



**PLANNING COVERAGE OF POINTS OF INTEREST VIA MULTIPLE
IMAGING SURVEILLANCE ASSETS: A MULTI-MODAL APPROACH**

THESIS

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AFIT/GOR/ENS/03-11

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AFIT/GOR/ENS/03-11

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THESIS

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Operations Research

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March 2003

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Acknowledgments

I would like to first and foremost thank my husband, and my wonderfully cute son. Also, I'd like to thank my wonderful parents who've not only been extremely supportive in my educational goals, but also let their grandson spend time with them allowing me time to focus on my thesis. All of my family have been very helpful and supportive throughout my life. To my classmates who helped with technical difficulties and just to lighten the mood...many Thanks.

Acknowledgements are in order for my advisor, Dr. Deckro, my reader, Dr. Chrissis, Capt Chambal for being very helpful, and my sponsors. They have all been helpful in this process.

Table of Contents

	Page
Acknowledgments	iv
List of Figures	vii
List of Tables.....	viii
Abstract	x
I. Introduction.....	1
Background.....	1
Problem Statement	3
Research Objectives.....	4
Assumptions.....	5
Methodology.....	6
Summary.....	6
II. Literature Review	8
Overview.....	8
Project Scheduling	9
Resource Constrained Project Scheduling Problem	11
Generalized Resource Constrained Project Scheduling Problem	13
Multi-Modal Generalized Resource Constrained Project Scheduling Problem	14
Goal Programming.....	16
Sensitivity Analysis	18
Previously Published Models.....	19
Summary.....	20
III. Formulation	21
Introduction.....	21
General Approach	22
The Dataset	29
Key Assumptions	30
Computational Effort	30
Summary.....	31
IV. Illustrative Analysis	33
Introduction.....	33
Problem.....	33
Notional Dataset.....	34

Examining the Results	37
Flexibility of the Formulation.....	42
Summary.....	48
V. Conclusions and Recommendations.....	50
Review	50
Recommendations.....	51
Conclusions.....	51
Appendix A. Information Used to Develop STK Model	53
Appendix B. Notional Dataset Obtained from STK	55
Appendix C. VBA Code.....	72
Appendix D. Solution to Notional Example	76
Appendix E. Gantt Charts from Notional Example	86
Bibliography.....	96

List of Figures

	Page
Figure 1. Map of POIs and starting position of UAV using STK®.....	35
Figure 2. Sample Gantt Chart for 3-hour time period	38
Figure 3. From STK®, graphical representation of solution.....	40
Figure 4. From STK®, changed priorities as part of sensitivity analysis.	41

List of Tables

	Page
Table 1. Parameters and Variables for RCPSP formulation	12
Table 2. Parameters and Variables for MMGRPSP formulation	15
Table 3. Parameters and Variables for WGP and Chebyshev GP	17
Table 4. Parameters for LGP model	18
Table 5. Parameter and Variable Definitions for General Formulization	22
Table 6. Parameters and Variables	27
Table 7. Notional POIs, Latitudes, Longitudes, T-Values, Priorities, and Weights	36
Table 8. Allocation for Q-west	39
Table 9. Satellite parameters used in STK model	53
Table 10. UAV Parameters used in STK model	53
Table 11. Sensor parameters used in STK model	54
Table 12. Actual values from STK model*	56
Table 13. Modified values used in Frontline Premium Solver Platform	65
Table 14. Allocation of assets for Q-West	76
Table 15. Allocation of assets for Basrah	77
Table 16. Allocation of Assets for Mosel	78
Table 17. Allocation of Assets for Shayka	79
Table 18. Allocation of Assets for H-Zalah	80
Table 19. Allocation of Assets for Hel-3494	81
Table 20. Allocation of Assets for I-Corp-HQ	82

	Page
Table 21. Allocation of Assets for Bridge.....	83
Table 22. Allocation of Assets for DIV.....	84
Table 23. Allocation of Assets for DIV2.....	85

Abstract

For the United States to maintain information superiority, it is necessary to have a means of allocating intelligence-gathering assets to collect information on particular points of interest. In today's geopolitical environment, however, the number of points of interest is growing rapidly, whereas the number of available assets is not. To aid in maintaining information superiority, this research explores the use of a Multi-Modal Goal Programming Resource Constrained Project Scheduling approach for allocating imaging surveillance assets (land, air, sea, and space) to a set of points of interest for a given time period. The multiple objectives of this formulation are to minimize the number of points of interest not covered at any time during the required period, minimize the deviation from the minimum image resolution of each point of interest, and minimize the time between successive imaging assets imaging each point of interest.

PLANNING COVERAGE OF POINTS OF INTEREST VIA MULTIPLE IMAGING SURVEILLANCE ASSETS: A MULTI-MODAL APPROACH

I. Introduction

Background

It is said, “a picture is worth a thousand words”. In the fall of 1962, however, a picture may have been worth over three billion lives. In October of 1962, the U.S. was able to prove, contrary to claims made by the Soviet Union, that offensive weapons, medium-range and intercontinental ballistic missiles were being placed in Cuba by the Soviet Union. The images taken with a U-2 reconnaissance aircraft helped to disprove Soviet claims that the military build-up in Cuba was solely defensive in nature (30). This knowledge, along with other intelligence, aided in the avoiding of a potentially devastating nuclear war

Knowledge, along with the means to successfully implement it, is the key to preventing battles, if possible, and winning them if they prove unavoidable. Whether by the use of force or through passive means, knowledge of “enemy forces, their composition, disposition, intentions, their locations, direction, speed, and combat readiness” (38) is vital to the side that emerges as the victor. In today’s geopolitical environment, this knowledge, also referred to as information dominance, is a necessity to maintain security and assure victory.

Information dominance (ID), as defined by FM 100-6,

“is the degree of information superiority that allows the possessor to use information systems and capabilities to achieve an operational

advantage in a conflict or to control the situation in operations short of war, while denying those capabilities to the adversary.” (14:Glossary-7)

With information dominance the United States is able to “engage the adversary more precisely and with greater lethal / non-lethal effects, because of our information advantage and the enemy’s corresponding inability to move or protect itself” (46). In addition, information dominance allows the US to “create high performance units that use information in a manner that allows them to accomplish their missions more effectively and quickly with minimum casualties.” (46)

In a time where there is no longer a single superpower foe, but rather a plethora of potential adversaries spread across the globe, gaining and maintaining ID becomes a complex and time consuming task. This task drives the need to optimize coverage of prioritized points of interest using land, air, sea, and space assets in order to obtain knowledge that can best serve the appropriate decision-makers. Maintaining continual imaging of a point of interest in a critical pre-attack period is a complex task, involving both timing and allocation of key space, land, air, and sea intelligence, surveillance, and reconnaissance (ISR) assets. Given the quantity of assets and the array of possible locations that may require coverage, the problem of allocating the available resources can become a complex and time consuming task. The need to utilize scarce resources to image key areas of interest (POI) suggests the need to optimize the tasking of various existing assets to best serve the decision-makers.

An optimization approach is useful in this instance because there are limited resources to be divided among several potential POIs. “Optimization deals with problems of minimizing or maximizing a function of several variables, usually subject to

equality and/or inequality constraints.” (30:v) This allows the decision maker to utilize limited resources in a way that optimizes the resource’s usefulness in achieving an objective.

Problem Statement

During the Cold War, the United States primarily faced a single super power opponent. Maintaining continuous coverage of one principal foe and its allies was a complex task, but was comparatively simple compared with current surveillance requirements. In today’s political environment, there is no longer one primary foe; there are several potential alliances of foes and thus an array of points of interest (POI), some of which change rapidly. Allocating surveillance assets among several potential POIs is difficult. Maintaining continuous or near continuous 24-hour coverage over a multitude of potential POIs is an even more complex task. Continuous, 24-hour coverage of a POI, therefore, may not exist when relations between the POI and the United States begin to spiral towards conflict. The need arises to be able to allocate surveillance assets to provide the required coverage over a new POI.

There have been several attempts at optimizing coverage of a POI. The size of the problem often makes complete enumeration impractical. Branch and bound techniques have been used to reduce the number of possible solutions, however the size of the search space may still be great due to the number of assets being considered (33). The most popular technique for allocating resources is via a “greedy” heuristic in which “the targets are prioritized and then assigned for imaging.” (33:218) These approaches prove inadequate to allocate multiple asset types over multiple targets in a timely manner because the analysts have to accomplish independent runs for different imaging assets

and then combine the solutions. By not accounting for the integration of various asset types, in space, air, land and sea, as part of the original formulation, the optimal solutions obtained through the individual asset type allocating models tend to become sub-optimal when combined together.

The approach presented here allocates an array of surveillance asset types to multiple target areas. Given the need for a quick solution to allocate available resources to provide continuous 24-hour coverage of an area, the problem is initially modeled using multi-modal resource constrained techniques to specify all relevant optimization considerations.

Research Objectives

The United States maintains a limited number of surveillance assets. The need for methods to integrate assets over various domains (space, air, land, and sea), therefore, is critical to efficiently obtain imaging surveillance of areas of interest. Additionally, the number of potential adversaries is great. Porto suggests the number of possible solutions given N surveillance assets and T targets is $[(N/2) \times (T-1)!]$. (33:217) If, for example, the United States had five potential surveillance assets available to provide coverage of 20 POIs, there are 6.1×10^{17} possible ways to allocate the five surveillance assets to cover the 20 POIs assuming all assets were capable of observing all POIs. Should the United States have 10 assets available for allocation and 25 POIs, the number increases to 3.1×10^{24} possibilities.

The addition of time intervals expands the problem even further. Clearly the potential problem solution space increases rapidly with the addition of assets and POIs. To exhaustively enumerate all possible solutions would be prohibitive. Because the time

interval of interest in this research is the 72 hours preceding the initiation of actions, this research focuses on those assets that are available to the theater in question. The approach however can be expanded to multiple theaters.

A list of the intelligence assets in a particular theater is given in the Theater Intelligence Architecture Plan. However, for use in this thesis, an unclassified generic database has been used. It contains a fictitious number of space, air, land, and sea-based imagery surveillance assets along with capabilities based on unclassified sources. These assets were modeled using a program which has already been independently verified and validated for use in aerospace applications, Analytical Graphic, Inc's, Satellite Toolkit® (STK).

Assumptions

To aid in the completion of this research, some principal assumptions were made. The first assumption made was that all points of interests are terrestrial. No points of interest such as launched missiles, aircraft in flight, launched space vehicles, or other vehicles or objects already in flight are taken into consideration in this model.

Secondly, this model does not take into consideration the retasking of satellites. This could however be incorporated into the approach by some manipulation to the data and the addition of some constraints. This issue is addressed in Chapter 5.

The third major assumption is that times are all integers. For example, the duration of an access of an asset to a point of interest is an integer value, and the start times of the accesses are also integer in nature. This was done to simplify some of the calculations accomplished in the model. Chapter 5 suggests ways of adjusting this assumption for more realistic representation of access times and durations.

Finally, is it assumed that there exist some proposed routes for UAVs. These routes may not be all the possible routes, however they are assumed to represent the first choice routes for the UAVs. Sensitivity analysis can then be used to provide some constraints for routes that can then be generated with the appropriate route generation programs.

Methodology

To allocate surveillance assets to provide near-continuous to continuous coverage of a point(s) of interest, a modeling approach was developed based on Project Scheduling Program (PSP) principles. More specifically, a Multi-Modal Resource Constrained Project Scheduling Program (MMRCPSP) approach was extended to this surveillance allocation problem. The model at minimizes the uncovered time gaps between assets covering the point of interest. In order to take into consideration the priority of the various areas of interest, a Goal Programming (GP) approach was also incorporated into the model. This was done to ensure that the point of interest with the highest priority are covered prior to assigning assets to lower priority targets.

Summary

This chapter has given an overview of the background of the problem, the purpose of this research, the scope of the research accomplished, the fundamental assumptions made during the research, and a brief overview of the approach and methodology used to provide a model to solve the allocation of imagery surveillance assets. Chapter 2 provides a literature review in order to provide the reader with a background of the approaches used to develop the model. Chapter 3 presents the methodology of developing the model. Chapter 4 illustrates the approach by analyzing a notional

example and demonstrates how the results can be used by the decision makers. Chapter 5 gives the conclusions arrived from the research and recommendations for future studies.

II. Literature Review

Overview

In 2000 the Rand Corporation conducted a study to address the...

“ability of the Air Force to effectively attack time critical targets (TCTs) and the extent to which its successes and failures in this area can be attributed to dynamic command and control and battle management capabilities (or their lack)” (19:iii)

it was noted that

“a major shortfall to optimal allocation of scarce ISR (Intelligence, Surveillance, and Reconnaissance) resources and to cross-cued and / or simultaneous collections is the lack of agreed-upon (by DoD [Department of Defense] and the intelligence community) CONOPS [Concept of Operations], TTP[Tactics, Techniques, and Procedures], and automated tools for integrated tasking and battle management of (1) sensors from multiple intelligence disciplines (multi-INT), (2) sensors from multiple platform domains (cross-domain), and (3) the associated PEDS [Processing, Exploitation, and Disseminations Systems] to support military monitoring, assessment, planning, and execution processes and timelines.” (19: 28)

Multi-INT refers to signals, measurement and signature, human, and imagery intelligence disciplines (19:28). *Cross-domain* refers to the integration of land, sea, air, and space (19:28). This research focuses on imagery intelligence, which is obtained from electro-optical, radar, infrared, and photography systems (28:16). This research does, however, take into consideration cross-domain allocation of imagery surveillance assets.

The main focus of this research is to develop a mathematical formulation that integrates land, air, sea, and space imaging surveillance assets to provide near-continuous to continuous coverage of POIs. The integration of Multi-Modal Resource Constrained Project Scheduling and Goal Programming accomplished this.

In this section, a description of the Project Scheduling Problem (PSP) is given to provide an introduction to approaches used. This introduction leads into the necessary background of Resource Constrained Project Scheduling Problem (RCPSP), Generalized RCPSP (GRCPSP), and Multi-Modal RCPSP (MMRCPSp). Next, a description of Multiple-Criteria Decision Making (MCDM) is given and lends itself to the discussion of Goal Programming (GP). Concluding the chapter is an initial look at the result of integrating the approaches for the purpose of this research, a Multi-Modal Goal Programming Resource Constrained Project Scheduling Problem (MMGPRCPSP) formulation.

Project Scheduling

There are four primary objectives of Project Scheduling: 1) minimize the completion time of a project, 2) determine the capacities of the renewable resources so that a deadline is met and resource costs are minimized, 3) maximize the net present value of a project, and 4) minimize both the estimated rework times and costs (13:65). To better understand these objectives, and in turn the essence of the PSP, some definitions are required.

A *project* is a set of *activities* (tasks) that are performed under a set of *requirements* (constraints) in order to complete a process satisfying a particular objective, typically within some time horizon. For example, construction of a satellite could be a project. In terms of this thesis, the project is gathering imaging of a POI or of a set of POIs near continuously or continuously. The objective is to minimize the number of POIs not covered at any time during the observation period, minimize the deviation from the required image resolution of each POI, and minimize time gaps between successive

imaging surveillance assets. This objective, as will be seen, is accomplished using Goal Programming rather than through a standard PSP formulation.

An *activity* (task) is one of possibly several events, with a given duration, needed to accomplish the project. For the satellite construction project again, examples of some of the activities necessary for the project include the design phase, assembly of the parts, and testing. For the purpose of this research, the activity(s) is the collection of imaging from the POI(s).

A *resource* is something that is used during the activity. There are three types of resources: renewable, non-renewable, and doubly constrained. A *renewable resource* is something that can be re-used during the project. In the satellite example, one renewable resource is the people assembling the parts. The people work during a certain shift and after they have finished a shift return at the start of their next scheduled shift. The land, air, sea, and space imaging surveillance assets are the renewable resources in this research.

A *non-renewable resource* is a resource which can be used only once during an activity. For instance, in assembling the satellite, the individual parts are non-renewable. After a part is attached to one satellite, it will not return to be used on another satellite. For the purpose of this research, a nonrenewable resource would be a one-way mission for an imaging asset.

Doubly constrained resources are resources that are constrained by both activity and the project. The most common example of this is money. There could be an allotted amount of money to be used for each the design phase, assembly phase, and the test phase, and then a specific budget for the entire project. Each amount of monetary

allotment cannot be exceeded. For the purpose of this research, doubly constrained resources (*i.e.* a satellite that was tasked to different points of interest each orbit) are not used; however, could easily be incorporated at a later time if deemed necessary.

Fundamentally, the Project Scheduling Problem is to optimally schedule multiple activities, requiring various types of resources, which completes a project while achieving the objective defined by the decision-maker. In attempting to accomplish this, there typically are constraints on the resources. This type of PSP is called the Resource-Constrained PSP (RCPSP). RCPSP is used in this research and therefore is described in more detail in the following section.

Resource Constrained Project Scheduling Problem

In the majority of projects undertaken, there is some limit or constraint on the resources available. Due to the addition of such constraints, which are not taken into consideration in the basic Program Evaluation Review Technique (PERT) or Critical Path Method (CPM) approaches to PSP, an extension on the basic PSP needs to be included to compensate for the limited resources. When the constraints on the resources are considered, the basic PSP may not provide an optimal solution; therefore, the use of the Resource Constrained Project Scheduling Problem (RCPSP) formulation is necessary. The RCPSP formulation given is adapted from Pritsker, Watters, and Wolfe (1969).

The objective function of this formulation, expression [2.1], (one of several given in Pritsker, Watters, and Wolfe, 1969) is to minimize the total project throughput time. Minimizing the total throughput time is equivalent to maximizing “the number of time periods remaining after the project is completed” (34:96).

