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A VALIDATION ASSESSMENT OF THUNDER 6.5'S INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE MODULE

THESIS

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THESIS

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Fran

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Abstract

A validation assessment of THUNDER 6.5's Intelligence, Surveillance, and Reconnaissance (ISR) module is accomplished using formulational and experimental validation techniques. A comparison of ISR purposes and processes according to military doctrine is made with the purposes and processes of ISR implemented within THUNDER 6.5. This comparison provides an overview of the process, an understanding of the level of aggregation within THUNDER, insight into possible problem areas in THUNDER, and a basis for improving THUNDER ISR processes. Sensitivity analysis of the ISR parameters as they relate to the Quality, Quantity, and Timeliness of ISR is also presented to provide insight into the responsiveness of THUNDER to changes in ISR capability for selected battle outcomes. Linear Regression and a Face-Centered Central Composite Design were used to generate a response surface. Ninety-percent confidence intervals were used to determine differences in mean response among the full factorial design points.

A VALIDATION ASSESSMENT OF THUNDER 6.5'S INTELLIGENCE, SURVEILLANCE, AND RECONNAISSANCE MODULE

1. Introduction

1.1 Combat Modeling Tools

The modeling and simulation community employs a multitude of models that differ according to their intended purpose. These models/simulations are grouped together into categories – engineering, engagement, mission, and campaign - according to their resolution, quantitative, and qualitative characteristics (see Figure 1). The numerous models and the degrees of resolution are necessary to accommodate the wide range of users and their fundamentally different information requirements [5].

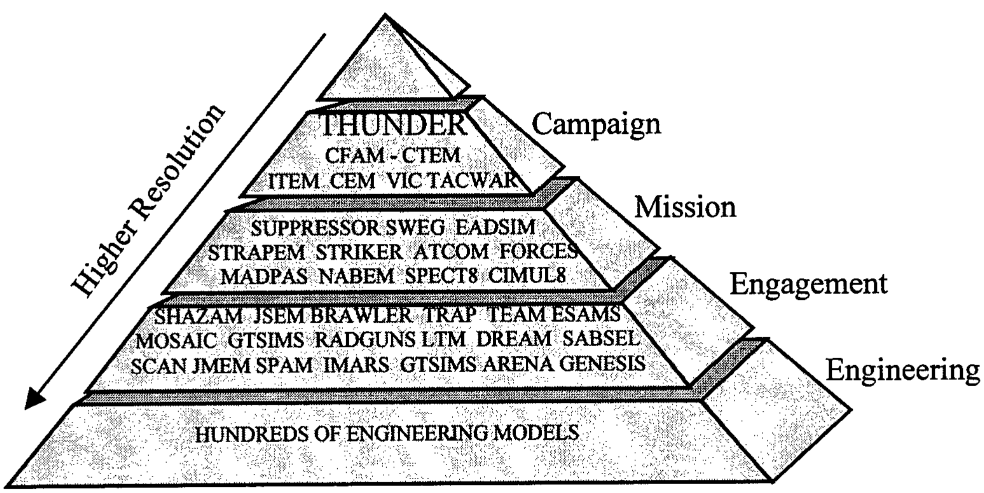


Figure 1. Air Force Analytical Toolkit Example [53]

The quantitative differences among models involve scope, scale, duration, and aggregation [5]. Each of these factors increases moving up the pyramid. The scope of an engineering model is limited to one system or subpart, whereas the scope of a campaign-level model includes the whole theater of war. The scale progresses up the pyramid from representing components of a system at the engineering-level to combat engagements of "many-on-many" in campaign-level models. The duration used in engagement models focuses on discrete times or events such as target acquisition, whereas campaign models include many operations and can simulate a whole war. The aggregation level of components also increases from engineering to campaign-level models. In fact, campaign-level models aggregate the output of engineering/engagement model and use this aggregated output as input data. Figure 2 displays the differences among model resolution and interactions.

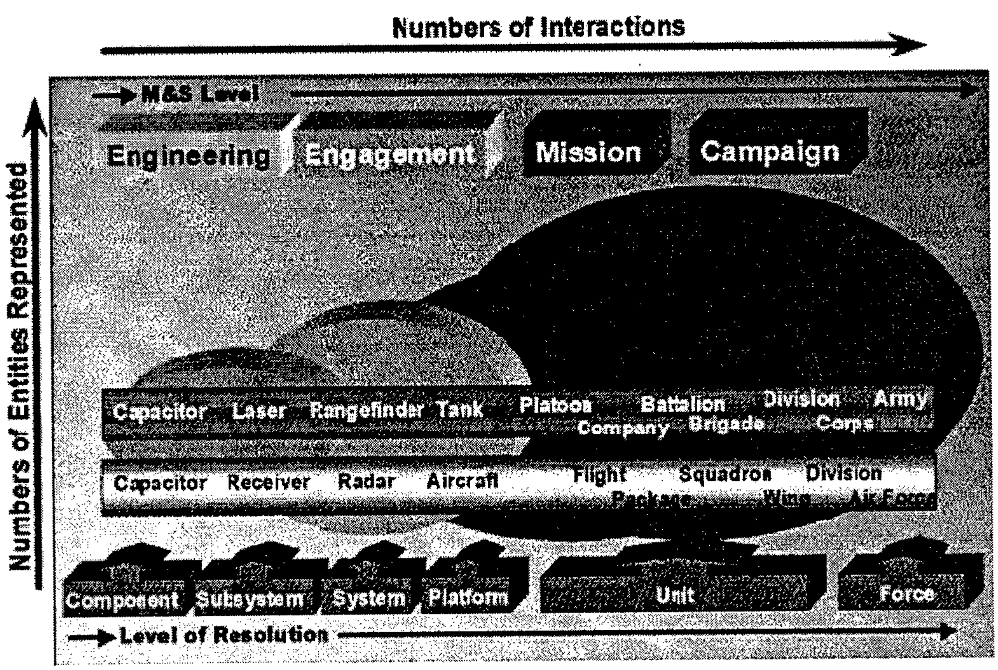


Figure 2. Comparison of Model Resolutions [5]

Qualitative differences also exist among the models. These differences include human behavior representation, measures of effectiveness employed, and use of the output. Human decision-making is seen in engagement and mission-level models. It is not found in engineering models since they are concerned with physical processes, and campaign level models exclude it mostly due to the large number of decision points and choices that can make it unmanageable [5]. The measures of effectiveness change as one moves up the pyramid. An engineering-level model measures its output in scientific terms such as amps, whereas campaign level models must relate their output to a warfighting context such as days to achieve air superiority [5]. How the output of the model is used also differs among the levels of the pyramid. As the quantitative and explicit representation of elements decreases, models become less useful in predictive capability and become more useful for simply providing insight into a system's influence on the warfighting scenario. "Given [the] level of complexity, the results of campaign simulations should be seen as less an 'answer' than an insight, less predictive than indicative" [5].

THUNDER is positioned in the Air Force's Analytical Toolkit (Figure 1) at the campaign-level and is considered the Air Force's premier campaign-level model. THUNDER is an "...analytical tool designed to help senior decision-makers evaluate strategy, tactics, force structure, and operational effectiveness in a joint warfighting context" [47]. It is an important tool in evaluating the impact of proposed weapon systems, technology, tactics, and doctrine on combat outcomes.

1.2 Problem Statement

Intelligence is critical to the success of military operations. Timely, accurate intelligence can be the defining element between victory and defeat. This aspect of war must be incorporated into combat models to ensure the model is an effective tool and that combat is correctly represented.

THUNDER has integrated intelligence, surveillance, and reconnaissance (ISR) representation into its combat processes. The ISR module of THUNDER affects many aspects of the war, including prioritization of targets, aircraft/munition selection, target acquisition, and ground unit attrition. Since the complex and compounding effects of ISR significantly impact campaign outcomes in the real world, one must ensure that the impact of ISR is accurately represented in THUNDER. Ensuring a model accurately reflects a real-world process is accomplished through validation. The purpose of this thesis is to assess the validity of the ISR module of THUNDER 6.5.

1.3 Validation of Models

Validation is defined by Joint Pub 1-02, Department of Defense Dictionary of Military and Associated Terms, as "The process of determining the degree to which a model or simulation is an accurate representation of the real world from the perspective of the intended uses of the model or simulation" [9:488].

Campaign-level models are very difficult to validate due to the complexity of factors and the lack of real world data. Also, because models like THUNDER are used for analyses on proposed future system, validating outcomes is often impossible. One inherent problem with validation is the definition of reality. The most common references for establishing validity are field experts and historical data. For this study, reality is defined by current military doctrine and instructions about ISR.

This thesis used two approaches to assess the validity of THUNDER 6.5's ISR module. The first approach examines the real world ISR process and to compares it with the ISR process within THUNDER, and the second is to perform an experiment to verify the sensitivity of the ISR processes on combat outcomes. Both of these approaches are necessary for validation, but neither one alone is sufficient. Comparative analysis between competing systems is a primary use of campaign models. A model that represents the parameters well, but lacks in providing representative output has limited use. On the other hand, a model that provides correct output, but does not represent the parameters well may be unable to provide insight if, or when, reality changes or a new scenario is introduced.

These two approaches also fit into the "four major interdependent types of validation" presented by Oral and Ketanni: formulational, experimental, operational, and data validation [32:223].

Comparing the processes provides for formulational validation as it is "...mainly concerned with the degree of capacity of the 'formal model' to describe correctly and accurately [real world events]" [32:224]. Experimental validation primarily deals with "...the quality of solutions, the types of solutions, the nature of solution techniques, and the efficiency of solution procedures" [32:224]. The experiment performed in this study focuses on the quality of solutions as it relates to the level of insight gained about the warfighting scenario and the sensitivity to changes in the values of the ISR parameters. Operational validation which refers to the "...usability, usefulness, timeliness, synergism, and the cost of implementing a decision based on the solutions provided by the 'formal model'" [32:226] is beyond the scope of this thesis. Data validation involving "...sufficiency, accuracy, appropriateness, availability, maintainability, reliability, and cost of data" [32:222] is not relevant to this thesis.

1.4 Modeling and Validating Intelligence

THUNDER's ISR module can be used to evaluate intelligence systems in terms of their contributions to combat outcomes. This evaluation allows for comparisons between systems and their capabilities as well as the combined value of a group of systems.

Intelligence is difficult to measure, and difficult to validate because of the uncertainty it adds to combat situations. A RAND study [2] on assessing the combat value of intelligence identifies two main reasons why modeling intelligence systems largely increases the uncertainty that already exists in a model. These reasons are soft (human) factors and nonlinearity.

Intelligence produces information. Information influences human decisions. Modeling a human decision process is difficult, hard to represent, hard to calibrate, and hard to validate; therefore, it is often poorly reflected in modeling [2:2]. "This neglect is sometimes justified either because human factors are believed to be less critical than 'hard' technical characteristics or because there are so many human actors involved that their actions can be represented statistically by aggregate probabilities, depending on the application" [2:2]. Combat elements such as target acquisition can be modeled with these hard characteristics, however, elements such as situation assessment require the commander's decision process to be modeled. "Focusing only upon target acquisition would provide a more tractable problem but would systematically underestimate the value of [intelligence]" [2:2].

Intelligence has a highly nonlinear effect on battle. In and of itself, intelligence is of no value, but its effectiveness is seen through the enhancement of other combat elements. The effect of intelligence can be largely dependent on the situation and decision at hand. For example, if an aircraft has expended its munitions, knowing where the next target is with a high degree of accuracy is of no consequence. However, when a "...single command decision means the difference between victory and defeat (for example deciding when to commit strategic reserves), ...the effect of one piece of critical intelligence is so nonlinear as to be essentially discontinuous" [2:3]. This fact increases the uncertainty. Small changes in input can result in large changes in output.

Although the difficulty in modeling ISR is great, the importance of ISR and its effects on combat outcomes make it an essential element that cannot be omitted if a model is to truly represent combat operations.

