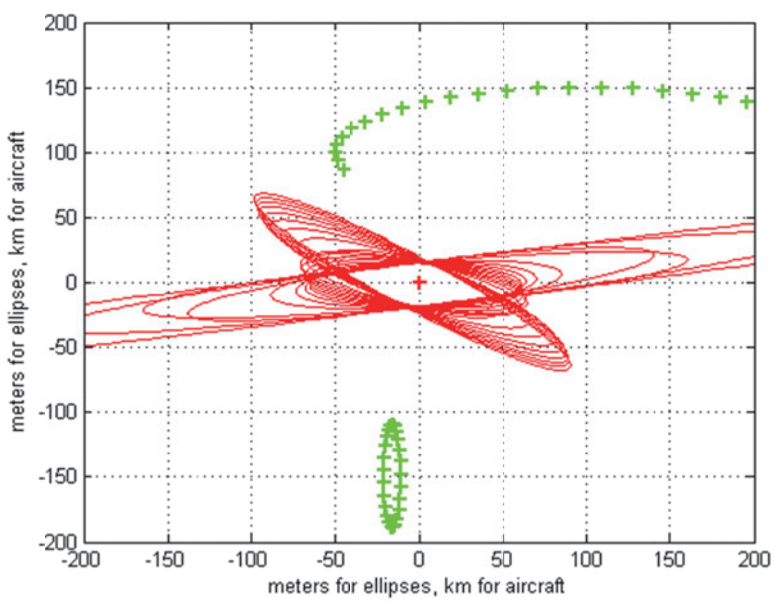
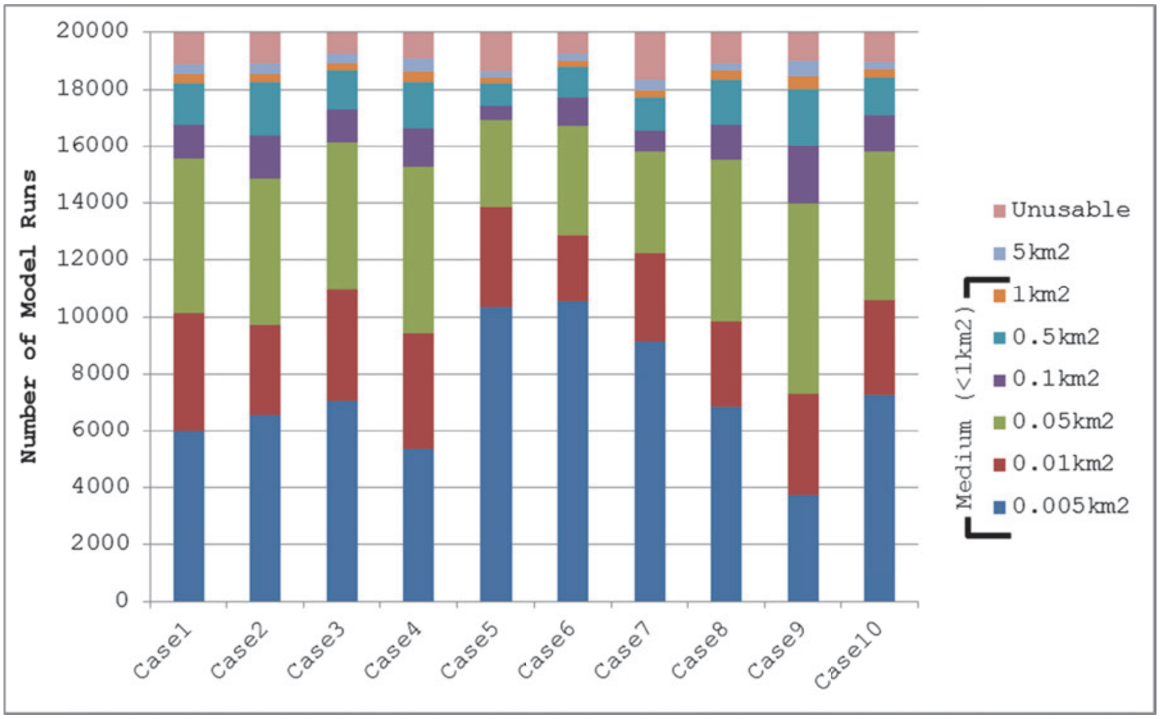


Figure B.8
Histogram of Scenario 4 Error Ellipse Areas



Scenario 5: GMTI-FMV2 cases summary

In this scenario, one of the UAS is flying a GMTI orbit and the other is flying a circular FMV orbit. The orbit parameters for each case are listed in Table B.5.