Table 1. Parameters and Variables for RCPSP formulation

Parameters:	
i	project number, $i = 1, 2, \dots, I$; I = number of projects
j	job number, $j = 1, 2, \dots, N_i$; N_i = number of jobs in project i
t	time period, $t = 1, 2, \dots, \max G_i$; G_i is the absolute due date
g_i	desired due date of project i
e_i	earliest possible period by which project i could be completed
d_{ij}	number of periods required to perform job j of project i
l_{ij}	earliest possible period in which job j could be completed
u_{ij}	latest possible period in which job j could be completed
k	resource or facility number, $k = 1, 2, \dots, K$; K = number of different resource types
r_{ijk}	amount of type k resources required on job j of project i
R_{kt}	amount of type k resource available in period t
a_k	is the amount of resource k available for the project
Variables:	
x_{ijt}	1 if job j of project i is completed in period t ; 0 otherwise
x_{it}	1 in period t if all jobs of project i have been completed by period t , 0 otherwise
x_{int}	0 for $t < \max \{a_{in} + d_{in} - 1; \max_{j \in P_{in}} (a_{ij} + d_{ij} + d_{in} - 1)\}$ where P_{in} is the set containing other jobs of project i that must precede job n , 1 otherwise
x_{imt}	0 for $t > \min_{j \in F_{im}} \{G_i - d_{ij}\}$ where F_{im} is the set containing other jobs of project i that must follow job m , 1 otherwise

$$\max \sum_{i=1}^I \sum_{t=e_i}^{G_i} x_{it} \quad [2.1]$$

subject to

$$\sum_{t=l_{ij}}^{u_{ij}} x_{ijt} = 1 \quad \text{for } i = 1, \dots, I; j = 1, \dots, N \quad [2.2]$$

$$x_{it} \leq (1 / N_i) \sum_{j=1}^{N_i} \sum_{q=l_{ij}}^{t-1} x_{ijq} \quad \text{for } i = 1, \dots, I; t = e_i, e_i + 1, \dots, G_i \quad [2.3]$$

$$\sum_{t=l_{im}}^{u_{im}} t * x_{imt} + d_{in} \leq \sum_{t=l_{in}}^{u_{in}} t * x_{int} \quad [2.4]$$

$$\sum_{i=1}^I \sum_{j=1}^{N_i} \sum_{q=t}^{t+d_{ij}-1} r_{ijk} \cdot x_{ijq} \leq R_{kt} \quad \text{for } k = 1, \dots, K; t = \min a_{ij}, \dots, G_i \quad [2.5]$$

$$x_{ijt}, x_{it}, x_{int}, x_{imt} \in \{0, 1\}$$

This quantity of remaining time periods is represented by the summation of x_{it} as t varies from the earliest possible start of a project, e_i , to G_i , project i 's absolute due date. This objective is then subject to precedence and resource constraints.

The first constraint, expression [2.2], dictates each job having only one completion time for each project. In other words, the jobs, which are being used in the set of projects, are only to be accomplished once for each project.

Expression [2.3] prevents project i to be completed until all of the jobs are completed for that project. This is to ensure that the project is completed and no jobs are skipped that are required to be done.

The precedence constraint, given by expression [2.4], is to ensure that a job is not started prior to the completion of another job(s), if there exist such a requirement. For instance, in the construction of a building, it is required to have the walls in place prior to the roof being added.

Finally, expression [2.5] is a resource-constrained set, therefore, there must exist a constraint on the availability of resources in each time period. Suppose “a job is being processed in period t if the job is completed in period q .” (34:98) Then expression [2.3] limits the consumption of resource k by all jobs for time t to the amount of k available. The model forces activities to be shifted in the schedule if the resource limits are reached.

Generalized Resource Constrained Project Scheduling Problem

The Generalized Resource Constrained Project Scheduling Problem (GRCPSP) allows for more flexibility in the precedence requirements of the activities. Precedence requirements allow the user to define one of two time-lag requirements between two activities, minimal or maximum time-lag. The minimal time-lag denotes the minimum

time allowed between two activities. The maximal time-lag denotes the maximum time allowed between two activities.

There are three minimal / maximal time-lag classifications used in GRCPSP; 1) a finish-start relation dictates a minimal / maximal time must elapse between the finish of activity i and the start of activity j , 2) a finish-finish relation defines the requirement for an amount of time that must occur between the completion of activity i and the completion of activity j to allow for cope with the output of activity i , 3) a start-finish relation represents the requirement for a time-lag between the start of activity i and the completion of activity j . The minimal time-lag relations can be used in combination and the maximal time-lag relations can be used in combination if needed to accurately define the relations between activities i and j (13).

Multi-Modal Generalized Resource Constrained Project Scheduling Problem

In some instances, there may be more than one way to accomplish an activity. Such instances can be represented by a Multi-Modal Generalized Resource Constrained Project Scheduling Problem (MMGRCPSP) formulation. The RCPSP is actually a generalized formulation of a MMGRCPSP in that it assumes the existence of only one way to accomplish an activity. The formulation given is adapted from Sprecher (41:8)

Expression [2.6], the objective function, represents the desire to minimize the *makespan*, the duration of the project. This objective is subject to a set of constraints. Expression [2.7] constrains the problem by allowing only one mode assignment to each activity, and only one completion time of that mode. To ensure the usage (consumption) of renewable (non-renewable) resources do not exceed the per-period availability of each resource type, Expressions [2.8] and [2.9] are included in the formulation.

Table 2. Parameters and Variables for MMGRPSP formulation

Parameters:	
J	number of jobs
M_j	set of modes in which job j can be performed
d_{jm}	duration of job j being performed in mode m
$R(N, D)$	set of renewable (non-renewable, doubly constrained) resources
T	upper bound on the projects makespan
$K_r^v \geq 0$ ($K_r^\delta \geq 0$)	number of units of non-renewable (double constrained) resource r , r in R (r in D)
$K_{rt}^\rho \geq 0$ ($K_{rt}^\delta \geq 0$)	number of units of renewable (double constrained) resource r , r in R (r in D) available in period t , $t=1, \dots, T$
EF_j (LF_j)	the earliest (latest) finish time of job j based on the modes with smallest duration
$k_{jmr}^\rho \geq 0$ ($k_{jmr}^\delta \geq 0$)	number of units of renewable (doubly constrained) resource r , r in R (r in D), used (consumed) by job j being performed in mode m at the period the job is in process
k_{jmr}^v	number of units of non renewable resource r , r in N , consumed by job j being performed in mode m
Variables:	
x_{jmt}	1 if job j is performed by mode m and completed in period t ; 0 otherwise

$$\min \sum_{m=1}^{M_j} \sum_{t=EF_j}^{LF_j} t x_{jmt} \quad [2.6]$$

subject to

$$\sum_{m=1}^{M_j} \sum_{t=EF_j}^{LF_j} x_{jmt} = 1 \quad j = 1, 2, \dots, J \quad [2.7]$$

$$\sum_{j=1}^J \sum_{m=1}^{M_j} k_{jmr}^\rho \sum_{q=t}^{t+d_{jm}-1} x_{jmq} \leq K_{rt}^\rho \quad r \in R; t = 1, 2, \dots, T \quad [2.8]$$

$$\sum_{j=1}^J \sum_{m=1}^{M_j} k_{jmr}^v \sum_{t=EF_j}^{LF_j} x_{jmt} \leq K_r^v \quad r \in N \quad [2.9]$$

$$x_{jmt} \in \{0, 1\}$$

Goal Programming

In the aforementioned formulations, each constraint was a hard constraint. In other words, each constraint must be satisfied as equal or less than the right hand side. However, what if the right-hand-side values were desired, but the decision maker would allow some deviation from these attainment levels? Goal programming allows the decision maker some flexibility in defining achievement levels or target values of various parameters in the problem. Within the appropriate constraints, a deviational variable is introduced to model whether or not the target value is obtained exactly, falls short or is exceeded. Allowing this controlled relaxation of the constraints opens up the possibility of a feasible solution where an infeasible solution previously existed when the constraints had to be met with strict regard to the inequality or equality specifications. “The overall purpose of GP is to minimize the deviations between the achievement of the goals and their aspirational levels.” (36:3)

There are three basic forms of GP: 1) Archimedean GP, 2) Chebyshev GP, and 3) non-Archimedean GP (21:12). The Archimedean form is used to minimize the sum or weighted sum of all deviations from the goals (21:12). This is also known as Weighted GP (WGP). The WGP formulation given here is adapted from Romero, 1991.

Table 3. Parameters and Variables for WGP and Chebyshev GP

Parameters:	
F	is the set of constraints
α_i	is the weighting factor for the negative deviation
β_i	is the weighting factor for the positive deviation
$f_i(\vec{x})$	is the i th constraint function
b_i	is the target value of the i th constraint
d	is the maximum deviation
Variables:	
n_i	is the negative deviation from goal i
p_i	is the positive deviation from goal i

$$\min \sum_{i=1}^k (\alpha_i * n_i + \beta_i p_i) \quad [2.10]$$

subject to

$$f_i(\vec{x}) + n_i - p_i = b_i \quad [2.11]$$

$$\vec{x} \in \{F\} \quad [2.12]$$

Ideally, in this formulation n_i and p_i will equal zero. However, if this is not possible, then the objective of the formulation is to minimize the positive and negative deviations, in proportional relation to the values of α_i and β_i .

Chebyshev GP, or minimax GP, is used to “minimize the ... maximum of the unwanted goal deviations.” (21:13) The following formulation is adapted from Romero 1991.

$$\min d \quad [2.13]$$

subject to

$$\alpha_i n_i + \beta_i p_i \leq d \quad [2.14]$$

$$f_i(\vec{x}) + n_i - p_i = b_i \quad [2.15]$$

$$\vec{x} \in \{F\} \quad [2.16]$$

The non-Archimedean form, also known as lexicographic goal programming, allows for prioritized goals. This concept of pre-emptive priorities lets the decision maker specify that one priority is preferred over another priority such that the goals should be fulfilled in a specific order, (*i.e.* “higher priority goals are satisfied first and it is only then that lower priorities are considered.” (36:4)) The LGP given is adapted from Ignizio 1985.

Table 4. Parameters for LGP model

Parameters	
$\mathbf{u}^T$	an ordered vector such that the k th, u_k term is of priority k
$\mathbf{A}$	coefficient matrix
$\mathbf{b}$	right hand side value/goal
$\mathbf{v}^T$	is the vector $[\mathbf{x} \ \mathbf{n} \ \mathbf{p}]$ where $\mathbf{x}$ is the vector of variables, $\mathbf{n}$ and $\mathbf{p}$ are the vectors of negative and positive deviations from the goal
$\mathbf{c}^{(k)T}$	the row vector of weights associated with deviations at rank k

$$\text{subject to} \quad \text{lex min } \mathbf{u}^T = \{\mathbf{c}^{(1)T} \mathbf{v}, \dots, \mathbf{c}^{(k)T} \mathbf{v}\} \quad [2.17]$$

$$\begin{aligned} \mathbf{A} \mathbf{v} &= \mathbf{b} \\ \mathbf{v} &\geq 0 \end{aligned} \quad [2.18]$$

By utilizing one of the aforementioned GP models, it is possible to allow some controllable deviations from the desired right-hand-side values. This controllable deviation allows the decision maker to have some flexibility in the mathematical representation of the problem, which in turn gives some insight to alternate solutions.

Sensitivity Analysis

Sensitivity analysis of solutions to optimization problems gives the decision maker insight into the robustness of a solution. It tests the effect of model assumptions and assists in measuring sensitivity to the precision of the data. It also allows the

investigation of some limited variations in the operational conditions without the need for re-solving the model. Perhaps at the time of the formulation, circumstances were less stressed, (*i.e.* plentiful resources, no deadlines). Now, however, after the formulation is complete, circumstances have changed, resources have been depleted unexpectedly, time is now critical. The decision maker is not going to wait for a new formulation to be developed and solved. Utilizing sensitivity analysis on the original formulation and solution could provide adequate alternative solutions for the new circumstances.

Additionally, sensitivity analysis may be used to provide solutions to “what-if” scenarios; what if there were more resources or more time. By looking ahead to such “what if” scenarios, the decision maker might opt to make “minor” changes in certain values in order to gain higher benefits from the objective function.

In GP there are seven discrete changes that allow sensitivity analysis to be performed: 1) change in the weighting factor at priority level, 2) change in the weighting factor of the deviation variable, 3) change in the original right-hand-side goal, 4) change in the coefficients, 5) addition of a new goal, 6) addition of a new decision variable, and 7) reorder the original priority levels. (20:453; 39:62)

Utilizing such changes, being proactive in providing a list of suggested changes with corresponding benefits, allows the decision maker to have potential contingency plans if unforeseen circumstances arise. This is an extremely important edge if the decisions made, based on the results, mean life or death.

Previously Published Models

There have been two models, which have been developed recently, in an attempt to incorporate multiple asset types, Teledyne Brown Engineering (TBE) developed the

Sensor-Platform Allocation Analysis Tool (SPAAT) and ALPHATECH Inc. developed the Multi Asset Synchronizer (MAS). SPAAT utilizes mixed integer programming techniques to determine “the optimum mix of sensors, platforms, and ground stations” (35:37) to be used in various scenarios. SPAAT offers selection of simple objectives that can drive the model. These objective functions include: minimizing cost, maximizing area coverage, minimizing coverage, and feasibility goals (which “is used as a diagnostic tool” (35:39)).

MAS modifies a networking technique known as the Vehicle Routing Problem with Time Windows (VRPTW). This program, however, is used to allocate only airborne surveillance assets. Additionally, its primary goal is to “resolve tradeoffs in platform route planning, sensor resource allocation, and collection scheduling to construct highly efficient ISR [imaging, surveillance, and reconnaissance] plans.”(27:44)

Summary

The purpose of this chapter was to review the basic background in fundamental elements that were used in the development of the mathematical program used in this thesis. Chapter 3 describes the methodology used to achieve the mathematical formulation developed in this research to allocate imaging assets to cover various POIs.

III. Formulation

Introduction

The concept of determining an optimal mix of imaging assets to provide required coverage of a POI seems daunting. There is a finite number of imaging surveillance assets that are allocated to a theater. A theater itself could contain upwards of 50 countries. Each country alone can have many points of interests, be they military bases, military support factories, fighter squadrons, or even troops moving from one place to another. The vast array of possibilities complicates the process of allocating limited imaging surveillance assets.

Additionally, determining which objective function would best capture the decision-makers' needs and preferences is difficult. Should cost be minimized? Should area of coverage be maximized? Should time spent observing targets be maximized? Should assets used be minimized? Should the number of targets be maximized? These are just a few of an array of possible objective functions.

This chapter develops a mathematical formulation for allocating imaging assets over a fixed time horizon. First, a general approach for a Multi-Modal Goal Programming Resource Constrained Project Scheduling Problem (MMGPRCPSP) is given. Following the general formulation development, the specific formulation that was used in this research is given. The data needed for this formulation, the key assumptions made in this program, and computational effort follows the formulations.

The general problem being looked at is to observe a set of POIs with a finite set of assets for a fixed time. Additionally, there is a desired resolution for each POI, which is to be met by each asset imaging that POI.

General Approach

To optimize the allocation of resources to accomplish required tasks, the concept of Multi-Modal Resource Constrained Project Scheduling Goal Programming is used. The MMRCPSP allows for the scheduling of assets (constrained resources) in such a way that different assets (multiple modes) can be used to accomplish a task. The goal programming (GP) aspect of the formulation incorporates the various pre-emptive priorities assigned to different tasks.

The overall intent of the formulation is to allocate pre-assigned assets to accomplish a set of tasks during an established time window. Given such a setting, three main goals are addressed in this thesis: 1) minimize the number of POIs not imaged at any time during the required period, d_i , 2) minimize the deviations from resolution requirements of the POIs, $d2_i$, and 3) minimize the time gap between assets imaging a POI, $d3_i$. The following sections discuss the constraints used to determine the value of these deviational variables.

Minimize POIs not Imaged During Time Horizon

As part of the objective function, it is necessary to minimize the number of POIs that are not imaged during the observation horizon. To assist in this goal, there must exist a means of counting the POIs not imaged. Expression [3.1] accomplishes this requirement. d_i is a goal programming deviation variable that will equal one if no asset is

imaging a POI at any time during the planning period, i.e. $\sum \sum x_{mit} = 0$. d_i will be minimized in the objective function. There will be one such constraint for each POI.

$$d_i + \sum_{m \in M} \sum_{t \in ST_{mia}} x_{mit} \geq 1 \quad \forall i \in POI \quad [3.1]$$

Table 5. Parameter and Variable Definitions for General Formulation

Parameters:	
P	an ordered vector such that the k th term is of priority k
P_k	pre-emptive weight for priority k POIs
$\mathbf{w}^{(k)}$	the vector of weights associated with deviations at rank k
w_{ij}	weight of deviation j for POI i
R	the set of possible routes for a particular asset
$NumSimulRts_R$	number of simultaneous routes an asset in R can travel
M	set of all assets
POI	set of all POIs
ST_{mia}	set of access times for mode m imaging POI i
$Satellites$	set of modes representing known satellites with known access times
MQ_i	minimum required image resolution for POI i
IQ_{mit}	image quality of mode m of POI i at time t
Variables:	
d	the is the vector of the deviation variables
d_{ij}	deviation variable j associated with POI i
$Routes_R$	1 if route c is chosen for UAV, 0 otherwise
DX_{mit}	1 if mode m is imaging is imaging POI i at time t , 0 otherwise
DEV_{it}	1 if no assets are imaging POI i at time t
F_{mit}	deviation from minimum required image quality of mode m on POI i at time t

Minimize Deviations from Desired Resolution of each POI

It is also desirable to minimize the deviation from the minimum image quality desired by each asset imaging a particular POI. We must first determine the deviation from a particular requirement for each asset at every time the asset is imaging a POI.