1.5 Thesis Outline

This thesis is organized into chapters according to subject areas. Chapter 2 presents an overview of THUNDER, some of its components, users, and history. Chapter 3 provides information on current military doctrine concerning the purposes and principles of ISR. Chapter 4 examines the ISR process and its elements. The objective of Chapters 3 and 4 is to demonstrate the complexity and breadth of the ISR process in the real world. This complex, sometimes unquantifiable, process has to be resolved into something that can be represented by a model, and Chapter 5 explains how THUNDER currently accomplishes that goal. The comparison between the ISR purposes and processes in the real world and in THUNDER is presented in Chapter 6. This comparison provides an overview of the process, an understanding of the level of aggregation within THUNDER, insight into possible problem areas in THUNDER, and a basis for improving THUNDER ISR processes. The scope of the comparison is reserved to major steps in the processes, with some discussion of lower details to analyze whether the aggregation within THUNDER is appropriate. Chapter 7 examines how THUNDER reacts to changes in ISR capability. Sensitivity analysis of parameters relating to the quality, quantity, and timeliness of ISR provides insight into the responsiveness of THUNDER to the ISR module. The final chapter, Chapter 8, presents the conclusions of this thesis and recommendations for improving THUNDER's ISR module.

Throughout this thesis, the term THUNDER refers to the THUNDER version 6.5.

2. THUNDER Overview

2.1 Introduction

THUNDER is a two-sided, stochastic, campaign-level model of conventional air and land warfare, with some naval representation. It is the campaign-level model of choice for the Air Force that has been used in high level decision-making activities such as determining the advantages of the F-22 and the effect of the Global Positioning System (GPS) on the warfighter. This chapter presents a brief overview of the model, its users, history, and verification and validation efforts.

2.2 Model Functional Design

The battlefield is modeled as a rectangular area which can be oriented in any direction that the user specifies. It is subdivided into grid squares, whose sizes are also defined by the user. A Forward Line of Own Troops (FLOT) line spans the width of the battlefield and divides the two opposing sides, referred to as Red and Blue. See Figure 3.

The battlefield is further divided into sectors and zones, as seen in Figure 4. Sectors represent commands that own units and can control portions of the FLOT. Each sector is divided into zones that generally represent areas in which certain ground activities take place. Units that are engaged in combat are located in the zone adjacent to the FLOT.

The ISR grid in THUNDER is similar in shape and form to the battlefield grid and can be thought of as overlaying the battlefield grid.

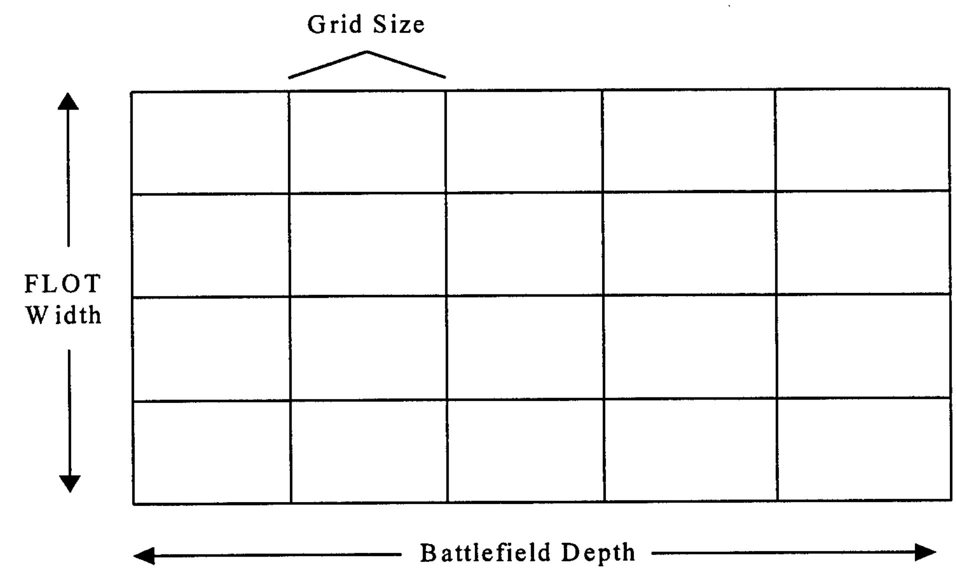


Figure 3. Battlefield Grid [51:3]

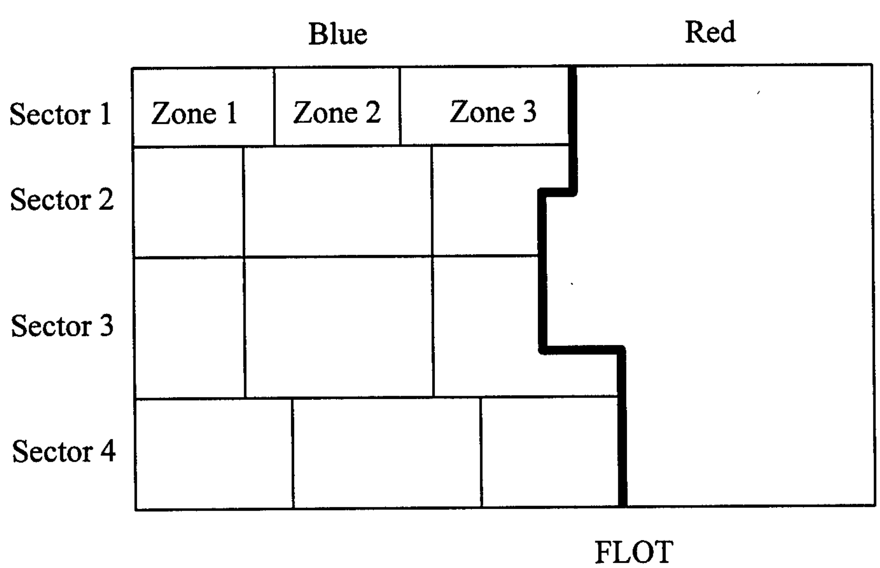


Figure 4. Battlefield Sectors and Zones [51:4]

The ground war within THUNDER is a deterministic model based on the United States Army's Concept Evaluation Model (CEM). The CEM uses the Attrition Calibration (ATCAL) process and the United States Army Concepts and Analysis Agency's Combat Sample Generator (COSAGE) model to adjudicate ground combat on a cyclical basis defined by the user. Units engaged in combat move strictly back and forth (similar to movement such as a piston) within a sector. Theater level supplies and logistics for both air and ground forces are modeled using mathematical transportation networks. Unit consumption data comes from the US Army Combined Arms Support Command (CASCOM).

For the air war, THUNDER simulates 27 different air missions such as airborne refueling, close air support, defensive counter-air, fighter sweep, long range air interdiction, reconnaissance, and standoff reconnaissance. Some of the missions defined in THUNDER are merely subsets of air missions defined by Air Force doctrine. These subsets allow for finer fidelity to capture desired effects, as well as for modeling convenience. THUNDER "...automatically generates Air Tasking Orders (ATOs) based on theater level apportionment and target priorities. A scheduler builds ATO packages, taking into consideration aircraft range, weather capability, weapons configurations, weapons effectiveness, weapons availability, and target availability" [54:2].

THUNDER is data driven and relies on a myriad of engineering and engagement models to provide its data inputs and calculations. For example, BRAWLER is used extensively for air-to-air information; ESAMS is used for surface-to-air missile probability of kill (Pk) data; and RADGUNS for anti-defense artillery Pks. Some other aspects of war modeled in THUNDER are: airbase operations including maintenance of aircraft and runway repair; cruise missile attacks and defense; intelligence, surveillance, and reconnaissance (ISR); perception and "fog of war"; strategic attacks; multiple-target missions; and the effects of weather.

THUNDER is written in SIMSCRIPT II.5, a general-purpose programming language particularly suited for large, discrete-event simulations. THUNDER contains about 300,000 lines of code divided into over 1,350 routines. It operates on Sun and Silicon Graphics Unix workstations.

2.3 Users

THUNDER is used by a large number of U.S. and allied defense organizations and contractors such as Air Force Studies and Analyses Information Superiority Branch (AFSAA/SAAI), AFSAA Wargaming Branch (AFSAA/SAAW), Air Force Wargaming, HQ ACC/XP-SAS, Boeing North American, Lockheed Martin Tactical Aeronautical, Northrop Grumman, and Raytheon Systems Company. It is also used internationally by British Aerospace, Defense Science and Technology Organisation (Australia), RAF Air Warfare Centre, and the Republic of Korea Air Force.

2.4 Assumptions

Because of the amount of aggregation needed in campaign level models, numerous assumptions are made regarding data validity. Users must understand how input data has been aggregated, and how the model uses the data. Aside from that, the three major assumptions identified for THUNDER for any campaign being studied are:

1) The war is between two nation-state sized adversaries in a single theater of operations.

2) A defined boundary exists between opposing sides in the model.

3) The campaign can be expressed by a four-part process: Perception, Planning, Execution, and Adjudication.

2.5 Origin and History

THUNDER was originally developed from TAC WARRIOR, a campaign-level model used in the 1970's and early 1980's. As TAC WARRIOR evolved, it became difficult to modify, the documentation no longer matched the code, and the assumptions of the model became invalid. To compensate for this, Air Force Studies and Analyses developed THUNDER from 1983-1986. THUNDER achieved its initial operating capability in 1985, and the first operational version was released in 1986. CACI, Inc. performed maintenance and upgrades from 1987-1993. Since 1993, both CACI, Inc. and System Simulation Solutions, Inc. (S3I) have maintained THUNDER. The most current version is THUNDER 6.5, released in November of 1997. Table 1 shows the history of THUNDER model releases and some of the developments.

Table 1. THUNDER Release Chronology [50:5-7,11]

Release Date	Version	Significant modification/enhancement
Aug 87	3.0	VAX/VMS support CACI Products Company assumes configuration control
May 88	4.0	SUN/UNIX support
Jan 89	4.4	Situation map Graphic utility
Nov 89	4.6	Enhancement of air defense module and ground module
Jun 90	5.1	Incorporation of rear-area transportation network Enhanced Suppression of Enemy Air Defenses functions
Jun 91	5.5	Enhancement of airfield attack mission Introduction of detailed logistics resource accounting methodology Enhancement of air mission planning
May 92	5.6	Addition of strategic target interdiction Enhanced ground attrition methodology

Dec 92	5.8	Addition of high-fidelity sortie rate profiles Addition of high-resolution aircraft maintenance module Improved methodology for treating overrun/abandoned airbases
Feb 93	5.9	Addition of time-dependent aircraft planning factors Accommodation of multiple target sorties
Sep 93	6.0	Incorporation of new flight missions: Enhanced terminal air defense logic
May 94	6.1	Deterministic weather model Major revision of air-to-surface adjudication methodology Enhanced/standardized target repair methodology Enhanced air-to-surface targeting prioritization
Jun 94	6.2	Higher resolution aerial refueling methodology Enhanced air mission abort rules Improved sortie scheduling algorithm in ATO generator Improved flight path logic Accommodate survivability in configuration selection More flexible SEAD corridor selection logic
Jun 95	6.3	Model effects of integrated air defense systems More explicit play of intelligence, surveillance, and reconnaissance (ISR) systems and effects Higher fidelity surface-to-air lethality data Accommodate integrated lethal/non-lethal SEAD mission Improved terminal delivery profile to accommodate weapon specific delivery requirements
Sep 96	6.4	Enhanced flight path generation algorithm to avoid area SAM threat Major ISR methodology improvements Addition of satellites to ISR module Incorporation of explicit TBM model and anti-TBM missions (pre/post-launch) Improved carrier battle group play
Nov 97	6.5	Interdictable ISR nodes Weather effects on ISR Weapons of Mass Destruction (Chem/Bio) Enhanced target acquisition and discrimination Improved air network paths Use perceived threat in air network survivability calculations Enhanced terminal air defense Incorporate tactical airlift Rule-based air planning Cyclic carrier operations Ground force engagement rules Grid-based air defense enhancements

2.6 Current Verification and Validation Efforts [54]

Verification of a model ensures that the model runs as intended. THUNDER conforms to the industry-accepted software standards for design and coding. The coding standards ensure that the code is understandable, promoting efficiency in maintenance and implementing new developments. The standards also give analysts the ability to quickly comprehend the algorithms, providing insights into model assumptions and expected outcomes. Along with "easy to read" code, comments embedded in the code are also helpful analysis tools.

THUNDER's Configuration Management Plan accounts for version control and release authority through a Revision Control System, a Configuration Control Board, and a formal release cycle and version numbering system. The Revision Control System archives changes to the model. The Configuration Control Board is the formal authority for reviewing model modifications and approving model changes.

All elements of the core THUNDER model were verified during the original implementation through requirements-to-design tracing, walkthroughs and formal reviews of the code, component and integration testing, and alpha and beta release test phases. These elements are also re-evaluated during significant modifications or enhancements to baseline releases.