Table B.5
Orbit Parameters for Scenario 5

	Aircraft 1: GMTI Orbit					Aircraft 2: Circular FMV Orbit			
	X Center	Y Center	Alt	RA	RB	X Offset	Y Offset	Alt	Radius
Case 1	100km	100km	20kft	100km	20km	150km	150km	15kft	20km
Case 2	100km	100km	20kft	150km	50km	200km	200km	20kft	20km
Case 3	0km	100km	25kft	100km	20km	200km	200km	20kft	20km
Case 4	0m	100km	25kft	150km	50km	300km	100km	25kft	50km
Case 5	100km	0km	30kft	100km	20km	250km	250km	30kft	20km

Case 6	100km	0km	30kft	150km	50km	150km	150km	15kft	50km
Case 7	100km	0km	20kft	100km	20km	150km	150km	15kft	20km
Case 8	0km	100km	20kft	150km	50km	150km	150km	15kft	10km
Case 9	150km	150km	30kft	100km	20km	150km	150km	30kft	10km
Case 10	150km	150km	30lft	150km	50km	150km	150km	20kft	10km

An example of the output of the model for this scenario is shown in Figures B.9 and B.10.

Figure B.9
Example of Scenario 5: One GMTI, One Circular FMV

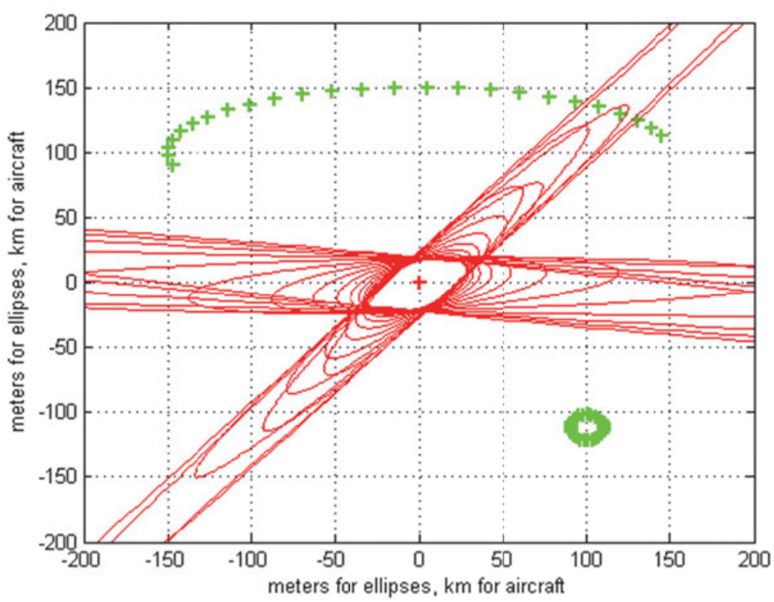
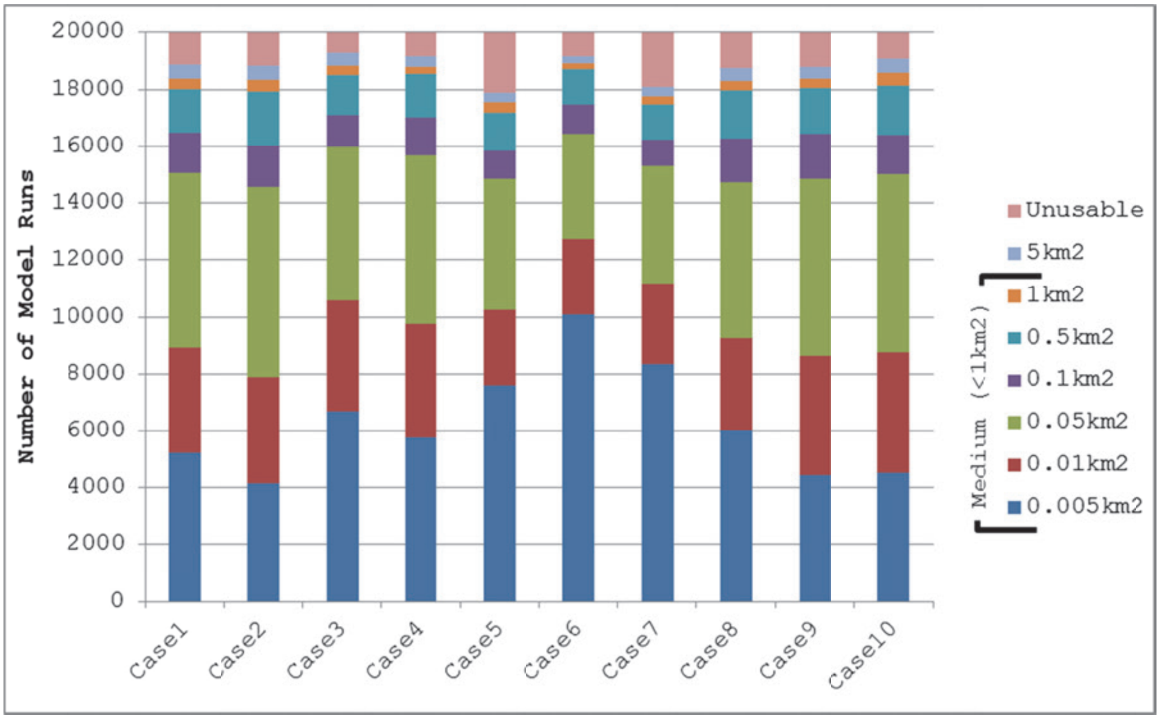


Figure B.10
Graph of Scenario 5 Error Ellipse Areas



C. CAP ALLOCATION MODEL

I used the Model Builder within ArcGIS to create the CAP model. The layout of the model is shown in Figure C.1. The model inputs are the altitude of the platforms, the number of CAPs to be modeled, and the line of sight distance to be used.

Figure C.1
CAP Model

1. Model CAP Locations

Create Random Points: Using the input for number of CAPS, random points are created within the boundaries of Afghanistan to represent the locations of the CAPs.

Add XY Coordinates: The latitude and longitude of each of these points is added to the attribute table and the point shapefile is saved.

2. Model Line of Sight Overlap

Buffer: Using the point shapefile, a ring is created around each point at the inputted line of sight distance.

Intersect: These rings are intersected with each other to determine sections that can be seen by multiple CAPs. Each intersection is a separate polygon within a polygon shapefile.

Clip: The intersected rings are cut to fit within the boundaries of Afghanistan.

Dissolve: The intersected rings are dissolved and a count field is added to keep track of the number of CAPs that have line of sight to each resulting intersection.

3. Add Areas

Project: The analysis until now has been performed using a Geographic Coordinate System. To enable ArcGIS to calculate the areas of each intersection in meters squared, the polygon shapefile needs to be projected into a Project Coordinate System. The standard WGS 84 to Plate Carree transformation is used.

Dissolve (2): The intersected polygons are dissolved based on the number of CAPs that have line of sight to each area. The result is a polygon shapefile with a polygon for example the areas that can be seen by 2 CAPs, and a separate polygon for the areas that can be seen by 3 CAPS, etc.

Add Field/Calculate Field: A field for the percentage area is added and calculated. A polygon shapefile with the polygons and areas by the number of CAPS is saved.