Towards this, the expressions [3.2] and [3.3] are used. F_{mit} is the goal programming deviational variable. The number of constraints [3.2] in the formulization will be equal to the sum of all the durations of each access time of each asset to each POI.

$$x_{mit}IQ_{mit'} - F_{mit} \leq x_{mit}MQ_i \quad \forall t \in ST[m, i, a], t' = t, \dots, t + Duration_{mia} \quad [3.2]$$

$$\sum_{m \in M} \sum_{t \in ST[m, i, a]} F_{mit} = d2_i \quad \forall i \in POI \quad [3.3]$$

Minimize the Time Gap Between Successive Imaging Assets

The final purpose of the objective function is to minimize the amount of time between successive assets imaging a particular POI. Constraints [3.4] and [3.5] work toward accomplishing this goal. Expression [3.4] introduces the deviational variable DEV_{it} , which is equal to one if there are no assets imaging task i at time t , to determine the times when no asset is imaging POI i at time t . Expression [3.5] then sums these deviations for each POI i . This sum, $d3_i$, is minimized in the objective function, thus selecting asset assignments that minimizes $d3_i$, the total time between assets imaging all POIs in the set. There will one constraint [3.4] for each time interval in *time* for each POI.

$$\sum_m DX_{mit} + DEV_{it} \geq 1 \quad \forall i \in POI, t \in time \quad [3.4]$$

$$\sum_{\forall j} DEV_{ij} = d3_i \quad \forall i \in POI \quad [3.5]$$

Additional Constraints

It is necessary to have a constraint that limits assets, which are only able to accomplish a set number of simultaneous routes. Equation [3.6] dictates that the sum of

the routes a particular asset travels must be less than or equal to the allowable number of simultaneous routes for that asset. Given a particular route, it is not possible for the resource to start a task at a time that is not in the route selected. This limitation is given by equation [3.7]. In the formulation, there will be a constraint [3.6] for each asset with more than one possible route, and a constraint [3.7] for each asset with multiple route possibilities, for each possible start time of that asset to image POI i at time t .

$$\sum_{c \in R} Routes_c \leq NumSimulRts_R \quad [3.6]$$

$$x_{cit} = Routes_c \quad \forall c \in R, i \in POI, t \in time \quad [3.7]$$

If there exists a set of assets that have unchangeable access times for each POI, then it is necessary to set x_{mit} equal one for those assets at the respective access times. This would be the acquire time of a satellite that is not to be re-established, for example. Mathematically, this is done via equation [3.8]:

$$x_{mit} = 1 \quad \forall t \in ST[m, i, a], m \in Satellites, i \in AOI, a \in access \quad [3.8]$$

In the overall formulization, there will be a constraint [3.3] for every asset with set start times, for every start time of that asset to image POI i at time t .

Objective Function

The goals in the objective function are numerically weighted, w_{ij} , within a priority class, and lexicographically weighted by priority class. As this is a pre-emptive goal program, lexicographic weights of the tasks to be accomplished control the prioritization. The tasks associated with the highest priority are required to be accomplished first; only after the first priority goals are attained does the solver consider accomplishing the tasks in the second highest priority. These pre-emptive weights are given as P_k , where

$k=1,2,\dots$, total number of priority classes and $P_1 \gg P_2 \gg \dots \gg P_k$. Mathematically, these goals and weights can be represented by the objective function given as expression [3.9]. Table 5 is a list of parameter and variable definitions used in this general formulization.

$$\text{lex min } \{P_1 \mathbf{w}^{(1)T} \mathbf{d}, \dots, P_k \mathbf{w}^{(k)T} \mathbf{d}\} \quad [3.9]$$

Specific Formulization

The following is a complete mathematical formulation used in this thesis. Table 5 gives the parameters and variables that are used in the specific formulation of this thesis. In this case, the project is to image a set of POIs for a given observation horizon. The resources are the different imaging surveillance assets and the tasks are the imaging of the various POIs. The objectives, in the example shown, are to minimize the number of POIs not imaged at all during the observation horizon, minimize the deviation from the minimum imaging resolution, and minimize the amount of time between each successive imaging asset for a particular POI. Of course, other objectives can be modeled with this approach.

The airborne imaging assets are only allowed to fly one route at a time. This requirement is adapted from expressions [3.2] and [3.3]. The special operations forces (SOF) team, also utilizes expressions [3.2] and [3.3], but the SOF team is allowed to image two POIs simultaneously, the equivalent of having two simultaneous routes.

Table 6. Parameters and Variables

Parameters:	
P_k	pre-emptive weight for priority k POIs
W_i	weight of having POI i imaged at any time during observation period
$W2_i$	weight of having POI i imaged within minimum imaging requirements
$W3_i$	weight of having POI i imaged with minimal time gaps
R	the set of possible routes for UAV
S	the set of 12-member SOF teams
ST_{mia}	set of access times for mode m imaging POI i
$Satellites$	set of modes representing known satellites with known access times
MQ_i	minimum required image resolution for POI i
IQ_{mit}	image quality of mode m of POI i at time t
Variables:	
d_i	1 if POI i is not imaged at any time during observing horizon, 0 otherwise
$Ftotal_i$	total deviation from minimum image resolution for POI i
$TotGAP_i$	total gap time deviation from allowable time gap for POI i
$RTUAV_i$	1 if route c is chosen for UAV, 0 otherwise
DX_{mit}	1 if mode m is imaging POI i at time t , 0 otherwise
DEV_{it}	1 if no assets are imaging POI i at time t
F_{mit}	deviation from minimum required image quality of mode m on POI i at time t

$$\text{lexmin}\{P_1 \sum_{i \in POIs \text{ in } P_1} W_i d_i + W2_i Ftotal_i + W3_i TotGAP_i, \dots, P_3 \sum_{i \in POIs \text{ in } P_3} W_i d_i + W2_i Ftotal_i + W3_i TotGAP_i\} \quad [3.10]$$

subject to

$$\sum_{c \in R} RTUAV_c = 1 \quad [3.11]$$

$$x_{cit} = RTUAV_c \quad \forall c \in R, i \in POI, t \in time \quad [3.12]$$

$$\sum_m \sum_{t=1}^{432} x_{mit} \leq 2 \quad \forall m \in S, \forall i \in POI \quad [3.13]$$

$$x_{mit} = 1 \quad \forall t \in ST[m, i, a], m \in Satellites, i \in POI, a \in access \quad [3.14]$$

$$d_i + \sum_{m \in M} \sum_{t \in ST_{mia}} x_{mit} \geq 1 \quad \forall i \in POI \quad [3.15]$$

$$x_{mit} IQ_{mit'} - F_{mit} \leq x_{mit} MQ_i \quad \forall t \in ST[m, i, a], t' = t, \dots, t + Duration_{mia} \quad [3.16]$$

$$\sum_{m \in M} \sum_{t \in ST[m, i, a]} F_{mit} = Ftotal_i \quad \forall i \in POI \quad [3.17]$$

$$\sum_m DX_{mit} + DEV_{it} \geq 1 \quad \forall i \in POI, t \in time \quad [3.18]$$

$$\sum_{\forall j} DEV_{ij} = TotGAP_i \quad \forall i \in POI \quad [3.19]$$

$$Ftotal_i, TotGAP_i, F_{mit} \geq 0$$

$$d_i, x_{mit}, RTUAV_c, DX_{mit}, DEV_{it} \in \{0,1\}$$

Throughout this formulation, goal programming is used with both numeric and pre-emptive weighting purposes. The pre-emptive prioritization is to ensure the first priority set of tasks is accomplished before the second priority tasks are considered. The second priority set of tasks is then satisfied prior to considering the third priority set of tasks, and so forth. This is helpful if the higher priority tasks change. Pre-emptive weights are based on expert opinion, target values or other appropriate consideration.

The numeric weights, or differential weights, give precedence within the set of tasks at the same priority. They allow discrimination within a priority, just as they would in a regular linear program. This weighting can be done relative to within each priority class, or over all tasks. A simple example of the use of these weights is as follows; one scenario might require that the minimization of the time gap is of highest priority, then minimizing deviations from certain requirements, then tasks not accomplished at all during the observation period and in each case, the tasks need to be accomplished in a particular order. The numerical weights, however have to be determined using an acceptable scale. This formulation allows a great deal of flexibility to the analysis. It can accommodate a wide range of objectives and requirements, allowing the fine tuning of the model and the analysis.

The Dataset

Data needed to run this model includes:

- 1) desired objectives,
- 2) a list of POIs that are prioritized and weighted,
- 3) total length of observation time,
- 4) a list of all assets (i.e. satellite with IR imaging, UAV with SAR capabilities) available to theater, if there are multiple assets of the same type, they are listed individually, if choosing from potential routes, each route is listed as a separate entry,
- 5) access times of each asset to the POIs throughout the duration of the observation period,
- 6) the duration of the access each asset to each POI,
- 7) minimum required resolution of each POI, and
- 8) quality of images available from asset based on common scale

A list of POIs, the length of the observation horizon, and the minimal resolution requirements for each POI are inputs from the persons interested in gathering the imagery. This could be a Theater Commander, a CINC, national leadership, or other appropriate authority. Prioritization of the POIs is based on appropriate classes and scales developed by the interested party. Scales should be developed using appropriate decision analysis and measurement theory (see Burke, Kirkwood, and others), or another tested means of assigning unbiased weights to different POIs based on characteristics of the POI in question and the commander's intent. In the notional dataset used, the process of prioritizing and weighting the different POIs is assumed to have been accomplished based on one of the aforementioned methods.

The list of assets and the number of each asset type in each theater are given by the Theater Intelligence Architecture Plan (TIAP). The duration of access of each asset to each POI is known to the operators of the assets. The quality of the images available from each asset is based on a predetermined common scale. The acquisition time of each

asset can be calculated given a starting location. The number of assets of one type that can be used in one time period is based on the Theater Commander's doctrine. Finally, the objectives used in the analysis will be based on the Commander's operational requirements.

Key Assumptions

As mentioned in Chapter 1, there were four main assumptions made in this research: 1) terrestrial points of interest, 2) the retasking of satellites is not allowed, 3) all times are integers, and 4) there exists predetermined routes for the UAV(s) to choose. However these are not the only assumptions made during the process of this research.

The weighting of POIs is assumed to have been accomplished using an acceptable analytical method. Additionally, this model does not account for any potential breakdowns of equipment, or the retasking of satellites. If an asset is in the database as available to the theater in question, it is assumed to be fully operational.

If there exist multiple areas of interest in different theaters, then those POIs are considered as separate problems and can be handled independently. This is because the model considers only the assets available in one particular theater and not across theaters. With this basic model, however, a decomposition approach could be used to coordinate theaters.

Computational Effort

The MMGRCPSP is known to be **NP**-hard. (see Schirmer) **NP** is a class of *decision problems*. *Decision problems* are problems that ask the question "is there a feasible solution?" These decision problems are analogous to the optimization problem of finding a feasible solution. The decision problem "is not

computationally harder than the corresponding optimization problem.” (13:22).

However, the two problems are computationally similar; if the decision problem is computationally hard, then so is the optimization problem.

An **NP**-class of decision problems is a set of problems “for which no polynomial time algorithms are known but for which the ‘yes’ answer can be verified in polynomial time.” (13:23) The term *polynomial time* comes from complexity theory, a means of classifying computational problems as either easy or hard based on the runtime of the approach. Polynomial time is basically runtime that is a polynomial function (in the amount of steps required of the algorithm) dependent on time that bounds the time an algorithm works to solve a problem. If this bound is not present, then the function is considered an *exponential-time* algorithm.

NP-complete problems are the “hardest problem in NP” (13:23). If an optimization problem is **NP**-hard, then the decision problem is **NP**-complete. Due to this ‘hardness’, computing a solution using this approach could prove time consuming and/or difficult to find a feasible solution. In such cases, using a heuristic to find a starting solution can speed up the process. If the problem is large enough, it may require a solution via a heuristic approach. The concept of developing a usable heuristic for the formulation presented in this chapter is discussed in Chapter 5.

Summary

This chapter provided the methodology used to develop a mathematical formulation to optimally allocate imaging assets to cover particular POIs during an

observation period, subject to POI, imaging and time gap constraints. Chapter 4 will apply this methodology to a notional example and analyze the solutions provided.

IV. Illustrative Analysis

Introduction

This chapter demonstrates the methodology presented in Chapter 3 using a small notional dataset. First, an overview of the problem is given. The overview is followed by a description of how the notional dataset was created. Finally, the results and analysis based on the proposed methodology, is presented.

Problem

As tensions slowly begin to increase, Command desires to obtain imaging surveillance on ten points of interest for a 72-hour period. The 72-hour period is to be divided into 10-minute intervals. There are, however, only six imaging assets available for use in covering the ten POIs: four satellites, one UAV, and one 12-member special operations forces (SOF) team. The SOF team can be broken into two teams of six members each, bringing the potential number of imaging assets to seven.

Due to other commitments, the four satellites are unable to be retasked at this time; the access times from each satellite to each target and the duration of these accesses are, therefore, known and fixed. The use of a UAV route generator, such as one described in Grimm (1992) or Kinney (2000), has been employed to provide two potential routes for the UAV. The six-member special operations teams are currently able to monitor one POI each, and under current conditions, the teams have no restriction as to which POIs they can monitor.

The ten POIs have been weighted using Decision Analysis, Measurement Theory or some other appropriate method (see Kirkwood, 1997; Burke, 1999), which takes into

consideration the decision makers values concerning each POI, including the priority of the POI. Additionally, due to operational requirements, the decision maker has provided minimum image resolution requirements for each POI.

The requirement is to allocate the available imaging assets to cover as many of the POIs as possible for as much time as possible during the 72-hour observation horizon. If complete coverage is not possible, precedence will be given to the POIs with greater prioritized weights over the lesser-weighted POIs. Included in allotting the assets, a choice as to which route the UAV should use is determined based on the potential routes given.

Notional Dataset

The ten POIs used in the notional dataset were taken from Fuller (1997). Fuller has two unclassified scenarios; an Iraqi scenario and a Middle East scenario. The POIs used in this notional dataset were extracted from the Iraqi scenario. Included in the POI data were the latitudes, longitudes, and notional target or T-values of the individual POIs, which are given in Table 7. For more information on the POIs, latitudes, longitudes, and notional values, refer to Fuller (1997). Figure 1 is a map of the POIs and the starting location for the UAV.

Command has prioritized the POIs based on their T-values. If the POI has a T-value of eight or higher, it is considered a priority 1 POI; a value of four to seven corresponds to a priority of 2, and a target value of three or less was classified as a priority 3 target. Additionally, the notional weights for each POI are in the form of integers between 1 and 100.

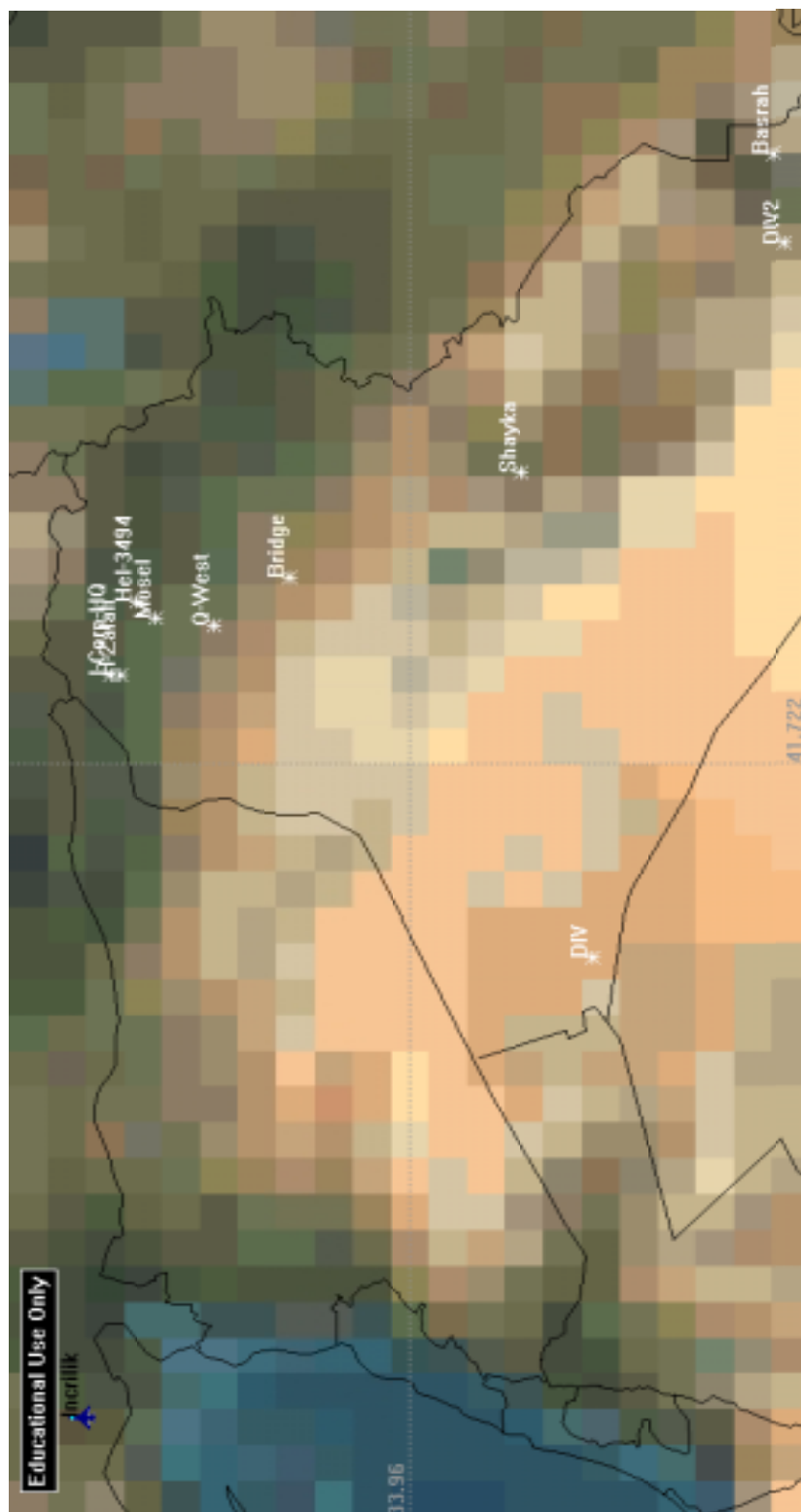


Figure 1. Map of POIs and starting position of UAV using STK®

Table 7. Notional POIs, Latitudes, Longitudes, T-Values, Priorities, and Weights

Name	POI #	Latitude	Longitude	T-Value	Priorities	Weights
Q-West	1	35.79	43.09	10	1	98
Basrah	2	30.57	47.75	10	1	87
Mosel	3	36.33	43.16	8	1	70
Shayka	4	32.92	44.60	8	1	66
H-Zalah	5	36.66	42.60	6	2	52
Hel-3494	6	36.50	43.33	6	2	51
I-Corp-HQ	7	36.75	42.60	3	3	50
Bridge	8	35.08	43.57	3	3	40
DIV	9	32.26	39.80	1	3	34
DIV2	10	30.47	46.86	1	3	11

The minimum resolution required is dependent on operational requirements associated with the POIs. A resolution of six-meters allows the decision maker or image analyzer to recognize large buildings. Depending on the intended use of the imagery, different minimal requirements are assigned to each POI. For use in this notional dataset a priority 1 POI is assumed to require a minimal resolution of one meter, and no POI requires a resolution of less than six meters. These resolution requirements were arbitrarily chosen based on the capabilities of a certain resolution.