Validation of a model ensures that the model accurately reflects the process or system that it represents. THUNDER uses two methods in its validation process: structural validation and output validation. In structural validation, subject matter experts evaluate the algorithms and code to determine if the implementation of the model will match the intent of the programmers. Output validation involves subject matter experts examining results to determine the extent that the implementation of the model matches expected outcomes. The output subject matter experts involved in THUNDER validation are usually members of the organization funding a modification.

2.7 Summary

THUNDER is an extremely large and complex model that is continually being updated to improve its ability to model various and new aspects of war. It can be cumbersome for the user as the model requires an enormous amount of data – almost 100 input files are required. However, the usefulness of the model cannot be overstated. Its real value comes from the analysis of various weapon types, capabilities, strategies, and their interactions. Using point estimates of model outcomes can be misleading due to the numerous input data assumptions and systemic limitations. The high level of aggregation in campaign models is somewhat of a disadvantage, but not something resolvable. Careful and valid data aggregation from higher resolution models is needed to lessen this disadvantage.

THUNDER is considered a valid, highly effective model for the Air Force. Its strength is that the Air War is modeled at a slightly higher resolution than is available elsewhere, with the automatic ATO generator saving a lot of user input time. The Ground War is deterministic, which saves on run-time, but it provides for somewhat limited interaction between air and ground units. Ship-to-ship naval warfare is not modeled, but that does not seem to impair the model's usefulness.

3. Intelligence, Surveillance, Reconnaissance Overview

3.1 Introduction

Intelligence, surveillance, and reconnaissance (ISR) operations are used for numerous military purposes and involve a variety of agencies and support systems to accomplish its objectives. This chapter presents some background on ISR, its purposes, players, products, and underlying systems.

3.2 Definitions

3.2.1 Intelligence, Surveillance, Reconnaissance

Intelligence, Surveillance, and Reconnaissance is defined as "The capability to collect, process, exploit and disseminate accurate and timely information that provides the battlespace awareness necessary to successfully plan and conduct operations" [15:8].

Intelligence is the "Product resulting from the collection, processing, integration, analysis, evaluation, and interpretation of available information concerning foreign countries, military capabilities, political groups, technological developments or certain geographic areas" [15:8]. Intelligence is obtained through surveillance and reconnaissance. Although surveillance and reconnaissance are similar, they are distinct enough to warrant separate definitions.

Surveillance is the "Sustained or systematic observation of aerospace, surface or subsurface areas, places, persons, or things, by visual, aural, electronic, photographic, or other means" [15:8]. A typical example of a platform used for surveillance is the E-8 Joint Surveillance Target Attack Radar System (J-STARS) which orbits for a relatively long period of time and provides continuous updates on enemy strength, location, and movement.

Reconnaissance is defined as "A transitory mission undertaken to obtain, by visual observation or other detection methods, information about the activities and resources of an adversary or potential adversary, or to secure data concerning the meteorological, hydrographic, or geographic characteristics of a particular area" [15:8]. As opposed to a sustained mission as in surveillance, reconnaissance missions do not provide continuous coverage of an area, but instead collect data on a discrete basis. An example of reconnaissance is a passing satellite taking a picture of a Scud missile launcher.

Another contrast between surveillance and reconnaissance is that surveillance data is generally passed on a real-time basis and usually comes from one source. The data provided is most often perishable and needed immediately, even before analysis. Reconnaissance data usually passes through a processing phase of evaluation by analysts and fusion with other data [34:14].

Surveillance and reconnaissance resources gather data that can be processed, analyzed, and/or fused to produce intelligence. Fusion is the process of combining data from various collection sources to produce more accurate information than from one source alone. Fusion provides a more comprehensive, yet focused, intelligence product.

3.3 Intelligence Purposes

The role of ISR in conducting a successful campaign is paramount. From before hostilities begin, through the end of the campaign and beyond, the Joint Force

Commander (JFC) must continually develop and refine the assessment of the ever-changing situation. With adequate ISR capability the JFC has the means to provide this assessment and in certain circumstances to attain information superiority. Knowing the enemy's vulnerabilities, strengths, and intentions allows the JFC to exploit opportunities and ultimately defeat the enemy. Intelligence derived from good ISR also provides the ability to assess the effectiveness of operations and aids in determining if and when the overall mission has been accomplished. Although there are many uses and purposes for intelligence, Joint Pub 2-0, "Joint Doctrine for Intelligence Support to Operations" [11:3.3-6], identifies the following as the six fundamental intelligence purposes:

1. Supporting the Commander – Intelligence should provide the commander knowledge of the situation to aid in optimal decision-making about operations.

2. Identifying and Determining Objectives – Intelligence should allow commanders to determine objectives that complement national security policy objectives and the derived military objectives.

3. Planning and Conducting Operations – Intelligence should provide necessary information to develop, plan and execute combat operations.

4. Security of Operations/Avoiding Deception and Surprise – Intelligence systems should be used to inhibit the enemy's attempt at deception and surprise.

5. Security of Operations through Deception – When planning operations, the commander should have knowledge of the enemy's command and control systems and intelligence systems so that deception can be used against the enemy.

6. Evaluating the Effects of Operations and Re-orienting Forces or Terminating Operations – Intelligence should assist in evaluating operational results and determining if objectives have been met.

3.4 ISR Principles

Commanders and decision-makers at all levels of war depend upon ISR operations to reduce uncertainties and to make better decisions. Certain "principles" or "attributes" of intelligence are identified in Air Force Doctrine Document 2-5.2 (Draft), "Intelligence, Surveillance, and Reconnaissance" [15:11-15] and Joint Pub 2-0 [11:4.14-16] which increase the responsiveness of ISR operations to commanders' needs. No one principle or attribute is more important than another as most depend upon each other, and sometimes trade-offs must be made. All of them must be considered to maximize ISR operational effectiveness. These principles are:

1. Accuracy – Intelligence reports will rarely be 100 percent accurate because of influences such as human error, the 'fog of war', the sophistication of enemy systems, deception, and our own technical limitations. However, ISR personnel must rely on their knowledge and experience, when corroborating all available information to provide the most accurate picture possible. Because absolute certainty cannot be achieved, a confidence level of the information should be provided, and commanders must be made aware of the limitations of the intelligence estimate given to them [34:2]. A confidence-level scale such as that shown in Figure 5 can be used to communicate the assessment of the intelligence provided.

2. Timeliness – To be used effectively, or to even be used at all, intelligence must be received before a decision is made or an opportunity is missed. To expend resources to gather intelligence, but then not have the intelligence available in time to be used defeats the purpose of ISR operations. New technology has influenced this principle more than any other, and continual improvements are being made due to its utmost importance [34:3].

3. Objectivity – Intelligence must be "...unbiased, undistorted, and free from political or other constraints" [11:4.14]. This relates to the principle of accuracy. Intelligence must not be manipulated to achieve a desired result or support a preconception.

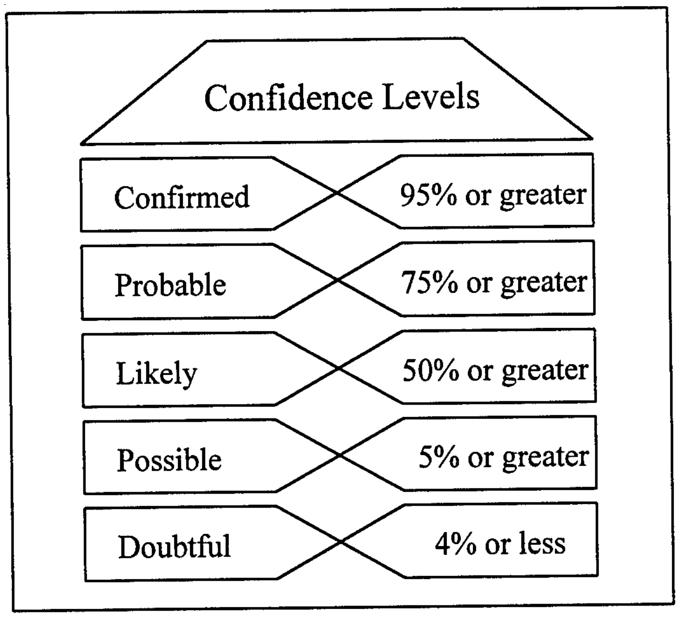


Figure 5. Confidence Levels of Intelligence Estimates [11:4.13]

4. Unity of Effort/Interoperability – Cooperation between the various military services and nationalities must exist at all levels of ISR operations. Information must be shared to minimize duplication and maximize effectiveness. Cross-cueing and analytical exchange can significantly increase operational effectiveness. Interoperability among systems is a must for this to occur.

5. Relevance – Intelligence produced should be applicable to determining, planning, conducting, and evaluating operations [15:12]. It should enhance situational awareness and support current and future operations. Relevance must be considered when planning for collection to ensure the user's requirements are met.

6. Usability – Intelligence must be disseminated in a form that does not require any additional processing or analysis. The commander, planner, or war fighter should be able to quickly identify and apply the intelligence received. Producers and users of intelligence should use common terminology and common means of communications to aid in usability. Producers must also understand the circumstances in which users are applying the intelligence received in order to best meet their needs.

7. Completeness – Commanders should have all available, relevant information required to accomplish the mission. Prioritization of requirements aids in ensuring that the most essential information is provided first.

8. Readiness – Intelligence organizations need to stay abreast of developing international situations and correctly identify potential trouble spots. During a crisis, the ability to anticipate possible intelligence needs increases the responsiveness of intelligence to the commanders that need it.

9. Fusion – Fusion helps to overcome the inherent weaknesses of individual collection systems and the deception efforts of the enemy by combining information from multiple sources and analyzing it to produce a comprehensive intelligence product. The process of fusing data takes time and counteracts the principle of timeliness. Although a fused product can increase usability and accuracy, a balance must be sought with timeliness. Fusion is not always required. Often, near-real-time collections must be acted upon without correlation in a reactive situation. In all cases, however, reliance on one source of information leaves the JFC subject to deception, which could outweigh the advantage of timeliness.

10. Accessibility – Raw data must be accessible to ISR operators and analysts in order for the ISR process to continue and for dissemination to take place. Users must also have access to the final products. A push/pull system in which users can "pull" the information they want and need provides them with relevant information without overloading them by "pushing" too much information. Security must be maintained, but classifying intelligence at the lowest level possibly allows for greater accessibility.

11. Security – We must protect our own capabilities and intentions, and safeguard our sources of intelligence. Declassification, sanitization, and releasability issues must be understood and adhered to by all personnel. Although overclassification is not desirable, using the need-to-know principle and multilevel secure communications will help prevent putting sources at unnecessary risk and will still enable users to receive needed information.

12. Survivability and Sustainability – The ISR system must not depend totally on one type of intelligence, one means of intelligence production, or one means of dissemination. The system must be survivable with adequate redundancy. There should be no one critical node that, if destroyed, cripples the whole system.

3.5 Intelligence Support

ISR supports conflict at all levels of war – strategic, operational, and tactical (Figure 6). At the strategic level, ISR is used to formulate policy, plans, and strategy at the national and theater levels. Strategic intelligence is used to form an overall picture before a crisis occurs, and then to enhance the overall picture once a crisis begins. It supports national objectives, the formulation of policies, and the determination of priorities. Strategic intelligence is also used to determine enemy capabilities, intentions, and their centers of gravity. The enemy's centers of gravity are those "Characteristics, capabilities, or [locations] from which a military force derives their freedom of action, physical strength, or will to fight" [9:87], such as the mass of the enemy army, the enemy's command structure, or public opinion.

Operational-level ISR is needed to aid the planning and conduct of major operations within the theater. It focuses on intelligence collection, identification, location, and analysis [19:6]. Identifying the enemy's capabilities and vulnerabilities is essential for operational activities such as determining targets or achieving air superiority.

Tactical intelligence is required for planning and conducting tactical operations at the component or unit level and focuses more on battles and engagements than long-range-planning [19:6]. Intelligence support to the tactical level of operations "...primarily focus on support to mission planning, targeting and combat assessment" [15:11].