This is repeated with a third dissolve to determine the area that can be seen by at least 2 CAPs. A polygon shapefile with the polygon and area for what can be seen by at least 2 CAPs is saved.

D. MANPOWER CALCULATIONS

I used Air Force Manual 38-208 Volume 2 to calculate the Minimum Manpower Factor (MMF) as follows:

$$MMF\ per\ CAP = \frac{(Days/Wk)(Hrs/Day)(4.348\ Wks/Mo)(DRF)(Crew\ Size)}{Manhour\ Available\ Factor\ \times Overload\ Factor}$$

I used the man-hour available factor and overload factor for a military work force on a 40-hour workweek.

$$MMF\ per\ CAP = \frac{(7)(24)(4.348\ Wks/Mo)(1)(1)}{151.5\ \times 1.077}$$

$$MMF\ per\ CAP = 4.476$$

The total MMF depends on the number of CAPs used for T/FDOA geolocation.

$$Total\ MMF\ = MMF\ per\ CAP\ \times Number\ of\ CAPs$$

References

480th ISR Wing (2010). Air Force Distributed Common Ground System (DCGS) Operational Planning Process Handbook (DOPP). 480th ISR Wing.

ACC Public Affairs (2012). "Fact Sheet: High-Speed Anti-Radiation Missile Targeting System." Air Combat Command.

ACC Public Affairs (2012). "Fact Sheet: MQ-1B Predator." Air Combat Command.

ACC Public Affairs (2012). "Fact Sheet: MQ-9 Reaper." Air Combat Command.

Adamy, D. (2001). EW 101. Boston, Artech House.

AFDD 2-0. *See* U.S. Air Force (2012).

AFISRAI-14-153. *See* U.S. Air Force (2009).

Alkire, B., J. Kallimani, et al. (2010). Applications for Navy Unmanned Aircraft Systems. Santa Monica, RAND Corporation.

Anonymous (3-4-2008). "Signal Strength." Air Force Magazine Daily Report.

Author Unknown. Date Unknown. "Algorithm Comparisons." National Security Agency. Fort Meade, MD. (copy available upon request)

Bardelli, R., D. Haworth, et al. (1995). "Interference Localisation for the Eutelsat Satellite System." IEEE Global Telecommunciations Conference. Vol. 3: 1641-1651.

Berens, P. (2006). "Introduction to Synthetic Aperture Radar (SAR)." Advanced Radar Signal and Data Processing. Neuilly-sur-Seine, France, NATO: 3-1 - 3-14.

Bone, E., and C. Bolkcom. (2003). Unmanned Aerial Vehicles: Background and Issues for Congress. Congressional Research Service.

Chestnut, P. (1982). "Emitter Location Accuracy Using TDOA and Differential Doppler." IEE Transactions on Aerospace and Electronic Systems. AES-18(No. 2): 214-218.

Cote, O. R. (2010). "Submaries in the Air Sea Battle." STS2010. Cambridge, MA.

Department of Defense. (2010). Quadrennial Defense Review Report.

Dunn, R. J. I., P. T. Bingham, et al. (2004). Ground Moving Target Indicator Radar. Northrop Grumman Analysis Center Papers.

Eaglen, M., and D. Nguyen (2011). "Super Committee Failure and Sequestration Put at Risk Ever More Military Plans and Programs." Backgrounder. Washington, DC, The Heritage Foundation. 2625: 1-19.

Elbert, B. R. (2008). Introduction to Satellite Communication. Boston, Artech House.

FAO Fisheries and Aquaculture Department (1988). The Application of Remote Sensing Technology to Marine Fisheries: An Introductory Manual.

Gear, J. R. (2011). USAF RPA Update: Looking to the Future.

Green, J. D. (2011). Integrating Mission Type Orders into Opertional Level Intelligence Collection. Joint Advanced Warfighting School. Norfolk, VA, National Defense University, Joint Forces Staff College. Master's Thesis: 124.

Highnam, P. (2001). "Advanced Tactical Targeting Technology (AT3)." DARPA Special Projects Office.