To determine the various access times of the assets to the POIs, data was collected using STK. One of the sponsors of this thesis provided orbital information for the notional set of satellites, as well as notional sensor data (including focal length and pixel pitch) for the satellites and UAV. COL William Klimack, USA, of the United States Military Academy, provided information concerning the special operations team (See Appendix A for details).

This information was programmed into STK and a three-day simulation was run. The simulation provided access times, the duration of each access, and the ground sampling distance (GSD) of each asset to each POI throughout the three-day period. The

GSD corresponds to the resolution obtainable from the sensors to the POI. This data is provided in Appendix B. In an actual operational setting this data would be obtained from various databases and analyses.

The data from STK was used as input to a Microsoft Excel® Worksheet. A code was written in Visual Basic Applications® to generate the coefficient and variable matrices for the optimization problem (see Appendix C). Those matrices were transferred to a worksheet for input to Frontline's Premium Solver Platform™ to solve the problem. More specifically, the Large-Scale LP Solver of the Frontline Premium Solver Platform was used. Using a Dell INSPIRON 8100 laptop with a Pentium 3 processor, it took under two minutes for the solver to find an optimal solution.

In this notional example, there was no distinction between minimizing the number of POIs not imaged during the time horizon and minimizing the deviation from the desired image resolution nor minimizing the time between successive imaging assets for a particular POI. Each deviation for a given POI was weighted equally. Additionally, the POIs in the pre-emptive priority 1 set are weighted more heavily than the POIs in pre-emptive priority 2 and 3 sets. Expression [4.1] gives the objective function used in this particular formulation.

$$\begin{aligned} \min P_1(98d_1 + 87d_2 + 70d_3 + 66d_4 + 98FTotal_1 + 87FTotal_2 + 70FTotal_3 + 66FTotal_4 + \\ 98TotGAP_1 + 87TotGAP_2 + 70TotGAP_3 + 66TotGAP_4) + P_2(52d_5 + 51d_6 + 52FTotal_5 + \\ 51FTotal_6 + 52TotGAP_5 + 51TotGAP_6) + P_3(50d_7 + 40d_8 + 34d_8 + 11d_{10} + 50FTotal_7 + \\ 40FTotal_8 + 34FTotal_9 + 11FTotal_{10} + 50TotGAP_7 + 40TotGAP_8 + 34TotGAP_9 + 11TotGAP_{10}) \end{aligned} \quad [4.1]$$

Examining the Results

Running the Large-Scale LP Solver produced a solution for allocation of the seven assets. The solution assigned the UAV to route 2, the soft team was divided into

two teams; one covering Q-West, and the other covering Basrah. By reviewing the solution, the analyst is capable of determining when each POI is being imaged, for how long and at what resolution. Table 8 gives the allocation of assets for Q-west, the remaining POIs are given in Appendix D.

Additionally, the information provided by the solution shows the analyst when a POI is not being imaged. This could prove useful to show when coverage is limited, and the decision-maker can plan accordingly. For example, Figure 2 is a Gantt chart for a 3-hour period, utilizing data provided in the solution for the notional example (see Appendix E for complete Gantt chart from notional example).

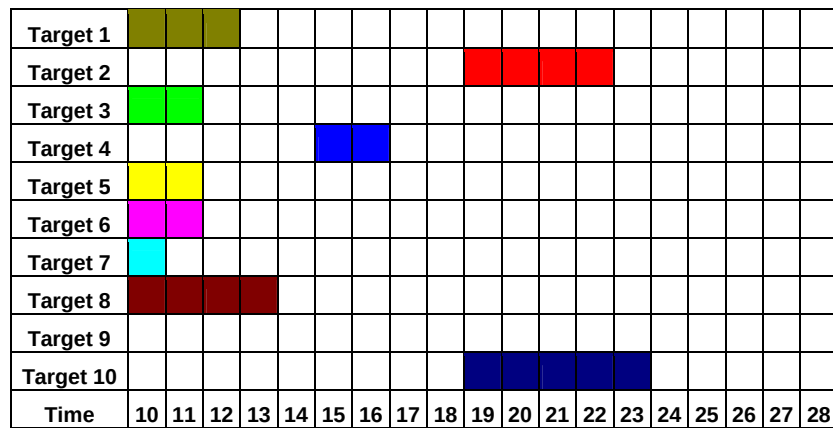


Figure 2. Sample Gantt chart for a 3-hour period (in 10 minute intervals)

This type of chart could be used by decision makers to determine how much coverage of a particular POI is available if a mission is planned for a particular time. Furthermore, if time allows, the analyst could give this information to the UAV route planners, so that another route could be planned or perhaps the decision-maker can deploy another soft team to provide additional coverage.

Table 8. Allocation for Q-west

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
Q-West	Quickbird 1	135	0	0.9481		65 intervals
		210	0	0.8498		
		426	0	0.8979		
	Quickbird 2	44	0	0.8836		
		257	0	0.8503		
		335	0	0.9683		
	Quickbird 3	112	0	0.8882		
		189	0	0.8697		
		402	0	0.9199		
	Quickbird 4	68	0	0.9066		
		280	0	0.8610		
		358	0	0.8989	1 to 9	
	UAV route 2	9	3	0.9126	13 to 36	
		37	2	1.1184	43	
		40	2	0.9307	45 to 67	
		68	2	1.1536	74 to 82	
		71	2	0.9270		
		99	2	1.1678		
		102	2	0.9425		
		130	2	1.1658		
		134	2	0.9337		
		161	2	1.2046		
		165	2	0.9540		
		193	2	1.1106		
		196	3	0.9245		
		224	2	1.1889		
		227	3	0.8993		
		255	2	1.1446		
		259	2	1.1555		
		272	2	1.1996		
	SOF team	83	349	0.5000		

Figure 3 graphically demonstrates another way the data from the solution can be used. It shows the solution for the notional example color-coded to show how many intervals each POI is not being imaged. Figure 3 is used to graphically demonstrate the solution when the priorities are changed, discussed in the next section. These types of figures could be used to easily compare and contrast different alternative solutions, which could arise from goal programming sensitivity analysis described in the next section.

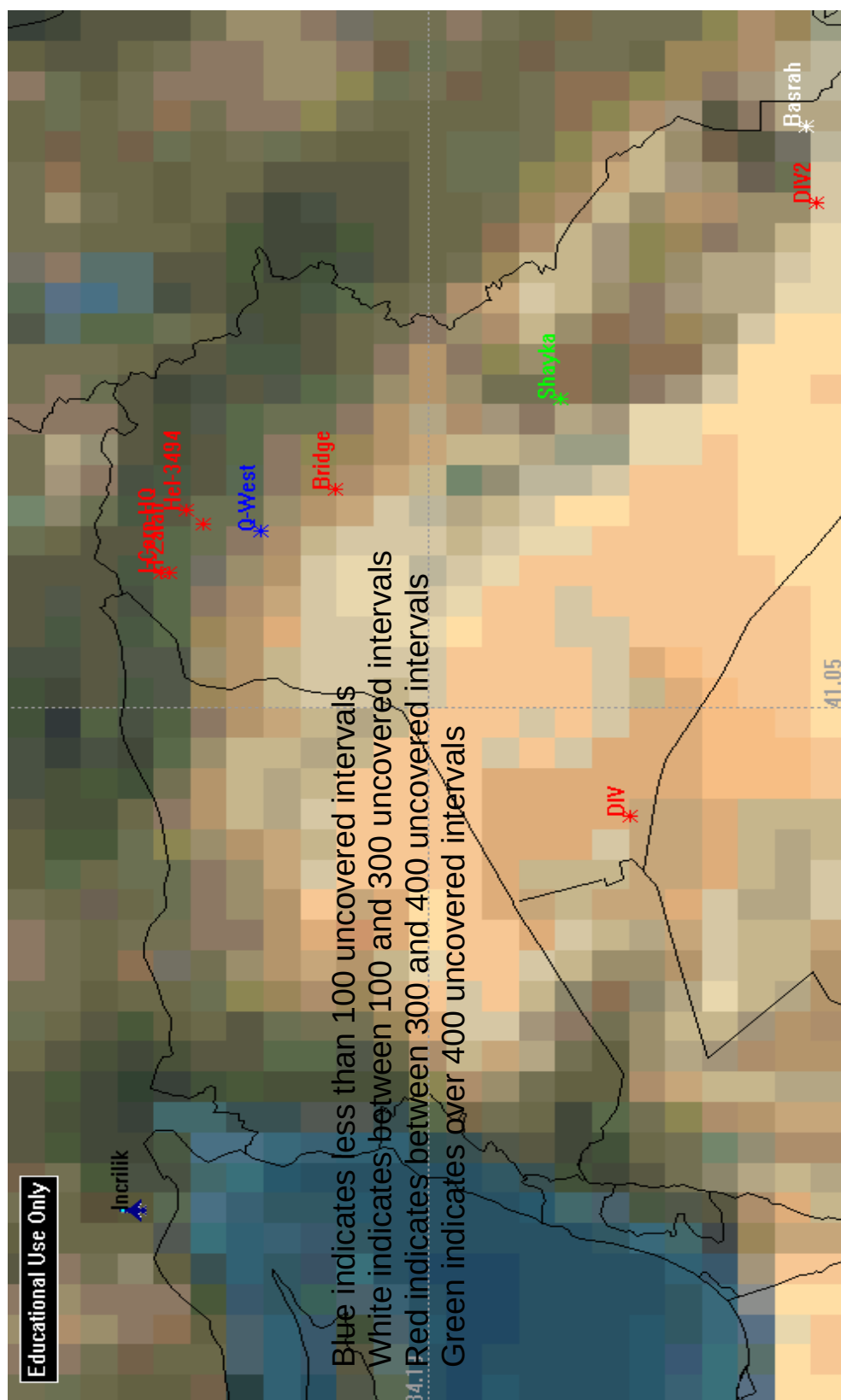


Figure 3. From STK®, graphical representation of solution

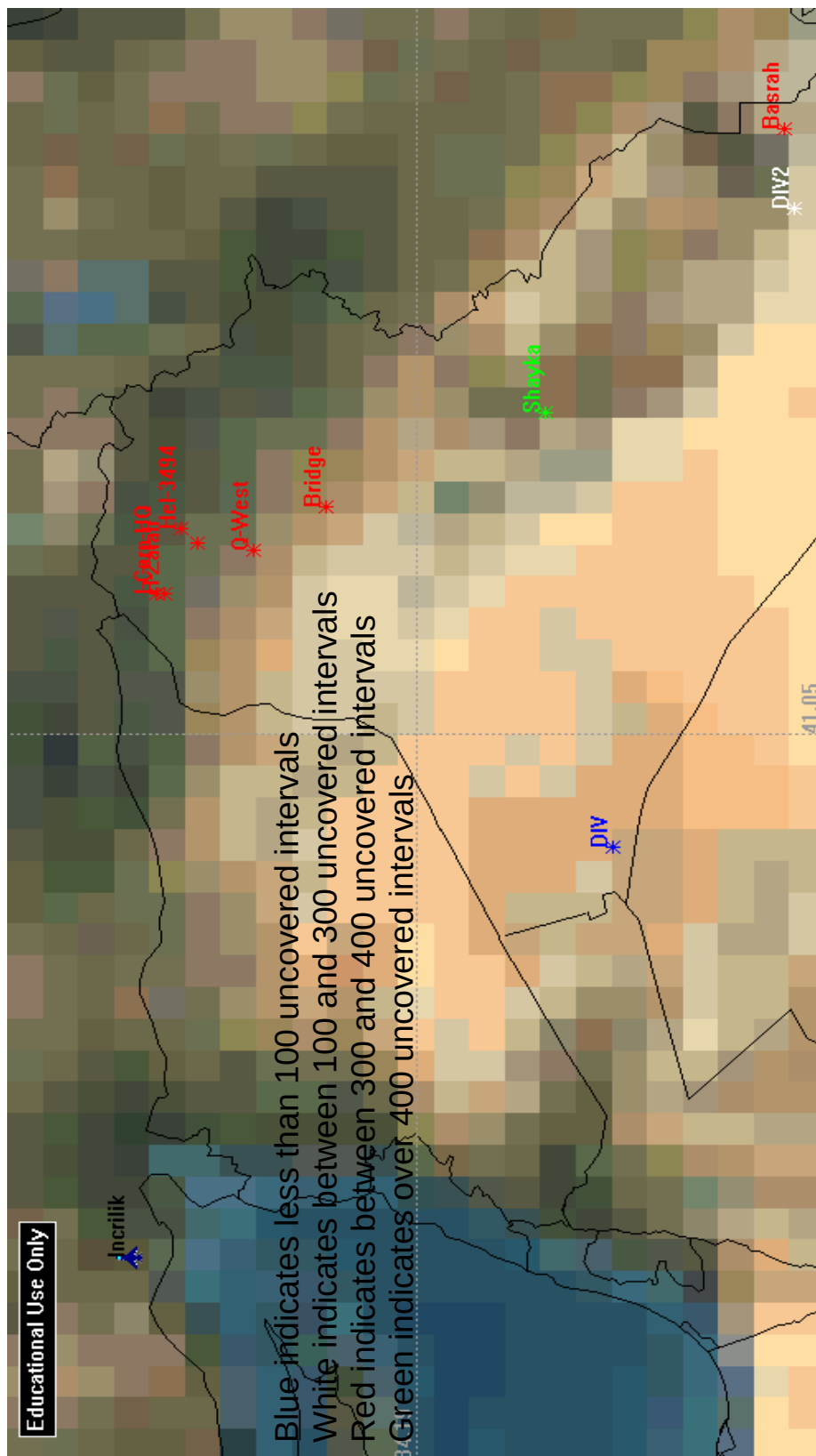


Figure 4. From STK®, changed priorities as part of sensitivity analysis

Goal Programming Sensitivity Analysis

One type of goal programming sensitivity analysis involves changing the priority weights - the pre-emptive weights. If the priorities of the targets change, causing the preferences for the POIs to change, this will change the solution. In this notional example, because it is small to illustrate the methodology and the capability of the formulation, such changes result in less dramatic impact. However, if the priorities are reversed, so that what was priority 3 is now priority 1, the solution changes to having the SOF team cover DIV and DIV2 instead of Q-west and Basrah. The route of the UAV stays the same because this route provides the most overall coverage of the POIs. The other route did not have as many access times of the various POIs.

In both examples the number of variables in the problem was 4853 and the number of constraints was 4833. This was just with seven imaging assets, 432 time intervals, and ten POIs. However, the number of variables and constraints is actually more. The $\mathbf{A}$ matrix in the optimization problem, is sparse. To reduce the problem size, this characteristic was exploited. Through this manual pre-processing, the solver did not take into consideration any variable that was already a zero. To determine which variables could equal only zero, the times of each access were examined. If no asset started at time t , then it can be concluded that the corresponding x_{mit} cannot equal one, and those x_{mit} variables were not included in the actual solving of the problem. This kept the problem at a manageable number of variables and constraints for the solver to handle. Such pre-processing aids in limiting the size of the problem and will also reduce computational time.

Flexibility of the Formulation

This formulation can be used with any number of assets, POIs, and time intervals. Limits on the number of assets, POIs, and time intervals considered are dictated by the solver capability and the computer it is run on.

Retasking of assets

This formulation, with slight modifications to the constraints, could be used to help retask satellites and or help plan the routes of the UAVs. To accomplish this, the constraint:

$$d_i + \sum_{m \in M} \sum_{t \in ST_{mia}} x_{mit} \geq 1 \quad \forall i \in AOI \quad [4.2]$$

would be modified by simply changing the summation range for $t \in ST$ to $t = ES$ to LS where ES_{mi} (LS_{mi}) are simply the earliest (latest) start times of asset m imaging POI i . This would then have the formulation determine when to have asset m image POI i .

In doing this, however, constraints would need to be added to enforce any downtime, turn time, or reorbit time an asset would require after it completed imaging a particular POI. This constraint type would also ensure that an asset was not scheduled to start imaging a successive POI prior to completion of imaging of a previous POI. Suppose that dur_{mit} is the duration of asset m imaging POI i if it starts imaging at time interval t , and that RDT_{mi} is the required downtime, turn time, or reorbit time of asset m after imaging POI i . Then an example of the constraint needed could be:

$$\sum_{i \in POI} \left(x_{mit} + \sum_{t'=t+1}^{t+dur_{mit}+RDT_{mi}} x_{mit'} \right) \leq 1 \quad \forall t, m \quad [4.3]$$

This constraint says if $x_{mit} = 1$ (asset m starts imaging POI i at time t), then

$x_{mit'} \neq 1$ if $t' < t + dur_{mit} + RDT_{mi}$.

The use of this modification to the original formulation unfortunately materially increases the size of the problem. This is because the model now considers every possible time t in the observation period, and adds an additional $t \cdot m$ constraints to the problem. It is recommended that efficient ways to implement this modification be investigated in future research. This would include only including assets that are likely to be candidates for re-tasking in this extension.

Bounding the time gap for each POI

Another modification that is possible is to place a lower bound the total time gap for each POI. Suppose the decision maker states there is some acceptable time gap, T_i , allowed between successive images of a POI assets. This condition could be incorporated into the problem by modifying constraint [3.11] to provide constraint [4.4] and adding another constraint [4.5]. This would change the deviational variable in the objective function from $TotGAP_i$ to $OVER_i$ to represent the amount over the allowable time gap each POI is over the allowed gap:

$$\sum_{j=t}^{t+T_i+2} DEV_{ij} - OVER_{iz} = T_i \quad \forall i \text{ and } \forall t \quad [4.4]$$

$$\sum_{\forall z} OVER_{iz} = OVER_i \quad \forall i \quad [4.5]$$

Again, this will increase the number of variables and constraints in the problem.

Given the basic formulation, a wide contingency of options can be modeled. The availability of such models provides a starting point to develop effective optimization and heuristic approaches.