3.6 Types of Intelligence

Imagery Intelligence (IMINT) is collected using "...visual photography, infrared sensors, lasers, electro-optics and radar sensors...where images of objects are reproduced optically on film, electronic display devices or other media" [34:16]. The main types of images produced are called optical and non-optical images. "Optical imagery uses

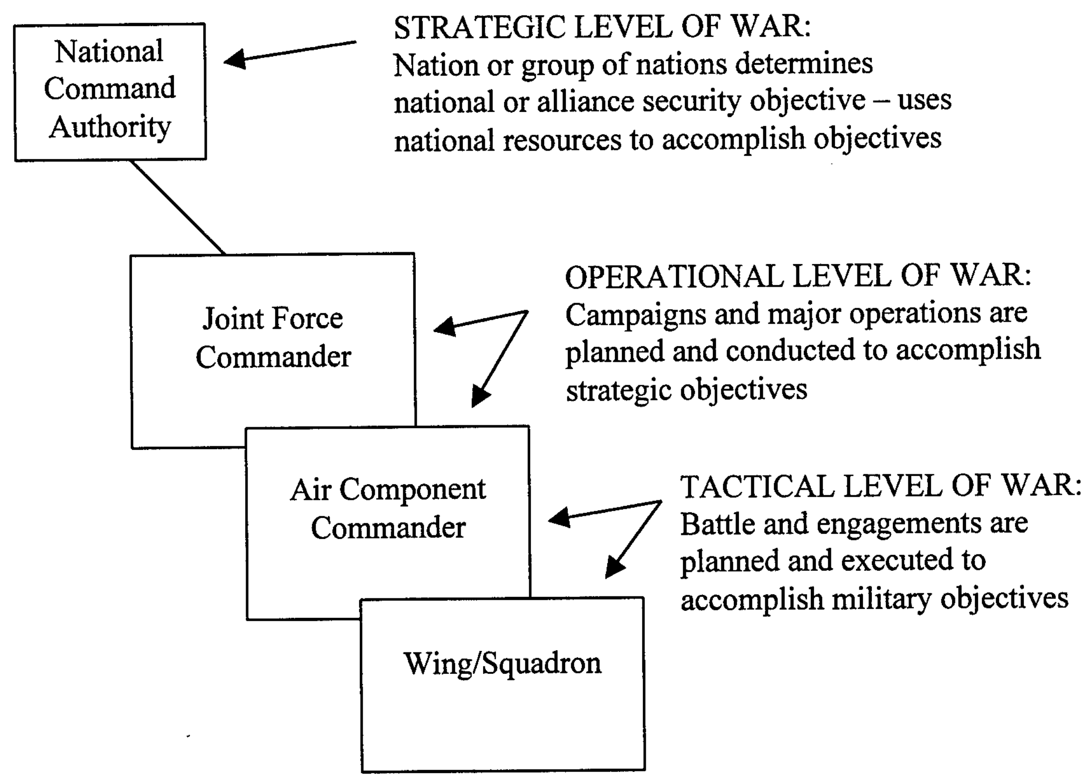


Figure 6. Intelligence Support at all Levels of War [4]

natural illumination in the portion of the spectrum that humans can perceive unaided. Non-optical imagery includes infrared and radar" [15:25]. Weather effects, such as moisture in the air or cloud cover, can inhibit various sensor's ability to collect IMINT.

Signals Intelligence (SIGINT) provides information based on enemy electromagnetic transmissions. SIGINT is categorized into Communications Intelligence (COMINT), and Electronic Intelligence (ELINT). ELINT can be broken down further into Foreign Instrumentation Signals Intelligence (FISINT), Telemetry Intelligence (TELINT), and Radar Intelligence (RADINT). COMINT involves intercepting and monitoring enemy communications. Although COMINT is an excellent source for discovering enemy intentions, among its drawbacks are "...susceptibility to deception, the requirement for linguists, and the requirement to have line of sight with the transmitter for very high frequency and ultra high frequency systems" [34:15]. ELINT involves intercepting and monitoring non-communication emissions, such as radar. As with COMINT, it also "...is susceptible to deception and suffers from a line-of-sight requirement" [34:16]. Within ELINT, FISINT contains the "...technical information derived from the intercept of electromagnetic emissions, such as telemetry, associated with the testing and operational deployment of foreign aerospace, surface, and subsurface systems" [15:26].

Measurement and Signature Intelligence (MASINT) is defined as "The information derived from the exploitation of sensor measurement and signatures…collected by ground, airborne, and space systems, to identify distinctive features of the source, emitter, or sender, such as infrared signatures or unique sound characteristics" [15:26]. MASINT includes a variety of different types. (See Table 2). A disadvantage of MASINT is the extended amount of time needed to produce the MASINT product.

Human Intelligence (HUMINT) is the collection of information by people with first-hand knowledge of an enemy situation. HUMINT can result from many different circumstances. Examples of HUMINT collection may be information collected by Special Forces missions, aircrew debriefings, or enemy prisoners of war.

Open Source Intelligence (OSINT) is information collected through media available to the general public. Foreign newspapers, radio, television, and the internet can provide valuable information on enemy knowledge and consciousness.

Technical Intelligence (TECHINT) is derived from the exploitation of foreign material. "Technical intelligence begins when an individual service member finds something new on the battlefield and takes the proper steps to report it. The item is then exploited at succeedingly higher levels until a countermeasure is produced to neutralize the adversary's technological advantage" [11:GL13].

Counterintelligence (CI) is information gathered to protect against espionage, sabotage, assassinations, or terrorism conducted by or on behalf of foreign governments or foreign persons.

Table 2. Types of Intelligence [11:2.2]

IMINT	Imagery Intelligence
PHOTOINT	Photo Intelligence
SIGINT	Signals Intelligence
COMINT	Communications Intelligence
ELINT	Electronic Intelligence
FISINT	Foreign Instrumentation Signals Intelligence
TELINT	Telemetry Intelligence
RADINT	Radar Intelligence
HUMINT	Human Intelligence
MASINT	Measurement and Signature Intelligence
ACINT	Acoustical Intelligence
OPINT	Optical Intelligence
ELECTRO-	Electro-optical Intelligence
IRINT	Infrared Intelligence
LASINT	Laser Intelligence
NUCINT	Nuclear Intelligence
RINT	Unintentional Radiation Intelligence
OSINT	Open Source Intelligence
TECHINT	Technical Intelligence
CI	Counterintelligence

3.7 Intelligence Community

Many agencies make up what is known as the "Intelligence Community". These agencies are comprised of both military and civilian personnel and are shown in Figure 7. Each element of the community has its own defined function, but the interaction and the cooperation among the individual elements is needed to support the ISR mission.

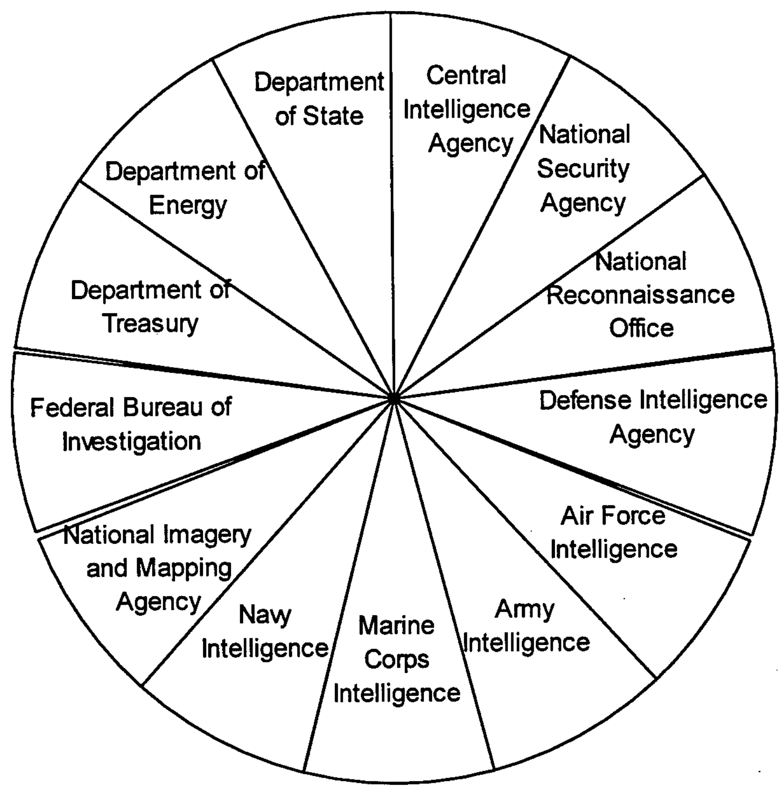


Figure 7. Intelligence Community Membership [13:2.3]

3.8 Communications for ISR Operations

Communication is a cornerstone of any military operation. The ISR process and its success also rest on the ability to communicate. Requesting information, tasking ISR assets, collecting data, and disseminating information, all rely on communication systems to fulfill their purpose. There are a myriad of Command, Control, Communications, Computer, and Intelligence (C4I) systems in existence, and most of them depend upon satellites to relay necessary communications such as voice, fax, message, raw data, imagery, and video. Communication satellites allow intelligence personnel to analyze data from a location hundreds or thousands of miles from the battlefield.

The military depends upon its own communication satellites (MILSATCOM), as well as commercially-leased communication satellites to move the massive amounts of information needed during both peacetime and conflict. In addition to the International Maritime Satellite System (INMARSAT) and the International Telecommunications Satellite (INTELSAT), which are the primary international commercial satellite carriers leased by the DoD [14:7.11-14], there are numerous domestic companies which provide leased communications through geosynchronous satellites. A handful of these communication satellites are summarized below.

3.8.1 Communication Satellites

3.8.1.1 Defense Satellite Communications System (DSCS)

The DSCS-III constellation currently has nine multi-channel Super-High Frequency (SHF) satellites in geosynchronous orbits. DSCS-III can selectively negate jamming directed at it with little impact to its transmission capabilities. It also contains a "...Ultra-High Frequency (UHF) single channel transponder package that serves AFSATCOM users providing increased capabilities in a stressed environment" [14:7.23]. "DSCS provides the backbone for the transmission of high capacity command and control, intelligence and multi-channel communications service" [10:33]. Additionally

DSCS directly supports the Global Command and Control System (GCCS). "DSCS earth stations connect to major voice, data, and message switching centers that rapidly link critical circuits and systems to the Defense Information System Network (DISN) and commercial networks" [10:33].

3.8.1.2 Milstar

Milstar is the next generation military satellite communication system designed to provide survivable, jam-resistant command and control communications for strategic and tactical forces worldwide. The Milstar constellation will consist of four satellites in low inclined near-geosynchronous orbit operating in the Extremely-High Frequency (EHF) band. "An advantage of Milstar over DSCS and UHF satellites is that it has a cross-linking capability that will allow direct transmission of communications from one satellite to another without the intervention of ground relay stations" [14:7.46].

3.8.1.3 NATO Satellite System

The NATO IV system is a single satellite positioned over the Atlantic Ocean, along with 27 satellite ground terminals, 2 control centers, and the NATO school segment at Latina, Italy [37]. The NATO IV satellite has four SHF channel and two UHF channels used "...primarily for diplomatic and military communications and intelligence support to the Commander-in-Chief of NATO and to the National Command Authority of NATO forces" [14:7.47]. The SHF footprint for the NATO IV-A contains Eastern Canada, the Atlantic, parts of North Africa, Europe, and Southeastern Greenland. The UHF footprint contains the Eastern United States, the Atlantic, South America, Africa, and most of Greenland [37].

3.8.1.4 Tracking and Data Relay Satellite System (TDRSS)

The TDRSS constellation consists of a small number of satellites in geosynchronous orbit that support near-real-time data transmission from low-earth orbiting reconnaissance satellites over approximately 85 percent of the earth's surface. "TDRSS offers a useful contingency capability, and the military pays $100M annually to use TDRSS" [14:7.48-49].

3.8.1.5 UHF Follow-On (UHF F/O) Program

The US Navy is deploying a new constellation of UHF satellites to replace their current Fleet Satellite Communications network; these satellites are called UHF F/O, or UFO satellites. The plan is to have eight satellites in orbit, with two on-orbit spares. The first UFO satellite was launched in 1994. These new satellites will "...employ Demand Assigned Multiple Access (DAMA) time division multiplexing techniques to allot capacity to more users. Demand-based assignment means that unused transponder space is dynamically reallocated in real-time based on precedence, greatly improving information throughput" [14:7.53]. The last six satellites to deployed will also carry EHF packages to improve "...anti-jam telemetry, command, broadcast and fleet communications....The EHF modes, formats, and data rates will be subsets of those employed on the MILSTAR system. Satellites 8, 9, 10 will also provide Global Broadcast (Joint Broadcast) Service (GBS)" [14:7.53].