Hosking, R. (2006). Digital Receiver Handbook: Basics of Software Radio. New Jersey, Pentek.

Isherwood, M. (2011). Layering ISR Forces. Mitchell Institute for Airpower Studies.

Joint Chiefs of Staff (1994). "Command and Control for Joint Air Operations." JP 3-56.1. Department of Defense.

Kempinski, B. (2011). Policy Options for Unmanned Aircraft Systems. Pub. No. 4083. Congressional Budget Office.

Kosinski, J. A. (2003). "Distributed Coherent RF Operations." Annual Precise Time and Interval Meeting. San Diego, CA.

Liang, J., and Q. Liang. (2011). "RF Emitter Location Using a Network of Small Unmanned Aerial Vehicles (SUAVs)." IEEE.

Marsh, L., D. Gossink, et al. (2007). "UAV Team Formation." IEEE Information, Decision and Control: 176-181.

Menthe, L., A. Cordova, et al. (2012). The Future of Air Force Motion Imagery Exploitation: Lessons from the Commercial World. Santa Monica, CA, RAND Corporation.

Musicki, D., R. Kaune, et al. (2010). "Mobile Emitter Geoocation and Tracking Using TDOA and FDOA Measurements." IEE Transactions on Signal Processing Vol. 58(No 3): 1863-1874.

Musicki, D., and W. Koch. (2008). "Geolocation Using TDOA and FDOA Measurements." IEEE.

Okello, N. (2006). "Emitter Geolocation with Multiple UAVs." 9th International Conference on Information Fusion.

Penn, B. (2008). "ASIP-2C Update." USAF Aeronautical Systems Center.

Pocock, C. (2008). Locating Trouble: Network-Centric Collaborative Targeting System goes Operational. C4ISR Journal.

Poisel, R. A. (2005). Electronic Warfare Target Location Methods. Boston, Artech House.

Raytheon (2004) "Advanced Tactical Targeting Technology." Technology Today. Vol 3.

Rockwell Collins. (2012). "ARC-210 Generation 5."

Scerri, P., R. Glinton, et al. (2007). "Geolocation of RF Emitters by Many UAVs." American Institute of Aeronautics and Astronautics.

Schanz, M. V. (2011) "The Reaper Harvest." Air Force Magazine.

Shanker, T. and E. Bumiller (6-12-2011). "Weighing Pentagon Cuts, Panetta Faces Deep Pressures." The New York Times.

Soumekh, M. (1999). Synthetic Aperture Radar Signal Processing with MATLAB Algorithms. Wiley.

Stewart, A. D. (1997). "Comparing Time-Based and Hybrid Time-Based/Frequency Based Multi-Platform Geolocation Systems." Monterey, CA, Naval Postgraduate School. Master's thesis.

Thompson, L. B. (2004). "Fleeting Targets, Rethinking Orbital & Airborne Sensors." ISR Integration 2004 Conference.

U.S. Congress Office of Technology Assessment (1987). New Technology for NATO: Implementing Follow-On Forces Attack. Washington, DC, U.S. Government Printing Office.

U.S. Air Force (2009). "Air Force Distributed Common Ground System (AF DCGS) Operations, Air Force ISR Agency." AFISRAI-14-153. Volume 3. Lackland Air Force Base.

U.S. Air Force (2011). "Operation Procedures - Air and Space Operations Center (AOC)." AFI13-1AOC. Space, Missile, Command, and Control.

U.S. Air Force (2012). "Intelligence, Surveillance, and Reconnaissance (ISR) Operations." AFDD 2-0. Maxwell Air Force Base.

U.S. Air Force SAF/FM (2007). United States Air Force FY2008/2009 Budget Estimates: Aircraft Procurement Volume 1. United States Air Force.

U.S. Air Force SAF/FM (2008). United States Air Force FY2009 Budget Estimates: Aircraft Procurement Volume 1. USAF.

Under Secretary of Defense for Acquisition, Technology, and Logistics (2009). FY2009-2034 Unmanned Systems Integrated Roadmap.