Different goals for the objective function

In addition to easily modifying the constraints in the formulation, the objective function is also flexible in its ability to incorporate various decision-maker goals. For instance, suppose the decision-maker has five goals: 1) ensure that each priority one target has some coverage during the observing period, 2) minimize the time gap of priority one targets to a fixed number T_i , 3) provide required resolution of each target in each priority set where priority sets are weighted 3:2:1, 4) ensure all other targets are covered at least once during the observing period, and 5) minimize all the time gaps for all targets where the priority sets are weighted 3:2:1.

Constraints for objective function

For the first goal, it is necessary to have a constraint which counts the targets not covered in the priority 1 set of targets. Constraint [4.6], similar to constraint [3.15], is used to count the number of targets not covered.

$$d_i + \sum_{m \in M} \sum_{t \in ST_{mia}} x_{mit} \geq 1 \quad \forall i \in P1 \quad [4.6]$$

where

$P1$ is the set of priority 1 targets

x_{mit} is 1 if at time t , asset m is imaging target i

d_i is 1 if at no time during observation period is target i being imaged

The second goal incorporates one of the previously mentioned modifications given by expressions [4.4] and [4.5]. To minimize the gap between successive imaging assets to a given amount, expressions [4.4] and [4.5] are combined with expression [3.18]. The constraints are:

$$\sum_m DX_{mit} + DEV_{it} \geq 1 \quad \forall i \in P1, \forall t \quad [4.7]$$

$$\sum_{j=t}^{t+T_i+2} DEV_{ij} - OVER_{iz} = T_i \quad \forall i \in P1, \forall t \quad [4.8]$$

$$\sum_{\forall z} OVER_{iz} = MINTIMEGAP_i \quad \forall i \in P1 \quad [4.9]$$

where

DX_{mit} is 1 if mode m is imaging target i at time t

DEV_{it} is 1 if at time t no asset is imaging target i

T_i is the minimum time gap allowed between assets for target i

$OVER_{iz}$ is the amount over the minimum allowed time gap for a particular time period

$MINTIMEGAP_i$ is the total amount of time over the allowed time gap

For the goal of providing the required resolution, the constraints are unchanged from the ones given in the specific formulation. (See table 6 for variable definitions)

$$x_{mit} IQ_{mit'} - F_{mit} \leq x_{mit} MQ_i \quad \forall t \in ST[m, i, a], t' = t, \dots, t + Duration_{mia} \quad [4.10]$$

$$\sum_{m \in M} \sum_{t \in ST[m, i, a]} F_{mit} = Ftotal_i \quad \forall i \in POI \quad [4.11]$$

The fourth goal, to ensure all remaining targets are imaged at least once during the observing horizon, has a constraint very similar to [4.6]. The difference is that instead of only looking at the targets in priority one, it looks at the remaining targets in priorities two and three.

$$d_i + \sum_{m \in M} \sum_{t \in ST_{mia}} x_{mit} \geq 1 \quad \forall i \in P2 \text{ and } P3 \quad [4.12]$$

where

$P2(P3)$ are the set of priority two (three) targets

The final goal is to minimize all time gaps for all targets. For this goal, the constraints are the same as [3.18] and [3.19]. (See table 6 for variable definitions)

$$\sum_m DX_{mit} + DEV_{it} \geq 1 \quad \forall i \in POI, t \in time \quad [4.13]$$

$$\sum_{\forall j} DEV_{ij} = TotGAP_i \quad \forall i \in POI \quad [4.14]$$

Objective function

The objective function, which incorporates the five goals of the decision-maker, is given by:

$$\begin{aligned} \text{lex min } \{ & P_1 \sum_{i \in P1} w_i d_i, P_2 \sum_{i \in P1} w_i MINTIMEGAP_i, P_3 \sum_{i \in P1} 3w_i Ftotal_i + P_3 \sum_{j \in P2} 2w_j Ftotal_j + \\ & P_3 \sum_{k \in P3} w_k Ftotal_k, P_4 \sum_{j \in P2 \& P3} d_j, P_5 \sum_{i \in P1} 3w_i TotGAP_i + P_5 \sum_{j \in P2} 2w_j TotGAP_j + P_5 \sum_{k \in P3} w_k TotGAP_k \} \end{aligned} \quad [4.15]$$

where

P_1, P_2, P_3, P_4, P_5 are the pre-emptive priorities for goals
 w_i is the weights associated for the particular deviations for each POI i

This formulation, given in its entirety below, is yet another demonstration of the flexibility and robustness of the general formulation given in Chapter 3. Utilization of the robustness, allows for a multitude of possible optimization problems to be solved and provide the necessary information to the decision maker.

The complete model:

$$\begin{aligned} \text{lex min } \{ & P_1 \sum_{i \in P1} w_i d_i, P_2 \sum_{i \in P1} w_i \text{MINTIMEGAP}_i, P_3 \sum_{i \in P1} 3w_i \text{Ftotal}_i + P_3 \sum_{j \in P2} 2w_j \text{Ftotal}_j + \\ & P_3 \sum_{k \in P3} w_k \text{Ftotal}_k, P_4 \sum_{j \in P2 \& P3} d_j, P_5 \sum_{i \in P1} 3w_i \text{TotGAP}_i + P_5 \sum_{j \in P2} 2w_j \text{TotGAP}_j + P_5 \sum_{k \in P3} w_k \text{TotGAP}_k \} \end{aligned} \quad [4.15]$$

subject to

$$d_i + \sum_{m \in M} \sum_{t \in ST_{mia}} x_{mit} \geq 1 \quad \forall i \in P1 \quad [4.6]$$

$$\sum_m DX_{mit} + DEV_{it} \geq 1 \quad \forall i \in P1, \forall t \quad [4.7]$$

$$\sum_{j=t}^{t+T_i+2} DEV_{ij} - OVER_{iz} = T_i \quad \forall i \in P1, \forall t \quad [4.8]$$

$$\sum_{\forall z} OVER_{iz} = \text{MINTIMEGAP}_i \quad \forall i \in P1 \quad [4.9]$$

$$x_{mit} IQ_{mit'} - F_{mit} \leq x_{mit} MQ_i \quad \forall t \in ST[m, i, a], t' = t, \dots, t + \text{Duration}_{mia} \quad [4.10]$$

$$\sum_{m \in M} \sum_{t \in ST[m, i, a]} F_{mit} = \text{Ftotal}_i \quad \forall i \in POI \quad [4.11]$$

$$d_i + \sum_{m \in M} \sum_{t \in ST_{mia}} x_{mit} \geq 1 \quad \forall i \in P2 \text{ and } P3 \quad [4.12]$$

$$\sum_m DX_{mit} + DEV_{it} \geq 1 \quad \forall i \in POI, t \in \text{time} \quad [4.13]$$

$$\sum_{\forall j} DEV_{ij} = \text{TotGAP}_i \quad \forall i \in POI \quad [4.14]$$

$$\text{Ftotal}_i, \text{TotGAP}_i, \text{MINTIMEGAP}_i, OVER_{iz}, F_{mit} \geq 0$$

$$d_i, x_{mit}, DX_{mit}, DEV_{it} \in \{0,1\}$$

Summary

A small notional example was used to demonstrate the model developed in Chapter 3. The formulation given in Chapter 3 was able to determine which

predetermined route for a UAV should be used and which POIs the SOF team should image. It also tells the analyst where there is no coverage of each POI available during the observation period. This is critical information for the decision-maker to have, especially in a planning environment. Using this information, the decision-maker could request more assets to fill gaps, develop alternate routes for the UAVs or other surveillance assets, or take other actions that would benefit the mission.

Additionally, this chapter described a couple of modifications that could be done to make this model more flexible. The main concern with the modifications given is that the number of variables and constraints increases dramatically, which limits the users choices in solvers to use to solve the problem.

Chapter 5 first reviews the research done for this thesis. Following the review, conclusions and recommendations based on this research are given.

V. Conclusions and Recommendations

Review

For the United States to maintain information dominance, it is necessary that surveillance and other information assets be allocated in the most efficient manner. Through efficient allocation, the necessary information can be obtained by analysts and passed to decision-makers for use in strategic and tactical planning. Towards this end, allocating available imaging surveillance assets to image points of interest becomes a vital tasking in the pre-critical timeframe. A means for optimizing the allocation of these assets in a timely fashion is of incredible importance.

Using a multi-modal resource constrained project scheduling approach along with goal programming is one way of optimizing the allocation of imaging assets. The formulation presented in Chapter 3 gives a means of optimizing surveillance assets in manner so as to minimize the number of POIs not covered at all, minimizing the deviation from a required imaging resolution for each POI, and minimizing the time gap between successive assets imaging a POI. These three objectives can be weighted to incorporate the decision-makers preferences as to the order of importance of the objectives. Using goal programming, the deviation variable associated with the most important objective is minimized first and then the second most important objective, and so forth.

The solution provided by solving the optimization problem suggests how to allocate the resources in a manner that maximizes coverage based on the three

objectives in the objective function. Additionally, the solution tells the analyst where there is a lack of imaging asset coverage. This information can be vital in the planning stages of a mission.

Recommendations

This approach works well when the data is of limited size. Unfortunately, as mentioned in Chapter 1, the problem exhibits combinatorial growth. In the small notional example presented in Chapter 4, there were over 4000 variables and over 4000 constraints, even with pre-processing during the problem generation phase. The methodology works, but the concern is how quickly the problem grows with additional POIs, assets, and time intervals.

To overcome the problem with dimensionality, it is suggested that a heuristic (or heuristics) be developed, to be used to generate feasible solutions, particularly in “quick turn” settings, and that can be used to generate starting solutions for the optimization, (see Calhoun 2000 and 2002), if an optimal solution is required. By providing a formulation of the problem, a first step has been taken in this process.

Furthermore, exploiting the potential structure in this problem of allocating assets could assist in limiting the dimensionality problems inherent to this problem. Different approaches could include formulating the problem as a set covering problem, a three-dimensional assignment problem, or a combination of decomposition approaches.

Conclusions

The need for accurate and timely information is a never-ending requirement for decision makers, especially for planning purposes. To provide this information, it is vital

to have a means of optimizing allocation of all imaging surveillance assets, be them land, sea, air, or space assets.

Keeping the problem manageable, in reference to size and computation time, while still providing the necessary information, is the key to creating useful optimization program. Unfortunately this kind of problem falls directly to the “curse of dimensionality”. It does not take much in the way of increasing POIs, assets, and time intervals to cause this problem to “explode”. The goal priority classes can assist, however, in limiting the search space.

The formulation presented is able to calculate an optimal allocation of resources and is robust and flexible so as to handle modifications and enhancements such as those addressed in Chapter 4. These modifications and enhancements, based on the decision maker’s needs and preferences, will provide the analyst with more information to better assist the decision-maker. The approach presented in this thesis is a firm foundation for future work in this area.

Appendix A. Information Used to Develop STK Model

All parameters for the satellites used in this model were provided by a sponsor. They were used to create an unclassified notional example to demonstrate the capability of the model. These parameters are given in Table 9.

Table 9. Satellite parameters used in STK model

Satellite	Propagator	Apogee & Perigee Alt.	Inclination	RAAN
Quickbird1	J4Perturbation	449.998960 km	97.218774 deg	279.276837 deg
Quickbird2	J4Perturbation	449.998960 km	97.218774 deg	219.276837 deg
Quickbird3	J4Perturbation	449.998960 km	97.218774 deg	219.276837 deg
Quickbird4	J4Perturbation	449.998960 km	97.218774 deg	279.276837 deg
Satellite	Coord. Type	Coord. System	True Anomaly	
Quickbird1	Classical	J2000	0.00000000 deg	
Quickbird2	Classical	J2000	0.00000000 deg	
Quickbird3	Classical	J2000	180.000000 deg	
Quickbird4	Classical	J2002	180.000000 deg	

For the UAVs, the turn points, which mark each route in STK, were randomly selected for both Route 1 and Route 2. However, in the most general sense, the routes started from the same location (Incirlik AB, Turkey) and were designed to encompass the ten targets. Additionally, the altitude and speed of the UAV were based on the data for a RQ-4A Global Hawk. The notional parameters were provided by a sponsor, and meant to create an unclassified notional example. These parameters are given in Table 10.

Table 10. UAV Parameters used in STK model

UAV Routes	Propagator	Starting/Finishing Latitude	Starting/Finishing Longitude	Altitude
Route 1	GreatArc	37.00 deg	35.26 deg	3.048 km
Route 2	GreatArc	37.00 deg	35.26 deg	3.048 km
UAV Routes	Speed	Enroute Altitude	Enroute Speed	
Route 1	10.490 km/min	19.812 km	7.00 km/min	
Route 2	10.490 km/min	19.812 km	7.00 km/min	

All parameters for the sensors used in this model were provided by a sponsor. They were used to create an unclassified notional example to demonstrate the capability of the model. These parameters are given in Table 11.

Table 11. Sensor parameters used in STK model

Sensor Information	Satellites	UAVs
Sensor Type	Simple Conic	Complex Conic
Outer Half Angles	N/A	79.039 deg
Cone Angle	45 deg	N/A
Focal Length	10 m	1.651m
Pixel Pitch	12 μ m	9 μ m

The Special Operations Forces teams access start times are based on the time it would take for a ground vehicle traveling approximately 55 kph from Incirlik AB, Turkey to arrive at the POI location. The divisibility of the team is from information provided COL Klimack, as mentioned in Chapter 4.

Appendix B. Notional Dataset Obtained from STK

The data obtained from the notional model created in STK includes the access start times of each asset to each POI during the length of the simulation, 72 hours. Additionally, the ground sample distance (GSD) was calculated to determine the resolution of each asset was capable of for each access time for each POI. The GSD was calculated using:

$$GSD = \frac{SlantRange \cdot PixelPitch}{focallength \cdot \sqrt{\sin(ElevationAngle)}}$$

An Access Report, generated by STK, was used to determine the durations of each access period of each asset for each POI. These values were placed into a Microsoft Excel Worksheet. The duration, each access, resolution, and something else is given in Table 12. The values for duration and start of access times were made integer values, by rounding, and then, because the time intervals of the problem are 10-minute intervals, the duration and access start times were divided by ten. (The length of the observation, which is 4320 minutes, is 432 time intervals.) These modified values are given in Table 13. However, in actual practice, this data would be developed from classified and unclassified databases. Access time of a particular POI would be generated through runs of STK or another coverage model using the actual operational parameters of the appropriate models, as available and required.

Table 12. Actual values from STK model*

Asset	Target Observing	1st access	2nd access	3rd access	4th access	5th access	6th access	7th access	8th access	9th access
UAV route 1	1	78.3416	360.613	663.5847	968.1017	1272.1504	1575.6869	1879.5857	2182.6243	2481.8098
	2	182.6977	486.0786	790.2973	1095.3882	1398.2245	1701.4919	2005.2699	2306.5384	2607.6767
	3	69.5426	366.5725	670.0166	974.3589	1278.6222	1582.116	1886.0333	2189.0446	2488.2237
	4	131.6416	437.4049	741.7479	1046.5692	1349.2325	1653.2967	1957.8298	2258.7881	2559.2372
	5	61.1315	367.5256	670.8185	974.8257	1279.5307	1583.0576	1887.0755	2190.1019	2489.148
	6	69.5223	370.244	673.6998	978.0715	1282.2916	1585.7626	1889.6619	2192.6611	2491.8695
	7	60.6882	368.9765	672.2583	976.2405	1280.98	1584.5161	1888.5462	2191.5785	2490.6059
	8	91.4114	396.0415	700.3452	1005.3158	1308.0499	1611.6886	1915.7944	2216.8188	2517.7748
	9	290.6748	594.1055	897.2395	1202.7782	1505.5382	1808.9971	2111.7329	2414.4886	2715.3998
	10	177.3689	481.217	785.41	1090.3321	1393.1426	1696.8291	2000.9713	2302.4171	2602.8494
UAV route 2	1	91.2317	365.9763	401.80	676.0376	712.3539	987.0902	1023.199	1300.8575	1336.9713
	2	192.5971	502.739	813.33	1123.7655	1437.7601	1751.7264	2060.2899	2373.4763	100000
	3	82.0675	371.4406	681.33	992.2472	1306.0338	1618.5282	1931.2027	2243.1419	2554.0772
	4	146.787	457.8338	768.36	1080.7875	1393.5827	1708.3627	2016.6865	2329.7489	100000
	5	75.2101	370.3101	679.90	990.6984	1304.5013	1616.6095	1930.1599	2241.3917	2552.6826
	6	80.4366	375.4095	685.37	996.2771	1310.0647	1622.6724	1935.1119	2247.2334	2558.08
	7	73.6287	371.6143	681.19	991.9789	1305.7828	1617.8719	1931.4698	2242.662	2553.9717
	8	104.29	414.85	725.41	1036.34	1350.06	1664.30	1972.56	2285.59	100000.00
	9	300.163	609.7582	920.43	1232.7654	1546.8887	1860.386	2170.6531	2483.5019	2649.2098
	10	188.0424	498.416	809.00	1120.2104	1433.7658	1747.9399	2056.7457	2370.0689	100000
Soft Team	1	834.76	100000	100000	100000	100000	100000	100000	100000	100000
	2	1606.707	100000	100000	100000	100000	100000	100000	100000	100000
	3	834.9515	100000	100000	100000	100000	100000	100000	100000	100000
	4	1134.3222	100000	100000	100000	100000	100000	100000	100000	100000
	5	771.3942	100000	100000	100000	100000	100000	100000	100000	100000
	6	857.544	100000	100000	100000	100000	100000	100000	100000	100000
	7	771.3942	100000	100000	100000	100000	100000	100000	100000	100000
	8	917.043	100000	100000	100000	100000	100000	100000	100000	100000
	9	789.8641	100000	100000	100000	100000	100000	100000	100000	100000
	10	1525.6904	100000	100000	100000	100000	100000	100000	100000	100000
Quickbird1	1	1351	2101	4256	100000	100000	100000	100000	100000	100000
	2	1349	3536	0	100000	100000	100000	100000	100000	100000
	3	1351	2128	4256	100000	100000	100000	100000	100000	100000
	4	1350	2129	4255	100000	100000	100000	100000	100000	100000
	5	1352	2128	4256	100000	100000	100000	100000	100000	100000
	6	1351	2128	4256	100000	100000	100000	100000	100000	100000
	7	1352	2128	4256	100000	100000	100000	100000	100000	100000
	8	1351	2129	4256	100000	100000	100000	100000	100000	100000
	9	2130	4255	100000	100000	100000	100000	100000	100000	100000
	10	1349	2131	3536	4255	100000	100000	100000	100000	100000
Quickbird2	1	442	2569	3347	100000	100000	100000	100000	100000	100000
	2	443	1850	2568	3974	100000	100000	100000	100000	100000
	3	442	2569	3347	100000	100000	100000	100000	100000	100000
	4	442	2568	100000	100000	100000	100000	100000	100000	100000