3.8.1.6 International Maritime Satellite System (INMARSAT)

The International Maritime Satellite Organization is headquartered in London, England with 79 member nations. INMARSAT provides voice, message, facsimile and data communications through four satellites in geosynchronous orbit and leased transponders on other communications satellites [14:7.12-13].

3.8.1.7 International Telecommunications Satellite (INTELSAT)

INTELSAT provides telephone, television and data distribution services to people on every continent, and is the world's largest commercial satellite communications provider. [14:7.14].

3.8.2 C4 Architectures

The military employs a variety of Command, Control, Communications, and Computers (C4) architectures as well. A few examples of these relating to ISR include Defense Information Systems Network (DISN), Global Command and Control System (GCCS), and Global Broadcast Service (GBS). These systems are briefly explained below.

3.8.2.1 Defense Information System Network (DISN)

"DISN provides Defense-wide communications for the day-to-day operations of the DoD and services at the core of DoD wartime communications for the National Command Authority (NCA), the Joint Chiefs of Staff, and Commanders-in-Chief (CINC), and other critical users" [10:25]. It is the DoD's worldwide telecommunications network that also incorporates interoperability with allied and coalition forces [42].

3.8.2.2 Global Command and Control System (GCCS)

The Global Command and Control System (GCCS), which replaced the World Wide Military Command and Control System, is a comprehensive worldwide system providing the National Command Authority (NCA), Chairman of the Joint Chiefs of Staff, combatant commanders, Services, Defense Agencies, Joint Task Force commanders and component commanders information processing and dissemination capabilities to conduct Command and Control operations. GCCS has numerous functions including providing situational awareness, readiness assessments, course of action development, imagery exploitation, intelligence mission supports, crisis planning, deliberate planning, operational plan generation, deployment of forces, indications and warning, and real-time combat execution from a C4I perspective [10:47].

3.8.2.3 Global Broadcast Service (GBS)

The Global Broadcast Service system, in development, will be a space-based, high data rate communications link for a one-way flow of intelligence, weather, and other information over a widespread geographic area.

The GBS will be a system of uplink sites, broadcast satellites, receiver terminals, and management processes for requesting and coordinating the distribution of information products. Each GBS satellite in a near-worldwide constellation will be served by a primary uplink site where information products are assembled and transmitted to a high-powered satellite for relay to forces over a large area. GBS will also have the capability to inject products directly from the theater it serves. A big advantage of GBS is that with small receive terminals, mobile forces are no longer restricted by the requirement for large, fixed antennas to receive information formerly available only to command centers [10:43].

"GBS is an extension of the Defense Information Systems Network (DISN) and a part of the overall DoD MILSATCOM Architecture. It will interface with, and augment other major DoD information systems, such as the Global Command and Control System (GCCS), as well as other theater information management systems" [21].

4. Intelligence, Surveillance, Reconnaissance Process during Theater-level Conflict

The Intelligence, Surveillance, Reconnaissance (ISR) process must be coordinated at all levels of command and among all branches of the military, as well as with national agencies. ISR involves many diverse assets that synergistically provide the fullest understanding of the enemy, his capabilities, and his weaknesses. "This understanding directly supports formulating military objectives and strategy, determining planning and conducting military operations, and identifying the adversary's strategic, operational, tactical centers of gravity" [15:3]. This chapter presents the ISR process used to accomplish the purposes of ISR presented in Chapter 3. The overall process, with some lower-level details, is presented to demonstrate the vast amount of operations, coordination, and diversity of elements that must all function together for the process to be successful.

4.1 Process Overview

The ISR process encompasses the methodology of transforming a need for information into a product that fulfills that need. The ISR process entails seven main steps: Plan, Task, Collect, Analyze, Disseminate, Evaluate, and Apply. This process cycles throughout a conflict and, in certain cases, is modified and adapted to the scenario at hand. For example, in some cases, analysis of raw data is not necessary, or even desirable, and therefore that step in the ISR process may be bypassed. Also, it should be realized that data is evaluated throughout the process to ensure sensors are functioning properly, and that the intended information is available. The ISR process is depicted in Figure 8. Each step in the process is explained below.

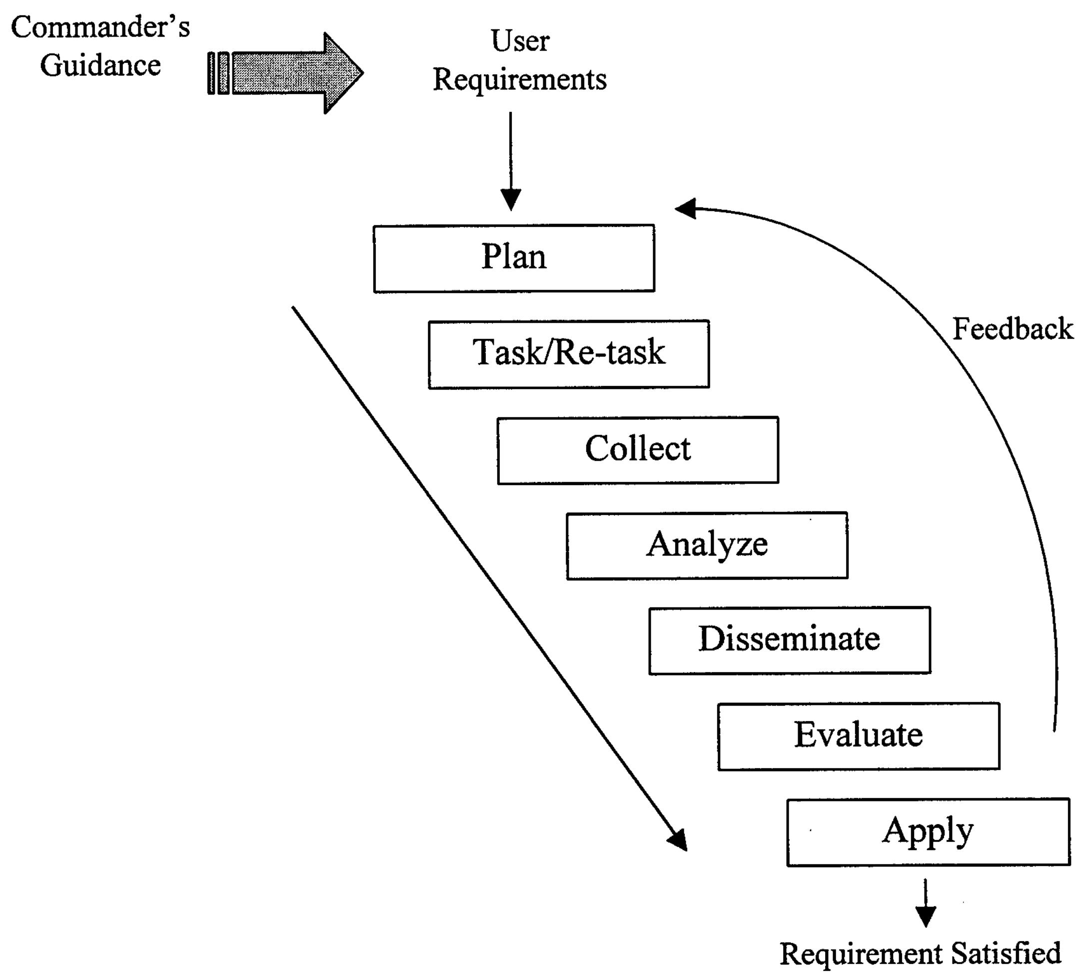


Figure 8. Intelligence, Surveillance, and Reconnaissance Process [15:24]

4.1.1 User Requirement

During the transition from peace to hostilities, the NCA tasks the appropriate CINC in the theater where military operations will occur. The CINC can assume the responsibility of JFC or delegate the authority to a subordinate. "The JFC is the commander of a unified command, subunified command, or Joint Task Force (JTF) authorized to exercise operational authority over a joint force to accomplish an assigned mission. The JFC determines appropriate military objectives and sets priorities for the entire joint force" [17:54].

Subordinate to the Joint Force Commander are the Commanders for the Joint Force Air Component (JFACC), the Joint Force Land Component (JFLCC), the Joint Force Maritime Component (JFMCC), and the Joint Force Special Ops Component (JFSOCC). Each of these Component Commanders translates JFC objectives into military operations. To conduct military operations, Component Commanders require knowledge of the enemy and of the effectiveness of completed missions.

Although intelligence requirements emanate from any level of command, the commander's information requirements are the principal drivers of the intelligence effort. For this study, the JFC is considered the primary user, the one setting requirements for the overall process.

The JFACC is the primary player in requesting intelligence support in this ISR process. The JFACC has the responsibility of overseeing all air and space operations, which form the backbone of intelligence operations. The JFACC "...recommends the proper employment of air and space forces....The JFACC also plans, coordinates, allocates, tasks, executes, and assesses air and space operations to accomplish assigned operational missions" [17:59]. The JFACC is responsible for the production and execution of the daily ATO. A key ingredient in the production of an effective ATO is having timely and accurate intelligence.

Requirements for intelligence tie to past, present, and future operations. For example, the JFACC must know the effectiveness of air strikes to make re-attack decisions; surveillance helps in acquiring targets; and knowledge of enemy air defense sites dictates air strike ingress and egress routes.

All levels of war have slightly differing requirements and uses of intelligence. At the strategic level, campaign planners may need information about enemy intentions and capabilities, available resources, and the geography of the battlefield. At the operational level, enemy doctrine, personalities of enemy commanders, and enemy centers of gravity are of interest. At the tactical level, the number, types, mobility, and equipment of enemy forces are required. Commanders require quantitative items such as the status of a bridge and the number of tanks; however, the commander also needs information on the intangibles, such as how the enemy views his potential courses of action, and which are the most likely to follow.

4.1.2 Planning

Intelligence organizations at the national level, in the combatant commands, and subordinate joint forces all interact and support each other in order to fill JFC requirements. The National Military Joint Intelligence Center (NMJIC), the combatant command intelligence officer (J-2), the Joint Intelligence Center (JIC), the subordinate joint force J-2 and Joint Intelligence Support Element (JISE) are all responsible for providing intelligence support to military operations.

The NMJIC is the national agency that serves as the focal point for all defense intelligence activities in support of joint operations. It also provides a conduit to the entire DoD intelligence community and organization in support of joint operations [11:xi].

At the theater level, the JIC has the primary responsibility for ensuring that combatant commanders and theater forces receive the required intelligence support [28:xi].

At the joint task force level, the JISE is responsible for the collection, analysis, and fusion of intelligence, as well as the dissemination of intelligence and intelligence products for the joint operations area [11:xi].

Requirements must be validated by the combatant command J-2 with the JIC tracking "…the status of research, validation, submission and satisfaction of all collection requests received…" [12:3.15].

After a requirement has been validated, it is determined whether a new collection effort is needed or if the information has already been collected. If a new collection is needed, planning begins to fulfill the requirement. Planning for ISR collection entails prioritizing requests; determining available assets, their capabilities, as well as their vulnerabilities; and considering the time constraints of the request versus the timeliness of an asset's response [15:17]. Planning for intelligence collection is usually done in conjunction with operational planning. Intelligence planning also requires coordinating priorities with national-level and other theater-level agencies, and ensuring communications support, manpower and equipment are available.

The Joint Air Operations Center (JAOC) supports the JFACC in planning theater ISR missions. It "...is the air and space operations planning and execution focal point for the JTF and is where centralized planning, direction, control, and coordination of air and space operations occurs" [17:75]. Since intelligence collection is closely tied to operations, the JAOC must work intimately with the JIC in planning for air and space intelligence collection.

The Joint Staff J-2 Deputy Directorate for Targeting Support, J-2T, is the manager for target intelligence from national systems. The J-2T operates the NMJIC Targeting and Battle Damage Assessment (BDA) Cell, which is the single national-level source of targeting and BDA support to the JCS and combatant commands [13:5.8].

Planning for intelligence collection involves deciding which sensor or system can best fill the requirement. This decision depends on numerous factors. Sensor capabilities are considered in conjunction with the target characteristics and location and the type of intelligence required. An asset's coverage footprint and its time over a target must meet collection requirements. Timeliness is an important factor when deciding which sensor to use; information that arrives too late is of no use. Planners need to think about the availability of resources, the time needed to plan the mission, collect the data, process and analyze the data and disseminate the results. Environmental factors including the threat, terrain, and weather need to be examined. Threats to assets must be identified. A sensor that must fly over a target is more vulnerable than a standoff system; satellite sensors are the least vulnerable assets. Terrain may interfere with sensor capabilities that require line-of-sight. Weather conditions such as cloud cover or rain can inhibit certain sensors' capabilities. Each of these factors must be considered, and weighed against each other, when planning for collection. Figure 9 shows the collection planning factors that need to be considered in sensor or system selection.

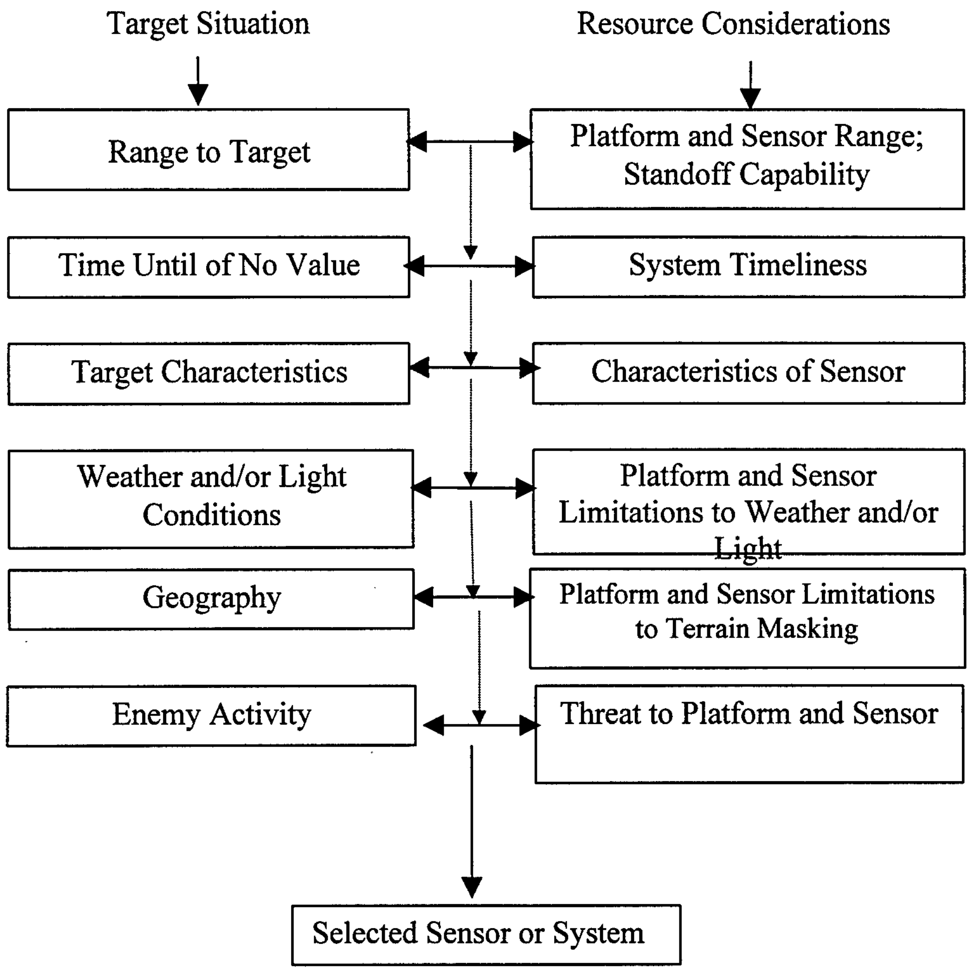


Figure 9. Collection Planning Factors [12:3.17]

Consideration is also given to how many sensors are needed. Redundancy may guarantee the information is obtained, or possibly guarantee more accurate information, but it will be at the cost of tying up limited ISR assets. Collection may need to be coordinated so that cross-cueing between sensors can be used.

Intelligence requirements are filled by a multitude of sensors, platforms, communication systems, dissemination systems, and analysts. Not all products are used in the same way and for the same purpose. Intelligence products can be categorized into many different uses. Some of these categories are indications and warning, near-real-time and real-time situational awareness, intelligence preparation of the battlespace, target intelligence, and battle damage assessment. Planning for ISR activities requires knowledge of the product required as that will have a big impact on the collector, platform, and dissemination system chosen.

4.1.3 Tasking

Tasking converts intelligence requirements into collection requirements. The Combat Plans Division in the JAOC schedules reconnaissance missions for theater ISR assets. The assets are then tasked through the JAOC's dissemination of an ATO directly to the units. National assets and HUMINT collectors are tasked slightly differently. For these collection requirements, the JIC submits the request to the NMJIC for tasking of the national systems and HUMINT collectors. The NMJIC is the focal point for intelligence activities at the national level during crises, and is co-located in the Pentagon with the National Military Command Center. A National Intelligence Support Team (NIST) traditionally deploys to the JTF headquarters to provide an additional conduit to the NMJIC.

National intelligence organizations that support the JFC on a full-time basis include: Central Intelligence Agency (CIA), Defense Intelligence Agency (DIA), National Security Agency (NSA), National Imagery and Mapping Agency (NIMA), and the State Department [13:1.3]. Most of these national agencies have liaison personnel or support teams that are either stationed in theater or deploy to the theater to ease communication and improve efficiency.

The CIA has primary expertise in HUMINT collection, imagery, political and economic intelligence. The Office of Military Affairs within the CIA is the point of contact for the CIA's military support.

The DIA's mission ranges throughout the ISR process, from planning and directing intelligence to carrying out BDA. The DIA's Directorate for Intelligence Operations (DO) oversees collection requirements and operations. "The DO also directs all non-tactical DoD HUMINT activities through the Defense HUMINT Services (DHS), and measurement and signature intelligence (MASINT) activities through the Central MASINT Office. The DHS provides HUMINT resources to support the joint force requirements" [13:6.5].

The NSA "...provides SIGINT and information security (INFOSEC), encompassing communications security (COMSEC) and computer security as well as telecommunications support and operations security (OPSEC)" [13:7.1].

The National Imagery and Mapping Agency's (NIMA) primary mission is to provide imagery intelligence and geospatial information. The NIMA coordinates imagery collection; manages and tasks national assets; provides advisory tasking for theater assets; and processes, exploits, disseminates, and evaluates imagery and IMINT.

The DIA is the overall coordinator for National Reconnaissance Office (NRO) support for DoD. The NRO provides the nation's space-based reconnaissance capabilities through the operation of IMINT and SIGINT satellites. "IMINT requirements are tasked through the NIMA and SIGINT requirements through the NSA" [13:9.2].

Each military service has intelligence activities supporting their individual missions. Examples of some of these organizations are US Army Intelligence and Security Command (INSCOM), National Maritime Intelligence Center (NMIC), National Air Intelligence Center (NAIC), and the US Marine Corps Intelligence Activity (MCIA).

Communicating with the appropriate agency for tasking an asset is an important endeavor that must be understood. However, even after the appropriate sensor/platform has been tasked, it is very possible that new, and possibly higher priority, or more time-sensitive collections must be executed. Some missions may be dynamically re-tasked with little consequence, while re-tasking may be impossible for others. The ability to dynamically re-task assets depends on the situation, the time-sensitivity, the assets and their capabilities, and the trade-offs between the current tasking and the new tasking.

4.1.4 Collection

Collection operations acquire information and provide it to processors and disseminators. Many of the collection planning factors are considered at the time of collection. Weather, vulnerability, threat, capabilities, along with other risks and the overall operational situation, all determine how and when a sensor will make an assigned collection. "For aerial-based systems, the wing or squadron commander normally has the responsibility to accomplish the ISR mission. For ground-based systems, like Special Operations Forces (SOF) or HUMINT, the responsibility lies with the competent authority at the tactical level. The JFACC is the final authority on determining whether the benefits of successfully accomplishing the mission outweigh the risks involved" [15:19].

Many different sensors are involved in ISR collection. There are manned and unmanned systems; airborne, space, and ground systems; military, non-military, and national systems; and technical versus human collection. Each system has particular advantages, disadvantages, capabilities, and limitations. One may be accurate, but slow to provide information, another may be highly survivable, but also highly predictable and therefore more easily deceived. "It is desirable to have sensors cross-cue each other to provide synergism that capitalizes on individual sensor strength. For example, J-STARS was able to cross-cue unmanned aerial vehicles operated by the Marines during Desert Storm. This allowed the Marines to pinpoint Iraqi defenses and monitor troop movements..." [34:50]. The military uses a mix of systems to accomplish ISR operations. Some of the common systems in today's ISR environment are identified below.

4.1.4.1 Airborne systems

4.1.4.1.1 Uninhabited Aerial Vehicles (UAVs)

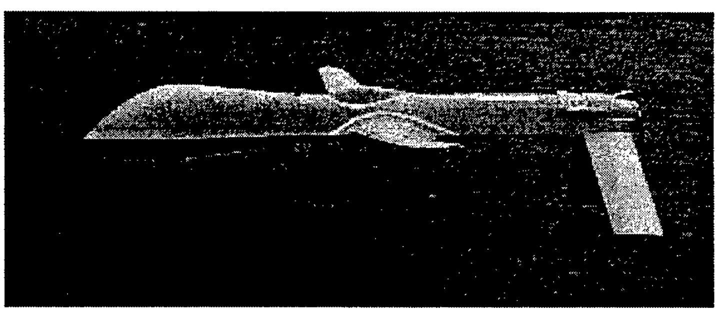


Figure 10. Predator Medium Altitude Endurance (MAE) UAV

The greatest advantage of UAVs is reduced risk to friendly personnel. UAVs have other advantages such as long loiter times and relative cost effectiveness when compared with manned aircraft missions. UAV support can provide near-real-time intelligence and BDA to all military services. Various types of UAVs provide a broad range of capabilities and uses. Tactical UAVs include Pioneer and Hunter, while UAVs with more of a focus on longer ranges and longer dwell times include Predator, Global Hawk, and DarkStar [49]. The main sensors found on UAVs are for SIGINT, Synthetic Aperture Radar (SAR), Electro-optical imagery, multispectral imagery, and real-time video imagery [15:27]. The UAV guidance and control systems are either remotely controlled, preprogrammed, or some combination of both.

4.1.4.1.2 RC-135

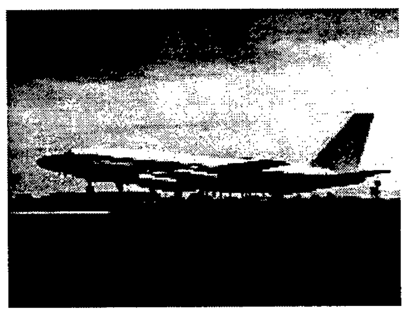


Figure 11. RC-135V/W RIVET JOINT

The RC-135 is an Air Force reconnaissance version of a Boeing 707. The RC-135's are considered national assets, but may be tasked by the theater commander during wartime for tactical roles [34:16]. Various models of the RC-135 such as RC-135 U Combat Sent, RC-135 V/W Rivet Joint, RC-135 X Cobra Eye, and RC-135 Cobra Ball all provide SIGINT, to include COMINT and ELINT, with Cobra Eye and Cobra Ball also providing MASINT [27].

4.1.4.1.3 E-8C J-STARS

Figure 12. E-8C J-STARS

The E-8C Joint Surveillance Target Attack Radar System (J-STARS) is a modified Boeing 707 with a primary mission of air-to-ground surveillance. An Army and Air Force multi-service system, J-STARS is used to locate, identify, and track ground targets – both fixed and mobile – in near-real-time. It primarily focuses on non-emitting targets making radar imagery intelligence its principal product [34:18]. J-STARS has a long loiter time and a long range and can look deep into enemy territory to detect and track ground movement in both forward and rear areas. It reports enemy location, size, direction, rate of movement, and type of target [10].

J-STARS uses a phased array radar for collection with a range of over 150 miles [30]. Comprehensive communications allow J-STARS to provide voice and data transmissions to a variety of platforms, weapons system, and ground modules. Satellite communications allow J-STARS to pass information to users not in its line-of-sight.