Asset	Target Observing	1st access	2nd access	3rd access	4th access	5th access	6th access	7th access	8th access	9th access
	5	442	2569	3347	100000	100000	100000	100000	100000	100000
	6	442	2569	3347	100000	100000	100000	100000	100000	100000
	7	442	2569	3347	100000	100000	100000	100000	100000	100000
	8	442	2569	3347	100000	100000	100000	100000	100000	100000
	9	443	1163	2569	3348	100000	100000	100000	100000	100000
	10	443	2568	100000	100000	100000	100000	100000	100000	100000
Quickbird3	1	1117	1894	4022	100000	100000	100000	100000	100000	100000
	2	1115	3301	100000	100000	100000	100000	100000	100000	100000
	3	1117	1894	4022	100000	100000	100000	100000	100000	100000
	4	1116	1895	3302	4021	100000	100000	100000	100000	100000
	5	1117	1894	4022	100000	100000	100000	100000	100000	100000
	6	1117	1894	4022	100000	100000	100000	100000	100000	100000
	7	1117	1894	4022	100000	100000	100000	100000	100000	100000
	8	1116	1894	4021	100000	100000	100000	100000	100000	100000
	9	1895	4021	100000	100000	100000	100000	100000	100000	100000
	10	1115	3302	100000	100000	100000	100000	100000	100000	100000
Quickbird4	1	676	2803	3581	100000	100000	100000	100000	100000	100000
	2	677	2802	100000	100000	100000	100000	100000	100000	100000
	3	676	2803	3581	100000	100000	100000	100000	100000	100000
	4	677	2802	100000	100000	100000	100000	100000	100000	100000
	5	676	2804	3581	100000	100000	100000	100000	100000	100000
	6	676	2803	3581	100000	100000	100000	100000	100000	100000
	7	676	2804	3581	100000	100000	100000	100000	100000	100000
	8	676	2803	3581	100000	100000	100000	100000	100000	100000
	9	1397	3582	100000	100000	100000	100000	100000	100000	100000
	10	677	2802	100000	100000	100000	100000	100000	100000	100000

Asset	Target Observing	10th access	11th access	12th access	13th access	14th access	15th access	16th access	17th access	18th access
UAV route 1	1	100000	100000	100000	100000	100000	100000	100000	100000	10000
	2	100000	100000	100000	100000	100000	100000	100000	100000	10000
	3	100000	100000	100000	100000	100000	100000	100000	100000	10000
	4	100000	100000	100000	100000	100000	100000	100000	100000	10000
	5	100000	100000	100000	100000	100000	100000	100000	100000	10000
	6	100000	100000	100000	100000	100000	100000	100000	100000	10000
	7	100000	100000	100000	100000	100000	100000	100000	100000	10000
	8	100000	100000	100000	100000	100000	100000	100000	100000	10000
	9	100000	100000	100000	100000	100000	100000	100000	100000	10000
	10	100000	100000	100000	100000	100000	100000	100000	100000	10000
UAV route 2	1	1613.5689	1651.2011	1925.7769	1959.3885	2238.0875	2272.3825	2548.8109	2585.3223	2717.5429
	2	100000	100000	100000	100000	100000	100000	100000	100000	100000
	3	2722.5512	100000	100000	100000	100000	100000	100000	100000	100000
	4	100000	100000	100000	100000	100000	100000	100000	100000	100000
	5	2720.7316	100000	100000	100000	100000	100000	100000	100000	100000
	6	2726.66	100000	100000	100000	100000	100000	100000	100000	100000
	7	2721.9985	100000	100000	100000	100000	100000	100000	100000	100000
	8	100000	100000	100000	100000	100000	100000	100000	100000	100000

Asset	Target Observing	10th access	11th access	12th access	13th access	14th access	15th access	16th access	17th access	18th access
	5	100000	100000	100000	100000	100000	100000	100000	100000	100000
	6	100000	100000	100000	100000	100000	100000	100000	100000	100000
	7	100000	100000	100000	100000	100000	100000	100000	100000	100000
	8	100000	100000	100000	100000	100000	100000	100000	100000	100000
	9	100000	100000	100000	100000	100000	100000	100000	100000	100000
	10	100000	100000	100000	100000	100000	100000	100000	100000	100000

Asset	Target Observing	duration1	duration2	duration3	duration4	duration5	duration6	duration7	duration8	duration9
UAV route 1	1	30.13833333	51.29461667	51.90053333	52.41436667	51.25838333	51.07033333	50.98046667	49.52165	51.06865
	2	25.691	25.925	24.913	25.254	25.253	25.602	24.883	26.606	26.03
	3	32.272	39.047	39.798	40.455	39.021	39.009	39.028	37.396	39.001
	4	21.796	18.102	17.892	18.286	18.56	17.361	16.162	16.685	17.727
	5	32.573	29.38	30.231	31.236	29.406	29.288	29.137	27.646	29.303
	6	30.245	33.956	34.738	35.351	33.921	34.004	34.111	32.36	33.988
	7	31.826	26.887	27.76	28.787	26.913	26.803	26.657	25.125	26.816
	8	29.733	27.952	27.786	27.86	28.015	27.695	27.37	27.894	27.745
	9	26.86	26.913	28.129	26.893	27.866	28.439	28.832	25.048	29.329
	10	43.145	42.848	41.759	42.404	42.418	42.178	40.808	42.319	42.826
UAV route 2	1	25.501	19.858	24.91	18.743	24.975	18.389	24.709	18.438	24.861
	2	25.784	25.373	25.38	27.552	27.328	26.893	28.743	28.292	0
	3	29.88	50.666	51.37	51.184	51.238	52.739	48.856	50.215	44.963
	4	13.38	11.853	11.96	8.438	10.6	9.151	9.556	9.756	0
	5	27.284	42.216	43.24	43.139	43.192	45.011	40.437	42.599	47.736
	6	30.648	45.925	46.56	46.429	46.451	47.891	44.138	45.259	36.956
	7	27.978	40.052	41.09	41.011	41.055	42.909	38.254	40.437	45.157
	8	25.19	24.61	24.67	24.21	24.47	24.11	24.75	25.08	0.00
	9	21.26	21.272	21.52	22.979	20.895	21.054	21.951	20.408	22.732
	10	42.086	41.269	41.27	42.587	42.947	42.112	43.854	43.033	0
Soft Team	1	3485.24	0	0	0	0	0	0	0	0
	2	2713.293	0	0	0	0	0	0	0	0
	3	3485.0485	0	0	0	0	0	0	0	0
	4	3185.6778	0	0	0	0	0	0	0	0
	5	3548.6058	0	0	0	0	0	0	0	0
	6	3462.456	0	0	0	0	0	0	0	0
	7	3548.6058	0	0	0	0	0	0	0	0
	8	3402.957	0	0	0	0	0	0	0	0
	9	3530.1359	0	0	0	0	0	0	0	0
	10	2794.3096	0	0	0	0	0	0	0	0
Quickbird1	1	1.410466667	2.204883333	2.03045	0	0	0	0	0	0
	2	2.168683333	1.845166667	0	0	0	0	0	0	0
	3	1.520133333	2.2054	1.995866667	0	0	0	0	0	0
	4	1.677183333	2.001733333	1.824433333	0	0	0	0	0	0
	5	1.30225	2.183433333	2.078133333	0	0	0	0	0	0
	6	1.6096	2.2065	1.9536	0	0	0	0	0	0
	7	1.3182	2.18225	2.0752	0	0	0	0	0	0
	8	1.527683333	2.1903	1.9677	0	0	0	0	0	0

Asset	Target Observing	duration1	duration2	duration3	duration4	duration5	duration6	duration7	duration8	duration9
	9	1.922216667	2.011866667	0	0	0	0	0	0	0
	10	2.067516667	0.355966667	1.5324	0.906916667	0	0	0	0	0
Quickbird2	1	2.080366667	2.19875	1.2426	0	0	0	0	0	0
	2	1.251133333	1.03085	1.440683333	0.7041	0	0	0	0	0
	3	2.073083333	2.191783333	1.302183333	0	0	0	0	0	0
	4	2.19115	2.1398	0	0	0	0	0	0	0
	5	1.959466667	2.206033333	1.605166667	0	0	0	0	0	0
	6	2.091983333	2.18045	1.23685	0	0	0	0	0	0
	7	1.955283333	2.20595	1.61595	0	0	0	0	0	0
	8	2.15455	2.184233333	0.642183333	0	0	0	0	0	0
	9	1.25915	0.7171	1.506616667	2.0146	0	0	0	0	0
	10	1.66395	1.800133333	0	0	0	0	0	0	0
Quickbird3	1	1.905316667	2.135033333	1.65575	0	0	0	0	0	0
	2	2.1763	2.120933333	0	0	0	0	0	0	0
	3	1.95745	2.144166667	1.58675	0	0	0	0	0	0
	4	2.0425	1.598783333	0.495316667	1.194983333	0	0	0	0	0
	5	1.84965	2.191916667	1.759583333	0	0	0	0	0	0
	6	2.001433333	2.131866667	1.5007	0	0	0	0	0	0
	7	1.856916667	2.193216667	1.75365	0	0	0	0	0	0
	8	1.965	2.041983333	1.521466667	0	0	0	0	0	0
	9	2.15065	2.1813	0	0	0	0	0	0	0
	10	2.192116667	1.980666667	0	0	0	0	0	0	0
Quickbird4	1	1.767366667	2.16405	1.819733333	0	0	0	0	0	0
	2	1.845033333	1.941716667	0	0	0	0	0	0	0
	3	1.753933333	2.1805	1.845616667	0	0	0	0	0	0
	4	2.160433333	2.197116667	0	0	0	0	0	0	0
	5	1.522466667	2.143316667	1.994883333	0	0	0	0	0	0
	6	1.794683333	2.192533333	1.813733333	0	0	0	0	0	0
	7	1.514516667	2.14595	2.00005	0	0	0	0	0	0
	8	1.935116667	2.182616667	1.588416667	0	0	0	0	0	0
	9	1.64825	2.1812	0	0	0	0	0	0	0
	10	2.037983333	2.1042	0	0	0	0	0	0	0
Asset	Target Observing	duration10	duration11	duration12	duration13	duration14	duration15	duration16	duration17	duration18
UAV route 1	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
UAV route 2	1	16.845	24.515	20.32	25.305	17.555	25.708	18.957	19.003	17.275
	2	0	0	0	0	0	0	0	0	0

Asset	Target Observing	duration10	duration11	duration12	duration13	duration14	duration15	duration16	duration17	duration18
	3	30.249	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	32.069	0	0	0	0	0	0	0	0
	6	26.14	0	0	0	0	0	0	0	0
	7	30.802	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Soft Team	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird1	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird2	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird3	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0

Asset	Target Observing	duration10	duration11	duration12	duration13	duration14	duration15	duration16	duration17	duration18
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird4	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0

Asset	Target Observing	Res 1	Res 2	Res 3	Res 4	Res 5	Res 6	Res 7	Resn 8	Res 9
UAV route 1	1	0.68264831	0.78957419	0.80428675	0.83459307	0.79051885	0.7958489	0.78642494	0.756029	0.795727226
	2	0.827979407	0.814697963	0.829269346	0.84783663	0.848018593	0.817425481	0.806409308	0.778995321	0.833777929
	3	0.74234474	0.60328988	0.58905941	0.60334469	0.60415539	0.60094983	0.59693941	0.59556338	0.60122832
	4	1.05246957	1.1775484	1.17393558	1.17023605	1.1589879	1.19411768	1.22640639	1.20755933	1.18024253
	5	0.66172135	0.71307229	0.70291038	0.68104979	0.71197926	0.72316952	0.73616139	0.74353697	0.72259758
	6	0.86138772	0.65644191	0.65368572	0.66596086	0.65766594	0.66799778	0.65658172	0.67777385	0.64694286
	7	0.65464852	0.74677489	0.73287952	0.70750167	0.74579314	0.75664475	0.76932725	0.80698893	0.75616529
	8	0.693061194	0.78734307	0.79922114	0.79398145	0.80383897	0.80563703	0.82839079	0.791311	0.80213024
	9	0.79354179	0.77917711	0.7663395	0.78003764	0.74583676	0.7418008	0.71468733	0.79829481	0.65941794
	10	0.58858546	0.58125341	0.58331937	0.58425843	0.58376111	0.59999239	0.60485036	0.61883714	0.58192016
UAV route 2	1	0.91259763	1.11836433	0.93071377	1.15359125	0.92698004	1.1678256	0.94251573	1.16584895	0.93366362
	2	0.822241	0.827646	0.825369	0.763438	0.79098	0.791931	0.88782	0.74064	100000
	3	0.68138103	0.74833392	0.77630394	0.78252153	0.78033413	0.82248854	0.7125325	0.77047002	0.89682674
	4	1.285321	1.309913	1.307365	1.361172	1.331577	1.35425	1.346413	1.342504	100000
	5	0.83456759	0.63790807	0.63661633	0.63960707	0.6380342	0.65343109	0.62522288	0.61171332	0.51906669
	6	0.64057759	0.6953264	0.72154942	0.72446131	0.72385744	0.7549861	0.68722841	0.73176757	0.93042137
	7	0.78555852	0.62994245	0.62425712	0.62655014	0.62516998	0.61377911	0.625046125	0.60122252	0.528947
	8	0.93208756	0.94882127	0.94545327	0.97169323	0.95667077	0.97806219	0.9401965	0.93829763	100000
	9	0.87100074	0.87051252	0.85564313	0.8076515	0.86476068	0.87936687	0.83529709	0.88829814	0.83526421
	10	0.59852005	0.60427649	0.60449826	0.62186005	0.59791552	0.6232128	0.61696373	0.64163069	100000
Soft Team	1	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	2	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	3	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	4	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	5	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	6	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	7	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	8	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	9	0.5	100000	100000	100000	100000	100000	100000	100000	100000
	10	0.5	100000	100000	100000	100000	100000	100000	100000	100000
Quickbird1	1	0.948054	0.84983075	0.8978625	100000	100000	100000	100000	100000	100000
	2	0.85484375	0.891826333	100000	100000	100000	100000	100000	100000	100000

Asset	Target Observing	Res 1	Res 2	Res 3	Res 4	Res 5	Res 6	Res 7	Resn 8	Res 9
	3	0.935915	0.8510745	0.90744625	100000	100000	100000	100000	100000	100000
	4	0.913898333	0.90201975	0.896636333	100000	100000	100000	100000	100000	100000
	5	0.961879667	0.85751475	0.88587	100000	100000	100000	100000	100000	100000
	6	0.925009667	0.850996	0.883629333	100000	100000	100000	100000	100000	100000
	7	0.960262667	0.8563445	0.88555975	100000	100000	100000	100000	100000	100000
	8	0.934042667	0.85329675	0.880487	100000	100000	100000	100000	100000	100000
	9	0.883643667	0.89959825	100000	100000	100000	100000	100000	100000	100000
	10	0.88251175	0.993293	0.930193667	0.9939455	100000	100000	100000	100000	100000
Quickbird2	1	0.883625	0.8502915	0.968275667	100000	100000	100000	100000	100000	100000
	2	0.963376667	0.989767333	0.941857	0.993388	100000	100000	100000	100000	100000
	3	0.88654075	0.85233	0.961811333	100000	100000	100000	100000	100000	100000
	4	0.851557	0.86519175	100000	100000	100000	100000	100000	100000	100000
	5	0.883071	0.84865925	0.926124	100000	100000	100000	100000	100000	100000
	6	0.88298275	0.85685375	0.969797333	100000	100000	100000	100000	100000	100000
	7	0.883715333	0.8502235	0.924639667	100000	100000	100000	100000	100000	100000
	8	0.863979	0.85490175	0.996967	100000	100000	100000	100000	100000	100000
	9	0.964172	0.995368	0.93374	0.89906625	100000	100000	100000	100000	100000
	10	0.913593667	0.897315	100000	100000	100000	100000	100000	100000	100000
Quickbird3	1	0.888166	0.86969465	0.919861333	100000	100000	100000	100000	100000	100000
	2	0.852167	0.86855025	100000	100000	100000	100000	100000	100000	100000
	3	0.882047333	0.86669	0.928555	100000	100000	100000	100000	100000	100000
	4	0.89049125	0.923178	0.996213667	0.9602135	100000	100000	100000	100000	100000
	5	0.89594	0.85366605	0.907890333	100000	100000	100000	100000	100000	100000
	6	0.9059255	0.8693635	0.939140333	100000	100000	100000	100000	100000	100000
	7	0.895081	0.8543275	0.908904	100000	100000	100000	100000	100000	100000
	8	0.879925	0.8941705	0.935255667	100000	100000	100000	100000	100000	100000
	9	0.861262	0.85243025	100000	100000	100000	100000	100000	100000	100000
	10	0.8757756	0.8156455	100000	100000	100000	100000	100000	100000	100000
Quickbird4	1	0.906599	0.861034	0.898893667	100000	100000	100000	100000	100000	100000
	2	0.891016667	0.879594333	100000	100000	100000	100000	100000	100000	100000
	3	0.908779	0.85596075	0.89618	100000	100000	100000	100000	100000	100000
	4	0.8598875	0.8476695	100000	100000	100000	100000	100000	100000	100000
	5	0.937406333	0.86743875	0.90778725	100000	100000	100000	100000	100000	100000
	6	0.903524333	0.85342225	0.900357667	100000	100000	100000	100000	100000	100000
	7	0.937636333	0.86612425	0.9050665	100000	100000	100000	100000	100000	100000
	8	0.884617333	0.85417975	0.926663333	100000	100000	100000	100000	100000	100000
	9	0.917833	0.85190175	100000	100000	100000	100000	100000	100000	100000
	10	0.8893925	0.87167975	100000	100000	100000	100000	100000	100000	100000
Asset	Target Observing	Res 10	Res 11	Res 11	Res 13	Res 14	Res 15	Res 16	Res 17	Res 18 18
UAV route 1	1	100000	100000	100000	100000	100000	100000	100000	100000	100000
	2	100000	100000	100000	100000	100000	100000	100000	100000	100000
	3	100000	100000	100000	100000	100000	100000	100000	100000	100000
	4	100000	100000	100000	100000	100000	100000	100000	100000	100000
	5	100000	100000	100000	100000	100000	100000	100000	100000	100000
	6	100000	100000	100000	100000	100000	100000	100000	100000	100000

Asset	Target Observing	Res 10	Res 11	Res 11	Res 13	Res 14	Res 15	Res 16	Res 17	Res 18 18
	3	100000	100000	100000	100000	100000	100000	100000	100000	100000
	4	100000	100000	100000	100000	100000	100000	100000	100000	100000
	5	100000	100000	100000	100000	100000	100000	100000	100000	100000
	6	100000	100000	100000	100000	100000	100000	100000	100000	100000
	7	100000	100000	100000	100000	100000	100000	100000	100000	100000
	8	100000	100000	100000	100000	100000	100000	100000	100000	100000
	9	100000	100000	100000	100000	100000	100000	100000	100000	100000
	10	100000	100000	100000	100000	100000	100000	100000	100000	100000
Quickbird4	1	100000	100000	100000	100000	100000	100000	100000	100000	100000
	2	100000	100000	100000	100000	100000	100000	100000	100000	100000
	3	100000	100000	100000	100000	100000	100000	100000	100000	100000
	4	100000	100000	100000	100000	100000	100000	100000	100000	100000
	5	100000	100000	100000	100000	100000	100000	100000	100000	100000
	6	100000	100000	100000	100000	100000	100000	100000	100000	100000
	7	100000	100000	100000	100000	100000	100000	100000	100000	100000
	8	100000	100000	100000	100000	100000	100000	100000	100000	100000
	9	100000	100000	100000	100000	100000	100000	100000	100000	100000
	10	100000	100000	100000	100000	100000	100000	100000	100000	100000

* Access start times greater than 4320 indicate no access of that asset, Res numbers equal to 10000 indicate that there was no access therefore no resolution calculation was done.