4.1.4.1.4 U-2

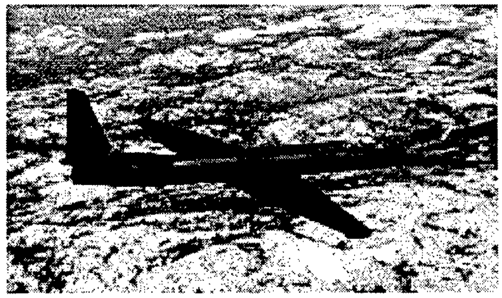


Figure 13. U-2

The U-2 is a high-altitude reconnaissance aircraft capable of gathering multi-sensor photo, electro-optic, infrared and radar imagery, as well as electronic intelligence [48]. The U-2 has proven to be a very reliable aircraft with high mission completion rates. Although it is not air-refuelable, it can fly for more than twelve hours, if necessary. The U-2 has a long standoff range and can down-link saved or near-real-time imagery to ground stations via line-of-sight transmissions [46].

4.1.4.1.5 EH-60L Quick Fix

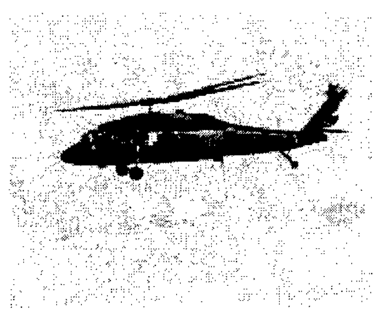


Figure 14. EH-60L Quickfix

The EH-60L is an Army tactical helicopter that provides SIGINT and electronic countermeasures (ECM) support to Army units. The data downlinked in near-real-time provides targeting information. System information provides input for the tasking and mission direction of other assets [40].

4.1.4.1.6 E-3 Sentry Airborne Warning & Control System (AWACS)

Figure 15. E-3 Sentry

The E-3 Sentry, AWACS, is a modified Boeing 707/320 commercial airframe with a rotating radar dome. It provides all-weather surveillance, command, control and communications to U.S. and NATO forces and has proven to be the "...premier air battle command and control aircraft in the world today" [20]. The radar has a range of more than 200 miles for low-flying targets and a significantly greater range for aircraft flying at medium or high altitudes. The E-3 also has navigation, communications, and data processing capabilities. Console operators view data in graphic or tabular formats to perform "...surveillance, identification, weapons control, battle management and communications functions" [20].

The E-3 systems gather detailed battlefield information such as position and tracking of enemy aircraft and ships, and the location and status of friendly aircraft and ships. "The information can be sent to major command and control centers in rear areas or aboard ships. In time of crisis, this data can be forwarded to the National Command Authority in the United States" [20].

The E-3 supports air-to-ground operations by providing information for interdiction, reconnaissance, airlift, and close-air support. For air defense, the E-3 can detect, identify, and track enemy forces and direct fighter-interceptor aircraft to enemy targets [32].

4.1.4.1.7 RC-12 Guardrail Common Sensor

Figure 16. RC-12Q GUARDRAIL COMMON SENSOR

The Army's Guardrail system supports the tactical commanders by providing near-real-time SIGINT and targeting information for deep battle and follow-on forces attack support. The Guardrail collects radio signals from selected low, mid and high bands in order to identify/classify the signals, determine source locations, and provide near-real-time reports to the commanders [24].

4.1.4.2 Space-based Systems

Satellite systems are an integral part of ISR operations. Satellites provide nearly worldwide coverage, and are fairly immune to enemy actions (at least for now). However, coverage is extremely predictable, and therefore susceptible to deception.

Weather effects also hinder some systems. Space assets provide a variety of ISR products including indications and warning of ballistic missile launches, weather and terrain information, imagery, and signals intelligence. Many of the national systems used are classified in name and capability. Two unclassified sensors are described below.

4.1.4.2.1 Defense Support Program (DSP)

The DSP satellites provide the nation's current space-based early warning system. DSP satellites detect ballistic missile launches around the world. They have the capability to detect short-range missiles, such Scuds, as well as the longer-range Intercontinental Ballistic Missiles (ICBM). The DSP system consists of the satellites, the ground processing stations, and the communication system. Although the communication of Scud launch detections to the Patriot batteries functioned well during Desert Storm, significant improvements in communications have made the DSP reports even more timely. Early warning capabilities will continue to be enhanced with new systems being developed such as the Space-Based Infrared Satellite (SBIRS) and Space-Based Radar.

4.1.4.2.2 SPOT Satellite System

The SPOT satellite Earth Observation System was designed by the CNES (Centre National d'Etudes Spatiales), France, and developed with the participation of Sweden and Belgium. The system comprises a series of satellites in circular, sun-synchronous orbits along with ground facilities for satellite control and programming, image production and distribution [44].

4.1.4.3 Ground-based systems

Some ground-based systems, such as those of the theater air control system (TACS) are not tasked as ISR assets, but do provide surveillance as a by-product of their primary mission. One ground-based ISR resource is the Space Surveillance Network which tracks and catalogs all manmade objects in space. The Ballistic Missile Early Warning System is a ground-based system of radars to detect strategic missile launches. HUMINT is gathered by people such as Special Operations Forces doing a reconnaissance mission, aircrews, dedicated HUMINT personnel, or prisoners. Below are three examples of the systems used in ground-based collection.

4.1.4.3.1 Counterintelligence/Human Intelligence Automated Tool Set

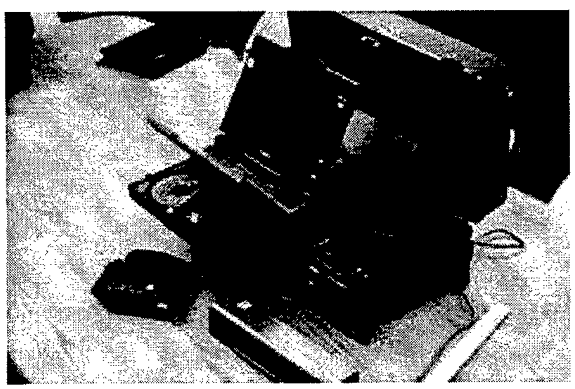


Figure 17. CHATS

The Counterintelligence /Human Intelligence (CI/HUMINT) Automated Tool Set (CHATS) can be operated up to the SECRET level. It provides CI/HUMINT teams in the field the capability to "...manage assets and analyze information collected through investigations, interrogations, collection, and document exploitation. With CHATS, CI units may electronically store collected information in a local database, associate information with digital photography, and transmit/receive information over existing military and civilian communications" [8].

4.1.4.3.2 Ground Based Common Sensor (GBCS)

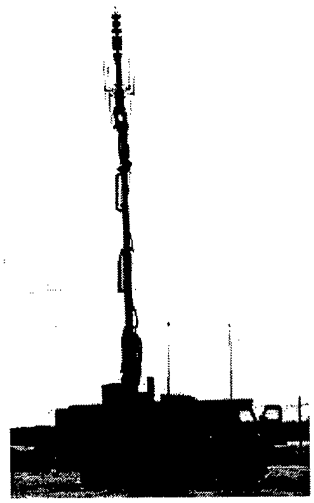


Figure 18. GBCS-H

"Ground-Based Common Sensor (GBCS Heavy and Light) GBCS is the Army's only on-the-ground, all-weather, all-terrain, self-contained, fully integrated, 24-hour signal intelligence and electronic warfare asset. The Electronic Attack (EA) module includes smart jamming capabilities. The GBCS preprocesses signal data at the sensor and provides target detection, identification, and location reports in near-real-time" [23].

4.1.4.4 Sea-based systems

Dedicated intelligence units, along with assets that have other primary functions, such as a destroyer at sea sending a surface contact report, conduct naval intelligence. In fact, naval forces are unique in that intelligence collection capabilities are resident in many of their weapons platforms. At the tactical and operational levels of warfare, intelligence collection is just one more capability of ships, submarines and aircraft [19:5].

For years the attack submarine has performed various ISR roles, and in the future Autonomous Underwater Vehicles (AUV) or drones may also be used to venture into areas unsafe for a submarine. These AUVs would be launched, travel into the area, perform the assigned mission, and then return to the submarine or transmit its data to a satellite [45].

4.1.5 Analyze

After data has been collected, it is processed and then analyzed. Some sensors have "on-board" processing capabilities, while others must send the raw data to a production center. Processing involves converting information into a format usable by intelligence personnel. After processing, the data is analyzed either at the production center or an intelligence center. Through analysis and fusion, information is then integrated into the battlefield picture. Fusion is the result of comparing and combining data from various collectors along with previous analysis to provide an integrated, hopefully more accurate, understanding of the true state of the object of collection. Analysis involves human thinking and determination in deciding which information is most correct and useful in determining the final conclusion. Knowledge of the enemy, professional experience, and judgment affect an analyst's ability to interpret and decipher the significance of new information, and determine its integration with previous intelligence. When trying to "fuse" data, analysts consider the means in which the data was collected, and its associated reliability and capability. They also factor in the time since the data was collected. Integrating new data with other sensor information and previous data is somewhat subjective to the experience level of the analyst. The level of work and the time allotted to arrive at a conclusion also impacts the ability of analysts to accurately fuse the data. Almost all data is fused and analyzed before being disseminated to the appropriate agencies. However, as stated before, some data can be processed and distributed in near-real-time from ISR assets directly to the users bypassing the analysis and fusion procedure. This "short-cut" intelligence process supports the "Sensor-to-Shooter" concept so that perishable data can be used right away in circumstances such as locating and killing an intruding aircraft [15:19]. This type of intelligence is useful at the tactical level, although most operational and strategic intelligence is most useful and reliable after being analyzed and fused. The resulting products from analysis are reports concerning items such as enemy capabilities, resources, and activities. BDA is a critical output of analysis heavily impacting target development and target nomination procedures.

Various forms of intelligence are processed differently and by different agencies. For example, HUMINT/CI information processing primarily involves report preparation by personnel within the J-2X. "Further processing human resource reporting is conducted by the JIC and joint force analytical and/or production activities; this primarily involves analyzing HUMINT/CI reporting for inclusion in all-source production and/or for data base maintenance" [12:3.26].

The JIC processes and exploits imagery in theater. The JIC can process the digital signal and display it on a workstation in softcopy form. The images can then be incorporated into an all-source product to aid in determining the status of a target or other item of interest. The images can also be used to update intelligence databases.

"COMINT processing is accomplished by NSA/CSS elements either assigned to or in support of the joint force mission. ELINT processing in support of a joint force may come from a number of sources including assets attached to the joint force, national ELINT centers, the JC2WC, and combatant command JICs" [12:3.28].

MASINT tends to be a processing-intensive collection discipline. The Central MASINT Office and Service intelligence centers process MASINT [12:3.28].

4.1.5.1 Processing and analysis systems

Processing and analysis can be made easier through the use of computers and computer systems. Some of the systems used by intelligence personnel are summarized below.

4.1.5.1.1 Joint Service Imagery Processing System (JSIPS)

JSIPS is a joint program developed by the USAF, US Navy (USN), and US Marine Corps (USMC) to provide a common ground station "...capable of receiving, processing, exploiting, and disseminating imagery intelligence products collected by national, theater, and selected tactical reconnaissance assets" [31].

4.1.5.1.2 Enemy Situation Correlation Element (ENSCE)

The Army and Air Force are developing better ways to coordinate the efficient use of surveillance/reconnaissance systems and selection of second-echelon targets through the use of automated intelligence fusion centers. "The Army All-Source Analysis System (ASAS) and the Air Force Enemy Situation Correlation Element (ENSCE) speed the fusion and correlation of intelligence sources and provide a common view of the battlefield. The ASAS/ENSCE system will be an all-source system, receiving inputs from tactical Army collection systems (such as Guardrail and Quicklook), J-STARS, and ATARS, and national intelligence sensors" [34:22].

4.1.5.1.3 Sentinel Byte

JSIPS and ENSCE only provide intelligence to the headquarters level. To transfer this all-source intelligence to the users at the wing and squadron level, the Air Force is deploying the Sentinel Byte system. "Sentinel Byte is an interactive intelligence system for passing intelligence, targeting, and battle damage assessment information up and down the chain of command within the tactical air control system" [34:23].

4.1.5.1.4 Constant Source

"Constant Source is a broadcast system designed to provide timely intelligence to combat units and elements of the tactical air control system at the secret or higher level" [34:24]. Constant Source integrates and correlates information received from the Navy's Tactical Receive Equipment and Related Applications (TRAP) and the Tactical Data Information Exchange System -Broadcast (TADIX-B) including data from national systems [7].

Constant Source correlates reports and compares new information with already existing, or known, information. It updates "...data bases, refines emitter locations, and identifies moving targets and movements of known sites" [34:24].