Table 13. Modified values used in Frontline Premium Solver Platform

Asset	Target Obs	1st access	2nd access	3rd access	4th access	5th access	6th access	7th access	8th access	9th access
UAV route 1	1	8	36	66	97	127	158	188	218	248
	2	18	49	79	110	140	170	201	231	261
	3	7	37	67	97	128	158	189	219	249
	4	13	44	74	105	135	165	196	226	256
	5	6	37	67	98	128	158	189	219	249
	6	7	37	67	98	128	159	189	219	249
	7	6	37	67	98	128	159	189	219	249
	8	9	40	70	101	131	161	192	222	252
	9	29	59	90	120	151	181	211	241	272
	10	18	48	79	109	139	170	200	230	260
UAV route 2	1	9	37	40	68	71	99	102	130	134
	2	19	50	81	112	144	175	206	237	10000
	3	8	37	68	99	131	162	193	224	255
	4	15	46	77	108	139	171	202	233	10000
	5	8	37	68	99	131	162	193	224	255
	6	8	38	69	100	131	162	194	225	256
	7	7	37	68	99	131	162	193	224	255
	8	10	42	73	104	135	166	197	229	10000
	9	30	61	92	123	155	186	217	248	265
	10	19	50	81	112	143	175	206	237	10000

Asset	Target Obs	1st access	2nd access	3rd access	4th access	5th access	6th access	7th access	8th access	9th access
Soft Team	1	84	10000	10000	10000	10000	10000	10000	10000	10000
	2	161	10000	10000	10000	10000	10000	10000	10000	10000
	3	84	10000	10000	10000	10000	10000	10000	10000	10000
	4	113	10000	10000	10000	10000	10000	10000	10000	10000
	5	77	10000	10000	10000	10000	10000	10000	10000	10000
	6	86	10000	10000	10000	10000	10000	10000	10000	10000
	7	77	10000	10000	10000	10000	10000	10000	10000	10000
	8	92	10000	10000	10000	10000	10000	10000	10000	10000
	9	79	10000	10000	10000	10000	10000	10000	10000	10000
	10	153	10000	10000	10000	10000	10000	10000	10000	10000
Quickbird1	1	135	210	426	10000	10000	10000	10000	10000	10000
	2	135	354	0	10000	10000	10000	10000	10000	10000
	3	135	213	426	10000	10000	10000	10000	10000	10000
	4	135	213	426	10000	10000	10000	10000	10000	10000
	5	135	213	426	10000	10000	10000	10000	10000	10000
	6	135	213	426	10000	10000	10000	10000	10000	10000
	7	135	213	426	10000	10000	10000	10000	10000	10000
	8	135	213	426	10000	10000	10000	10000	10000	10000
	9	213	426	10000	10000	10000	10000	10000	10000	10000
	10	135	213	354	426	10000	10000	10000	10000	10000
Quickbird2	1	44	257	335	10000	10000	10000	10000	10000	10000
	2	44	185	257	397	10000	10000	10000	10000	10000
	3	44	257	335	10000	10000	10000	10000	10000	10000
	4	44	257	10000	10000	10000	10000	10000	10000	10000
	5	44	257	335	10000	10000	10000	10000	10000	10000
	6	44	257	335	10000	10000	10000	10000	10000	10000
	7	44	257	335	10000	10000	10000	10000	10000	10000
	8	44	257	335	10000	10000	10000	10000	10000	10000
	9	44	116	257	335	10000	10000	10000	10000	10000
	10	44	257	10000	10000	10000	10000	10000	10000	10000
Quickbird3	1	112	189	402	10000	10000	10000	10000	10000	10000
	2	112	330	10000	10000	10000	10000	10000	10000	10000
	3	112	189	402	10000	10000	10000	10000	10000	10000
	4	112	190	330	402	10000	10000	10000	10000	10000
	5	112	189	402	10000	10000	10000	10000	10000	10000
	6	112	189	402	10000	10000	10000	10000	10000	10000
	7	112	189	402	10000	10000	10000	10000	10000	10000
	8	112	189	402	10000	10000	10000	10000	10000	10000
	9	190	402	10000	10000	10000	10000	10000	10000	10000
	10	112	330	10000	10000	10000	10000	10000	10000	10000
Quickbird4	1	68	280	358	10000	10000	10000	10000	10000	10000
	2	68	280	10000	10000	10000	10000	10000	10000	10000
	3	68	280	358	10000	10000	10000	10000	10000	10000
	4	68	280	10000	10000	10000	10000	10000	10000	10000
	5	68	280	358	10000	10000	10000	10000	10000	10000
	6	68	280	358	10000	10000	10000	10000	10000	10000

Asset	Target Obs	1st access	2nd access	3rd access	4th access	5th access	6th access	7th access	8th access	9th access
	7	68	280	358	10000	10000	10000	10000	10000	10000
	8	68	280	358	10000	10000	10000	10000	10000	10000
	9	140	358	10000	10000	10000	10000	10000	10000	10000
	10	68	280	10000	10000	10000	10000	10000	10000	10000

Asset	Target Obs	10th access	11th access	12th access	13th access	14th access	15th access	16th access	17th access	18th access
UAV route 1	1	10000	10000	10000	10000	10000	10000	10000	10000	1000
	2	10000	10000	10000	10000	10000	10000	10000	10000	1000
	3	10000	10000	10000	10000	10000	10000	10000	10000	1000
	4	10000	10000	10000	10000	10000	10000	10000	10000	1000
	5	10000	10000	10000	10000	10000	10000	10000	10000	1000
	6	10000	10000	10000	10000	10000	10000	10000	10000	1000
	7	10000	10000	10000	10000	10000	10000	10000	10000	1000
	8	10000	10000	10000	10000	10000	10000	10000	10000	1000
	9	10000	10000	10000	10000	10000	10000	10000	10000	1000
	10	10000	10000	10000	10000	10000	10000	10000	10000	1000
UAV route 2	1	161	165	193	196	224	227	255	259	272
	2	10000	10000	10000	10000	10000	10000	10000	10000	10000
	3	272	10000	10000	10000	10000	10000	10000	10000	10000
	4	10000	10000	10000	10000	10000	10000	10000	10000	10000
	5	272	10000	10000	10000	10000	10000	10000	10000	10000
	6	273	10000	10000	10000	10000	10000	10000	10000	10000
	7	272	10000	10000	10000	10000	10000	10000	10000	10000
	8	10000	10000	10000	10000	10000	10000	10000	10000	10000
	9	10000	10000	10000	10000	10000	10000	10000	10000	10000
	10	10000	10000	10000	10000	10000	10000	10000	10000	10000
Soft Team	1	10000	10000	10000	10000	10000	10000	10000	10000	10000
	2	10000	10000	10000	10000	10000	10000	10000	10000	10000
	3	10000	10000	10000	10000	10000	10000	10000	10000	10000
	4	10000	10000	10000	10000	10000	10000	10000	10000	10000
	5	10000	10000	10000	10000	10000	10000	10000	10000	10000
	6	10000	10000	10000	10000	10000	10000	10000	10000	10000
	7	10000	10000	10000	10000	10000	10000	10000	10000	10000
	8	10000	10000	10000	10000	10000	10000	10000	10000	10000
	9	10000	10000	10000	10000	10000	10000	10000	10000	10000
	10	10000	10000	10000	10000	10000	10000	10000	10000	10000
Quickbird1	1	10000	10000	10000	10000	10000	10000	10000	10000	10000
	2	10000	10000	10000	10000	10000	10000	10000	10000	10000
	3	10000	10000	10000	10000	10000	10000	10000	10000	10000
	4	10000	10000	10000	10000	10000	10000	10000	10000	10000
	5	10000	10000	10000	10000	10000	10000	10000	10000	10000
	6	10000	10000	10000	10000	10000	10000	10000	10000	10000
	7	10000	10000	10000	10000	10000	10000	10000	10000	10000
	8	10000	10000	10000	10000	10000	10000	10000	10000	10000
	9	10000	10000	10000	10000	10000	10000	10000	10000	10000
	10	10000	10000	10000	10000	10000	10000	10000	10000	10000

Quickbird2	1	10000	10000	10000	10000	10000	10000	10000	10000	10000
	2	10000	10000	10000	10000	10000	10000	10000	10000	10000
	3	10000	10000	10000	10000	10000	10000	10000	10000	10000
	4	10000	10000	10000	10000	10000	10000	10000	10000	10000
	5	10000	10000	10000	10000	10000	10000	10000	10000	10000
	6	10000	10000	10000	10000	10000	10000	10000	10000	10000
	7	10000	10000	10000	10000	10000	10000	10000	10000	10000
	8	10000	10000	10000	10000	10000	10000	10000	10000	10000
	9	10000	10000	10000	10000	10000	10000	10000	10000	10000
	10	10000	10000	10000	10000	10000	10000	10000	10000	10000
Quickbird3	1	10000	10000	10000	10000	10000	10000	10000	10000	10000
	2	10000	10000	10000	10000	10000	10000	10000	10000	10000
	3	10000	10000	10000	10000	10000	10000	10000	10000	10000
	4	10000	10000	10000	10000	10000	10000	10000	10000	10000
	5	10000	10000	10000	10000	10000	10000	10000	10000	10000
	6	10000	10000	10000	10000	10000	10000	10000	10000	10000
	7	10000	10000	10000	10000	10000	10000	10000	10000	10000
	8	10000	10000	10000	10000	10000	10000	10000	10000	10000
	9	10000	10000	10000	10000	10000	10000	10000	10000	10000
	10	10000	10000	10000	10000	10000	10000	10000	10000	10000
Quickbird4	1	10000	10000	10000	10000	10000	10000	10000	10000	10000
	2	10000	10000	10000	10000	10000	10000	10000	10000	10000
	3	10000	10000	10000	10000	10000	10000	10000	10000	10000
	4	10000	10000	10000	10000	10000	10000	10000	10000	10000
	5	10000	10000	10000	10000	10000	10000	10000	10000	10000
	6	10000	10000	10000	10000	10000	10000	10000	10000	10000
	7	10000	10000	10000	10000	10000	10000	10000	10000	10000
	8	10000	10000	10000	10000	10000	10000	10000	10000	10000
	9	10000	10000	10000	10000	10000	10000	10000	10000	10000
	10	10000	10000	10000	10000	10000	10000	10000	10000	10000

Asset	Target Obs	dur1	dur2	dur3	dur4	dur5	dur6	dur7	dur8	dur9
UAV route 1	1	3	5	5	5	5	5	5	5	5
	2	3	3	3	3	3	3	3	3	3
	3	3	4	4	4	4	4	4	4	4
	4	2	2	2	2	2	2	2	2	2
	5	3	3	3	3	3	3	3	3	3
	6	3	3	4	4	3	3	3	3	3
	7	3	3	3	3	3	3	3	3	3
	8	3	3	3	3	3	3	3	3	3
	9	3	3	3	3	3	3	3	3	3
	10	4	4	4	4	4	4	4	4	4
UAV route 2	1	3	2	3	2	3	2	3	2	3
	2	3	3	3	3	3	3	3	3	0
	3	3	5	5	5	5	5	5	5	5
	4	1	1	1	1	1	1	1	1	0
	5	3	4	4	4	4	5	4	4	5

Asset	Target Obs	dur1	dur2	dur3	dur4	dur5	dur6	dur7	dur8	dur9
	6	3	5	5	5	5	5	4	5	4
	7	3	4	4	4	4	4	4	4	5
	8	3	3	3	2	2	2	3	3	0
	9	2	2	2	2	2	2	2	2	2
	10	4	4	4	4	4	4	4	4	0
Soft Team	1	349	0	0	0	0	0	0	0	0
	2	271	0	0	0	0	0	0	0	0
	3	349	0	0	0	0	0	0	0	0
	4	319	0	0	0	0	0	0	0	0
	5	355	0	0	0	0	0	0	0	0
	6	346	0	0	0	0	0	0	0	0
	7	355	0	0	0	0	0	0	0	0
	8	340	0	0	0	0	0	0	0	0
	9	353	0	0	0	0	0	0	0	0
	10	279	0	0	0	0	0	0	0	0
Quickbird1	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird2	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird3	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird4	1	0	0	0	0	0	0	0	0	0

Asset	Target Obs	dur1	dur2	dur3	dur4	dur5	dur6	dur7	dur8	dur9
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0

Asset	Target Obs	dur10	dur11	dur12	dur13	dur14	dur15	dur16	dur17	dur18
UAV route 1	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
UAV route 2	1	2	3	2	3	2	3	2	2	2
	2	0	0	0	0	0	0	0	0	0
	3	3	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	3	0	0	0	0	0	0	0	0
	6	3	0	0	0	0	0	0	0	0
	7	3	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Soft Team	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird1	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0

Asset	Target Obs	dur10	dur11	dur12	dur13	dur14	dur15	dur16	dur17	dur18
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird2	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird3	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0
Quickbird4	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0
	9	0	0	0	0	0	0	0	0	0
	10	0	0	0	0	0	0	0	0	0

Appendix C. VBA Code

This VBA code was used to create the coefficient matrices used by Frontline Premium Platform Solver to accomplish the optimization. This code was designed to create every entry in the 3-dimensional matrices used. Three of these matrices are required, a duration matrix, an x matrix, and an image resolution matrix. Afterwards, the program exports the corresponding matrices to a worksheet for use in the constraints used in the solver.

Option Base 1

```
Sub RunSolver()
'need to dimension all of my variables
Dim xmit(7, 10, 432) As Integer, IQxmit(7, 10, 432) As Double, IQ(7, 10, 18) As Double, _
    m As Integer, I As Integer, a As Integer, t As Integer, _
    ST(7, 10, 18) As Integer, Duration(7, 10, 18) As Integer, DX(7, 10, 432) As Integer, p As
Integer
'fill ST matrix
For m = 1 To 7
    For I = 1 To 10
        For a = 1 To 18
            ST(m, I, a) = Worksheets("Sheet2").Range("E2").Offset((10 * (m - 1) + (I - 1)), (a -
1)).Value
        Next a
    Next I
Next m
'fill Duration matrix
For m = 1 To 7
    For I = 1 To 10
        For a = 1 To 18
            Duration(m, I, a) = Worksheets("Sheet2").Range("X2").Offset((10 * (m - 1) + (I - 1)), (a -
1)).Value
        Next a
    Next I
Next m
'fill IQ matrix
For m = 1 To 7
    For I = 1 To 10
        For a = 1 To 18
            IQ(m, I, a) = Worksheets("Sheet2").Range("AQ2").Offset((10 * (m - 1) + (I - 1)), (a -
1)).Value
        Next a
    Next I
Next m
'fill in IQx matrix
For m = 1 To 7
```

```

    For I = 1 To 10
        For a = 1 To 18
            If Worksheets("Sheet2").Range("E2").Offset((10 * (m - 1) + (I - 1)), (a - 1)).Value <> 0 Then
                IQxmit(m, I, (Worksheets("Sheet2").Range("E2").Offset((10 * (m - 1) + (I - 1)), (a - 1)).Value)) =
                    IQ(m, I, a)
            End If
        Next a
    Next I
Next m
'print to worksheet3
For m = 1 To 7
    For I = 1 To 10
        For t = 1 To 432
            Worksheets("Sheet3").Range("b2").Offset(((t - 1) + 432 * (I - 1)), (2 * (m - 1))).Value = IQxmit(m, I, t)
        Next t
    Next I
Next m
'xmit 's and IQxmit's for satellites (modes 4-7)
For m = 4 To 7
    For I = 1 To 10
        For a = 1 To 18
            For t = 1 To 432
                If t = ST(m, I, a) Then
                    xmit(m, I, t) = 1
                End If
            Next t
        Next a
    Next I
Next m
'create Dxmit matrix
For m = 1 To 7
    For I = 1 To 10
        For a = 1 To 18
            For t = 1 To 432
                If t = ST(m, I, a) Then
                    For p = t To t + Duration(m, I, a)
                        DX(m, I, p) = 1
                    Next p
                End If
            Next t
        Next a
    Next I
Next m
For m = 1 To 7
    For I = 1 To 10
        For t = 1 To 432
            Worksheets("Sheet4").Range("b2").Offset(((t - 1) + 432 * (I - 1)), (m - 1)).Value = DX(m, I, t)
        Next t
    Next I
Next m

```

After a solution was found, the DEV variables placed into one column. This column was then divided into multiple columns such that a column of data represented one POI. The following program was developed to create a Gantt chart from that data in Microsoft Excel. Due to the size of the graph, the time intervals are on the y-axis and the targets on the x-axis. In order to place these charts in this thesis, the axes were transposed.

```
Sub GHANTT()
```

```
'This is a subroutine to color code a gantt chart. It specifically looks at 10 targets  
'and then colors in when there is an asset imaging that target at time t. one color for  
'each target.
```

```
Dim i As Integer, j As Integer, k As Integer
```

```
For i = 2 To 11
```

```
  For j = 2 To 433
```

```
    If Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Value = 0 Then
```

```
      If i = 2 Then
```

```
        With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
```

```
          .ColorIndex = 12
```

```
          .Pattern = xlSolid
```

```
        End With
```

```
      End If
```

```
      If i = 3 Then
```

```
        With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
```

```
          .ColorIndex = 3
```

```
          .Pattern = xlSolid
```

```
        End With
```

```
      End If
```

```
      If i = 4 Then
```

```
        With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
```

```
          .ColorIndex = 4
```

```
          .Pattern = xlSolid
```

```
        End With
```

```
      End If
```

```
      If i = 5 Then
```

```
        With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
```

```
          .ColorIndex = 5
```

```
          .Pattern = xlSolid
```

```
        End With
```

```
      End If
```

```
      If i = 6 Then
```

```
        With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
```

```
          .ColorIndex = 6
```

```
          .Pattern = xlSolid
```

```
        End With
```

```

End If
If i = 7 Then
    With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
        .ColorIndex = 7
        .Pattern = xlSolid
    End With
End If
If i = 8 Then
    With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
        .ColorIndex = 8
        .Pattern = xlSolid
    End With
End If
If i = 9 Then
    With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
        .ColorIndex = 9
        .Pattern = xlSolid
    End With
End If
If i = 10 Then
    With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
        .ColorIndex = 10
        .Pattern = xlSolid
    End With
End If
If i = 11 Then
    With Worksheets("sheet5").Range("B1").Offset(j - 1, i - 2).Interior
        .ColorIndex = 11
        .Pattern = xlSolid
    End With
End If
End If
Next j
Next i
For k = 2 To 11
    For i = 2 To 433
        Worksheets("sheet5").Range("B1").Offset(i - 1, k - 2).Value = ""
    Next i
Next k
End Sub

```

Appendix D. Solution to Notional Example

The following tables summarizes the solution for the small notional example described in Chapter 4. There is one table for each POI.

Table 14. Allocation of assets for Q-West

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
Q-West	Quickbird 1	135	0	0.9481		65 intervals
		210	0	0.8498		
		426	0	0.8979		
	Quickbird 2	44	0	0.8836		
		257	0	0.8503		
		335	0	0.9683		
	Quickbird 3	112	0	0.8882		
		189	0	0.8697		
		402	0	0.9199		
	Quickbird 4	68	0	0.9066		
		280	0	0.8610		
		358	0	0.8989	1 to 9	
	UAV route 2	9	3	0.9126	13 to 36	
		37	2	1.1184	43	
		40	2	0.9307	45 to 67	
		68	2	1.1536	74 to 82	
		71	2	0.9270		
		99	2	1.1678		
		102	2	0.9425		
		130	2	1.1658		
		134	2	0.9337		
		161	2	1.2046		
		165	2	0.9540		
		193	2	1.1106		
		196	3	0.9245		
		224	2	1.1889		
		227	3	0.8993		
		255	2	1.1446		
		259	2	1.1555		
		272	2	1.1996		
	SOF team	83	349	0.5000		

Table 15. Allocation of assets for Basrah

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
Basrah	Quickbird 1	135	0	0.8548		
		354	0	0.8918		
	Quickbird 2	44	0	0.9633		
		185	0	0.9897		
		257	0	0.9418		
		397	0	0.9933		
	Quickbird 3	112	0	0.8521		
		330	0	0.8685	1 to 18	
	Quickbird 4	68	0	0.8910	22 to 43	
		280	0	0.8795	44 to 49	
	UAV route 2	19	3	0.8222	54 to 67	
		50	3	0.8276	68 to 80	137
		81	3	0.8253	84 to 111	
		112	3	0.7634	115 to 134	
		144	3	0.7909	135 to 143	
		175	3	0.7919	148 to 160	
		206	3	0.8878		
		237	3	0.7406		
	SOF team	161	271	0.5000		

Table 16. Allocation of Assets for Mosel

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
Mosel	Quickbird 1	135	0	0.9359		
		213	0	0.8510	1 to 7	
		426	0	0.9074	12 to 36	
	Quickbird 2	44	0	0.8865	43	
		257	0	0.8523	45 to 67	
		335	0	0.9618	74 to 98	
	Quickbird 3	112	0	0.8820	105 to 111	
		189	0	0.8666	113 to 130	
		402	0	0.9285	137 to 161	
	Quickbird 4	68	0	0.9087	168 to 188	
		280	0	0.8559	190 to 192	
		358	0	0.8961	199 to 212	
						368
	UAV route 2	8	3	0.6813	214 to 223	
		37	5	0.7483	230 to 254	
		68	5	0.7763	260 to 271	
		99	5	0.7825	276 to 279	
		131	5	0.7803	281 to 334	
		162	5	0.8224	336 to 357	
		193	5	0.7125	359 to 401	
		224	5	0.7704	403 to 425	
		255	4	0.8968	427 to 432	
		272	3	1.8685		
	SOF team	83	349	0.5000		

Table 17. Allocation of Assets for Shayka

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
Shayka	Quickbird 1	135	0	0.9138	1 to 14	
		213	0	0.9020	17 to 43	
		426	0	0.8966	45	
	Quickbird 2	44	0	0.8515	48 to 67	
		257	0	0.8651	69 to 76	
	Quickbird 3	112	0	0.8904	79 to 107	
		190	0	0.9231	110 to 111	
		330	0	0.9962	113 to 134	
		402	0	0.9602	136 to 138	
	Quickbird 4	68	0	0.8598	141 to 170	
		280	0	0.8476	173 to 189	
	UAV route 2	15	1	1.2853	191 to 201	405
		46	1	1.3099	203 to 211	
		77	1	1.3073	213 to 231	
		108	1	1.3611	234 to 255	
		139	1	1.3315	257 to 278	
		171	1	1.3542	280 to 328	
		202	1	1.3464	330 to 400	
		233	1	1.3425	402 to 424	
	SOF team	113	319	0.5000	426 to 432	

Table 18. Allocation of Asset for H-Zalah

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
H-Zalah	Quickbird 1	135	0	0.9618		
		213	0	0.8575	1 to 7	
		426	0	0.8858	12 to 36	
	Quickbird 2	44	0	0.8830	42 to 43	
		257	0	0.8486	45 to 67	
		335	0	0.9261	73 to 98	
	Quickbird 3	112	0	0.8959	104 to 111	
		189	0	0.8536	113 to 129	
		402	0	0.9078	136 to 161	
	Quickbird 4	68	0	0.9374	168 to 188	
		280	0	0.8674	190 to 192	
		358	0	0.9077	198 to 212	
	UAV route 2	8	3	0.8345	214 to 223	
		37	4	0.6379	229 to 254	
		68	4	0.6366	261 to 271	
		99	4	0.6396	276 to 279	
		130	4	0.6380	281 to 334	
		162	5	0.6534	336 to 357	
		193	4	0.6252	359 to 401	
		224	4	0.6117	403 to 425	
		255	5	0.5190	427 to 432	
		272	3	0.9288		373
	SOF team	77	355	0.5000		

Table 19. Allocation of Assets for Hel-3494

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
Hel-3494	Quickbird 1	135	0	0.9250		
		213	0	0.8510		
		426	0	0.8836	1 to 7	
	Quickbird 2	44	0	0.8830	12 to 37	
		257	0	0.8569	45 to 67	
		335	0	0.9698	75 to 99	
	Quickbird 3	112	0	0.9059	106 to 111	
		189	0	0.8694	113 to 130	
		402	0	0.9391	137 to 161	
	Quickbird 4	68	0	0.9035	168 to 188	
		280	0	0.8534	190 to 193	368
		358	0	0.9004	199 to 212	
	UAV route 2	8	3	0.6406	214 to 224	
		38	5	0.6953	231 to 255	
		69	5	0.7215	261 to 272	
		100	5	0.7245	277 to 279	
		131	5	0.7239	281 to 334	
		162	5	0.7550	336 to 357	
		194	4	0.6872	359 to 401	
		225	5	0.7318	403 to 425	
		256	4	0.9304	427 to 432	
		273	3	1.8568		
	SOF team	86	346	0.5000		

Table 21. Allocation of Assets for I-Corp-HQ

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
I-Corp-HQ	Quickbird 1	135	0	0.9602		
		213	0	0.8563	1 to 6	
		426	0	0.8855	11 to 36	
	Quickbird 2	44	0	0.8837	42 to 43	
		257	0	0.8502	45 to 67	
		335	0	0.9246	73 to 98	
	Quickbird 3	112	0	0.8950	104 to 111	
		189	0	0.8543	113 to 130	
		402	0	0.9089	136 to 161	
	Quickbird 4	68	0	0.9376	167 to 188	
		280	0	0.8661	190 to 192	374
		358	0	0.9050	198 to 212	
	UAV route 2	7	3	0.7855	214 to 223	
		37	4	0.6299	229 to 254	
		68	4	0.6242	261 to 271	
		99	4	0.6265	276 to 279	
		131	4	0.6251	281 to 334	
		162	4	0.6137	336 to 357	
		193	4	0.6250	359 to 401	
		224	4	0.6012	403 to 425	
		255	5	0.5289	427 to 432	
		272	3	0.7745		
	SOF team	77	355	0.5000		

Table 22. Allocation of Assets for Bridge

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
Bridge	Quickbird 1	135	0	0.9340		
		213	0	0.8532	1 to 9	
		426	0	0.8804	14 to 40	
	Quickbird 2	44	0	0.8639	45 to 67	
		257	0	0.8549	69 to 72	
		335	0	0.9969	76 to 103	
	Quickbird 3	112	0	0.8799	107 to 111	
		189	0	0.8941	113 to 124	
		402	0	0.9352	128 to 155	
	Quickbird 4	68	0	0.8846	159 to 178	395
		280	0	0.8541	180 to 186	
		358	0	0.9266	190 to 202	
	UAV route 2	10	3	0.9320	204 to 218	
		41	2	0.9488	223 to 246	
		73	2	0.9454	248 to 269	
		104	2	0.9716	271 to 324	
		135	2	0.9566	326 to 347	
		166	2	0.9780	349 to 401	
		197	2	0.9401	203 to 425	
		229	3	0.9382	427 to 432	
	SOF team	92	340	0.5000		

Table 23. Allocation of Assets for DIV

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
DIV	Quickbird 1	213	0	0.8836	1 to 29	
		426	0	0.8995	33 to 43	
	Quickbird 2	44	0	0.9641	45 to 60	
		116	0	0.9953	64 to 91	
		257	0	0.9337	95 to 115	
		335	0	0.8990	117 to 122	
	Quickbird 3	190	0	0.8612	126 to 139	
		402	0	0.8524	141 to 154	
	Quickbird 4	140	0	0.9178	158 to 185	
		358	0	0.8519	189	395
	UAV route 2	30	2	0.8710	191 to 212	
		61	2	0.8705	214 to 216	
		92	2	0.8556	220 to 247	
		123	2	0.8076	251 to 256	
		155	2	0.8647	258 to 264	
		186	2	0.8793	268 to 334	
		217	2	0.8352	336 to 357	
		248	2	0.8882	359 to 401	
		265	2	0.8352	403 to 425	
	SOF team	79	353	0.5000	427 to 432	

Table 24. Allocation of Assets for DIV2

POI	Asset covering	Start time	Duration	Image Resolution	Intervals not covered	Total intervals not covered
DIV2	Quickbird 1	135	0	0.8825	1 to 18	
		213	0	0.9932	24 to 43	
		354	0	0.9301	45 to 49	
		425	0	0.9939	55 to 67	
	Quickbird 2	44	0	0.9135	69 to 80	
		257	0	0.8973	86 to 111	
	Quickbird 3	112	0	0.8757	117 to 134	
		330	0	0.8156	136 to 142	
	Quickbird 4	68	0	0.8893	148 to 174	
		280	0	0.8716	180 to 205	
	UAV route 2	19	4	0.5985	211 to 212	383
		50	4	0.6042	214 to 236	
		81	4	0.6044	242 to 256	
		112	4	0.6218	258 to 279	
		143	4	0.5979	281 to 329	
		175	4	0.6232	331 to 353	
		206	4	0.6169	355 to 424	
		237	4	0.6416	426 to 432	
	SOF team	153	279	0.5000		

Appendix E. Gantt Charts from Notional Example

Using the VBA code described in Appendix C, the following Gantt charts were developed. For each target, if the time interval is colored, that corresponds to the target being imaged at that time.

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	15	16	17	18	19	20	21	22	23	24	25	26	27	28

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	29	30	31	32	33	34	35	36	37	38	39	40	41	42

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	43	44	45	46	47	48	49	50	51	52	53	54	55	56

Target 1																	
Target 2																	
Target 3																	
Target 4																	
Target 5																	
Target 6																	
Target 7																	
Target 8																	
Target 9																	
Target 10																	
Time	57	58	59	60	61	62	63	64	65	66	67	68	69	70			

Target 1																	
Target 2																	
Target 3																	
Target 4																	
Target 5																	
Target 6																	
Target 7																	
Target 8																	
Target 9																	
Target 10																	
Time	71	72	73	74	75	76	77	78	79	80	81	82	83	84			

Target 1																	
Target 2																	
Target 3																	
Target 4																	
Target 5																	
Target 6																	
Target 7																	
Target 8																	
Target 9																	
Target 10																	
Time	85	86	87	88	89	90	91	92	93	94	95	96	97	98			

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	99	100	101	102	103	104	105	106	107	108	109	110	111	112

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	113	114	115	116	117	118	119	120	121	122	123	124	125	126

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	127	128	129	130	131	132	133	134	135	136	137	138	139	140

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	141	142	143	144	145	146	147	148	149	150	151	152	153	154

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	155	156	157	158	159	160	161	162	163	164	165	166	167	168

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	169	170	171	172	173	174	175	176	177	178	179	180	181	182

Target 1															
Target 2															
Target 3															
Target 4															
Target 5															
Target 6															
Target 7															
Target 8															
Target 9															
Target 10															
Time	183	184	185	186	187	188	189	190	191	192	193	194	195	196	

Target 1															
Target 2															
Target 3															
Target 4															
Target 5															
Target 6															
Target 7															
Target 8															
Target 9															
Target 10															
Time	197	198	199	200	201	202	203	204	205	206	207	208	209	210	

Target 1															
Target 2															
Target 3															
Target 4															
Target 5															
Target 6															
Target 7															
Target 8															
Target 9															
Target 10															
Time	211	212	213	214	215	216	217	218	219	220	221	222	223	224	

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	225	226	227	228	229	230	231	232	233	234	235	236	237	238

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	239	240	241	242	243	244	245	246	247	248	249	250	251	252

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	253	254	255	256	257	258	259	260	261	262	263	264	265	266

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	267	268	269	270	271	272	273	274	275	276	277	278	279	280

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	281	282	283	284	285	286	287	288	289	290	291	292	293	294

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	295	296	297	298	299	300	301	302	303	304	305	306	307	308

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	309	310	311	312	313	314	315	316	317	318	319	320	321	322

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	323	324	325	326	327	328	329	330	331	332	333	334	335	336

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	337	338	339	340	341	342	343	344	345	346	347	348	349	350

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	351	352	353	354	355	356	357	358	359	360	361	362	363	364

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	365	366	367	368	369	370	371	372	373	374	375	376	377	378

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	379	380	381	382	383	384	385	386	387	388	389	390	391	392

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	393	394	395	396	397	398	399	400	401	402	403	404	405	406

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	407	408	409	410	411	412	413	414	415	416	417	418	419	420

Target 1														
Target 2														
Target 3														
Target 4														
Target 5														
Target 6														
Target 7														
Target 8														
Target 9														
Target 10														
Time	421	422	423	424	425	426	427	428	429	430	431	432		

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1. REPORT DATE (DD-MM-YYYY) 25-03-2003		2. REPORT TYPE Master's Thesis		3. DATES COVERED (From – To) Jun 2002 – Mar 2003	
4. TITLE AND SUBTITLE PLANNING COVERAGE OF POINTS OF INTEREST VIA MULTIPLE IMAGING SURVEILLANCE ASSETS: A MULTI-MODAL APPROACH				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Jackson, Sarah E. Captain, USAF				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way, Bldg 642. WPAFB OH 45433-7765				8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/GOR/ENS/03-11	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Col T.S. Kelso, Director Air Force Space Analysis Center HQ Air Force Space Command Peterson AFB, CO 80914				10. SPONSOR/MONITOR'S ACRONYM(S) AFSAC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT For the United States to maintain information superiority, it is necessary to have a means of allocating intelligence-gathering assets to collect information on particular points of interest. In today's geopolitical environment, however, the number of points of interest is growing rapidly, where as the number of available assets is not. To aid in maintaining information superiority, this research explores the use of a Multi-Modal Goal Programming Resource Constrained Project Scheduling approach for allocating imaging surveillance assets (land, air, sea, and space) to image a set of points of interest for a set time period. The objective of this formulation is to minimize the number of points of interest not covered at any time during the required period, minimize the deviation from the minimum image resolution of each point of interest, and minimize the time between successive imaging assets imaging each point of interest.					
15. SUBJECT TERMS Surveillance, goal programming					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 111	19a. NAME OF RESPONSIBLE PERSON Richard F. Deckro, DBA
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) (937) 255-6565, ext 4325 (richard.deckro@afit.edu)