Constant Source can also filter data according to the user's desires. The display can provide color graphics of correlated tracks overlaid on a map. An alarm is used to alert the user to high-interest events, and the user may watch events in near-real-time as well as review past events.

4.1.6 Dissemination

The joint intelligence architecture allows collectors, producers, and users of intelligence to be interconnected and share information. Interoperable systems link intelligence agencies at all levels – theater JICs, JISEs, Service intelligence, and national organizations.

Information is only useful if those who require it actually receive it. Dissemination is the distribution of intelligence to users in a suitable form. It is a critical step as timely dissemination of information is necessary for optimal decision-making. Decisions can only be based upon previous knowledge and relevant new information that has been received. If new information does not arrive in time to provide a better understanding of the current situation, decisions must be made somewhat in ignorance. This can cost money, resources, and human lives.

Dissemination comes is a variety of forms and includes physical transfer of information, digital and analog media, video-teleconference, telephone, FAX machine, remote access to data bases, radio, satellite broadcasts, *etc.* However, the aim of dissemination is not to overwhelm the user with massive amounts of data. The concept for dissemination today is a push/pull methodology that emphasizes pushing intelligence to the warfighter (through over-the-air updates) and allows the warrior to pull information on demand [11:2.7]. Dissemination should provide an optimum, rather than a maximum, amount of information.

The Defense Intelligence Dissemination System (DIDS) manages the push concept. Before "pushing" information, the producer queries the DIDS. The pull concept involves accessing information through databases, files, or other means used by intelligence organizations. "Pull" products are available through a number of ways, including INTELINK and the GBS.

While hardcopy distribution of intelligence is possible, with new technology and the need to improve timeliness, most intelligence products are disseminated in electronic form. Some of the communication tools used to share information are Joint Worldwide Intelligence Communications System (JWICS), Joint Deployable Intelligence Support System (JDISS), DoD Intelligence Information System (DoDIIS), Open Source Information System (OSIS), Global Command and Control System (GCCS), INTELINK, and GBS [12:3.43]. "The joint intelligence architecture uses JWICS and JDISS as the joint standard and foundation for commonality among support systems" [11:7.5]. The GCCS and GBS were presented earlier in this report; the rest of the tools are summarized below.

4.1.6.1 Department of Defense Intelligence Information System (DODIIS)

DODIIS comprises the worldwide inter-computer network linking Intelligence Data Handling Systems (IDHS). It encompasses the intelligence storage and retrieval devices (IDHS), the transmission means (JWICS) and the interface (JDISS or other computer interface systems).

DODIIS provides input processing for a variety of intelligence products, including "...imagery exploitation, ELINT, COMINT and HUMINT, as well as, intelligence data development, target material production, target data development and scientific and technical intelligence" [14:7.34-35].

4.1.6.2 Joint Deployable Intelligence Support System (JDISS)

The JDISS allows for connectivity and interoperability with the intelligence systems at the headquarters level as well as the deployed units. JDISS has evolved into a widely accepted intelligence workstation standard and is the "...technical baseline for the

DoDIIS client/server environment" [29]. It provides the JIC, JTF and operational commanders with on-site automation support such as transmitting and receiving specific requests for intelligence, accessing databases, supporting digitized imagery exchange, and performing multi-media functions such as electronic publishing and video teleconferencing. "Based on a SunSparc workstation with an open systems architecture, JDISS is equipped with a core set of software applications that give the intelligence analyst access to a large number of intelligence databases...as well as the ability to perform independent multi-disciplined intelligence analysis in the field" [14:7.32].

4.1.6.3 Joint Worldwide Intelligence Communications System

JWICS is the SCI portion of DISN. Owned and operated by DIA, it provides DODIIS users a SCI-level high-speed multimedia network using high-capacity communications to handle data, voice, imagery, and graphics. The system uses JDISS as its primary means of operator interface and display. "In addition to being a communications system, JWICS provides secure, interactive video teleconferencing to the members of the DoD Indications and Warning system at Unified Commands and service headquarters within the US and overseas. This system enables Indications and Warning centers to share information with other watch centers throughout DoD" [14:7.36-37]. It is used to broadcast daily and /or crisis intelligence briefings from any one site to one or more sites [10:69].

4.1.6.4 Open Source Information System (OSIS)

The Open Source Information System (OSIS) consists of an unclassified group of systems serving the intelligence community with open source intelligence. Community Open Source Program Office (COSPO) supports all aspects of open source information systems, spanning collection, processing, analysis, and dissemination, to include network and distributed computing resources. The contents of OSIS includes the Central Information Reference and Control Database of over 10 million titles on scientific and technical topics, including patents, standards, military equipment and systems; Conference Database of upcoming symposia, congresses, and conventions in the areas of science, technology, engineering, politics, and economics; Digital Terrain Elevation Data map collection (from NIMA) providing global coverage; Foreign Broadcast Information Service products including the Daily Reports, Science & Technology Perspectives, Trends, and Pacific Rim Economic Review; abstracts and complete articles on telecommunications related topics; and Technical Equipment List indexes with over 100,000 brochures and manuals on telecommunications and related equipment [38].

4.1.6.5 INTELINK

"Intelink, which began testbed operation in 1994, is both an architectural framework and an integrated intelligence dissemination and collaboration service providing uniform methods for exchanging intelligence among intelligence providers and users" [26]. Patterned after the Internet, Intelink provides a global network to allow the sharing of documents and other resources among numerous intelligence agencies (*e.g.* FBI, CIA, DEA, NSA, NRO).

4.1.7 Evaluate

After receiving the intelligence, the user evaluates it to ensure it satisfies the requirement. A requirement is most often considered satisfied if the "...intelligence provided to the requestor is complete, timely, and in a usable format" [12:3.2]. If the intelligence is satisfactory, the user may provide feedback to ensure that the ISR process continues to fulfill the user's requirements. If, after evaluation, the user is not satisfied, the user must convey the dissatisfaction, and part, or all, of the ISR process may have to be re-accomplished. Dissatisfaction can result from the information being not what was asked for, not to the degree of resolution needed, or not timely enough to be of use.

Air Force Instruction 14-201 [16:12] gives an example Requirement Satisfaction report providing areas for evaluation and a rating scale as seen in Table 3.

Table 3. Requirement Satisfaction

Areas for Evaluation	Rating Values (scale from 0-6)
1. Timeliness	0. Totally unacceptable
2. Objectivity	1. Poor
3. Usability	2. Marginal
4. Readiness	3. Fair
5. Completeness	4. Good
6. Accuracy	5. Excellent
7. Relevance	6. Outstanding

4.1.8 Apply

Upon satisfaction of the intelligence received, the final step in the ISR process is the application of the product. Application can come in many different forms. For near-real-time collection, intelligence can be applied by a pilot to re-strike a target. Situation displays providing information to a variety of users can be updated to inform them of enemy locations. Briefings to decision-makers may also be the result of an ISR product. Each requirement has its own application, and the ISR product must meet the needs of the user to ensure application is viable.

4.2 Summary

The ISR process is a continual, somewhat complicated cycle, vital to military success. Many organizations, assets, and personnel are involved in making the process run smoothly and efficiently. The coordination and communication needed among ISR personnel, warfighters, and decision-makers is essential to ensure the optimal level of information is provided and is useable. ISR operations will only continue to increase in importance as information, and information superiority, become more critical elements in conducting war.

5. THUNDER Intelligence, Surveillance, and Reconnaissance Methodology

5.1 Introduction

Intelligence, Surveillance, and Reconnaissance is a fairly recent addition to the THUNDER model. Previous chapters have covered the actual ISR process. This chapter will demonstrate how THUNDER has implemented ISR in order to capture this process. THUNDER represents ISR effects using parameters such as processing time, probability of coverage, and perception, along with modeling various ISR resources such as satellites, airborne assets, and ground based assets. The THUNDER ISR module is designed to capture the effects of "...information collection on air planning, sensor and target performance attributes, requirement for and value of Battle Damage Assessment (BDA), and processing delay and timeliness of information" [54].

5.2 Levels of ISR

THUNDER has three levels of ISR resolution: Low, High and Very High. The user specifies each side's ISR level. The names used for the levels of resolution can be slightly misleading, as they do not in any way indicate the quality of ISR provided. Low resolution is equivalent to "perfect" intelligence. Essentially, Low resolution does not show the uncertainty of ISR effects since the side has perfect knowledge of the enemy. In High and Very High resolutions, decisions are based on perceptions of the truth. The quality of these perceptions may degrade over time until new observations are made.

The main distinction between High and Very High is in the detail of the perceptions generated. High resolution maintains perceptions on the enemy's zone/sector areas, while Very High maintains perceptions on specific enemy targets. High resolution intelligence comes from aircraft assets while Very High intelligence also involves satellites and scripted observations. Scripted observations may represent any intelligence source desired by the user, such as army ground sensors or HUMINT. The most realistic scenario entails using Very High resolution, and thus, this study only examines and explains Very High ISR methodology.

Two THUNDER ISR terms need differentiating: perception and confidence. A simple example illustrates what these terms mean. When a sensor makes an observation, a random draw is made for the perception of a target. A confidence level is given by a user-input default value. The confidence level of a sensor inversely affects the variability of the perception – the higher the confidence, the less variability from the truth. If a target has 10 tanks, the random draw may cause the sensor to only perceive 7 tanks. However, the confidence may be 90% that there are 7 tanks. As time goes on, the confidence that there are 7 tanks may degrade to, say, 80%. When planning for air-to-ground strikes, the ATO generator selects sortie allocation and aircraft/munition configuration by using the highest confidence level for each target attribute among all sensor observations of the target. A small example of how this works is seen in Table 4. This methodology is an attempt at fusing data from more than one source of information. THUNDER uses the data with the highest confidence, even though this perceived data may, in fact, be incorrect.

Table 4. Example of "Fusing" Sensor Reports

Sensor	Target Attribute	Report	Confidence
"A"	Number of tanks	10	90%
"B"	Number of tanks	20	80%
"A"	Velocity	5	75%
"B"	Velocity	15	85%
Used for Planning	Number of tanks	10	
Used for Planning	Velocity	15	

5.3 ISR Sensors/Platforms

ISR sensors and their capabilities are defined and differentiated through input data parameters. The parameters that identify each type of sensor include:

- Real-time or batch sensor delivery. As expected, Real-time indicates that the sensor can pass intelligence data over a communications link in a real-time manner. Batch delivery represents sensors that do not disseminate data in a real-time manner and therefore must physically "deliver" the data before processing can begin.

- Processing time. Time to process and analyze raw data is represented by a probability distribution.

- Night Capable. Indicates if the sensor is able to gather information at night.

- Min/Max Sensor Range. Denotes the observation range limitation of the sensor. Not used for standoff reconnaissance missions.

- Two Sigma Target Location Error. The sensor will report the location of a target with this random error.

- Maximum Number of Targets Per Sorties/Pass. The sensor will observe a maximum number of the highest priority targets during a pass.

- Sensor Type (Grid or FLOT). This parameter only has significance for scripted events. A sensor denoted as "Grid" will only look in the specified Grid locations; the ISR Grid is defined by the user. A "FLOT" sensor will scan along the FLOT (Forward Line of Own Troops) given its min/max range.

- Overfly the Target. Denotes whether the sensor must overfly the target in order to make an observation.

- Observe Through Clouds. Indicates whether cloud coverage will inhibit the sensor's ability to gather information on a target.

- Standoff Range. Distance from the target in which a standoff reconnaissance sensor can make an observation. Only used for standoff sensors.

- Perception Update Interval. Time between observations for a sensor hovering over an area or site of interest.

Any aircraft, satellite, or scripted event identified as having an ISR sensor may collect intelligence data. Aircraft assets typically modeled in THUNDER include J-STARS, AWACS, U-2, and UAV. Any flight group carrying appropriate sensors may conduct BDA upon execution of an air-to-ground attack. Satellites are described by orbital parameters that determine when the satellite will be in coverage and the range of that coverage. Scripted events are usually identified as either Grid or FLOT sensor events and given a probability distribution to generate times between observations. Grid sensor events are defined as observations made in certain grid cells of the ISR grid. FLOT sensor events are observations made within the maximum range of the sensor, along the FLOT. Aircraft can carry only one ISR sensor whereas satellites or scripted events may be defined as having more than one sensor. Figure 19 shows the various types of intelligence platforms that can be used in THUNDER and a sample coverage area each provides.

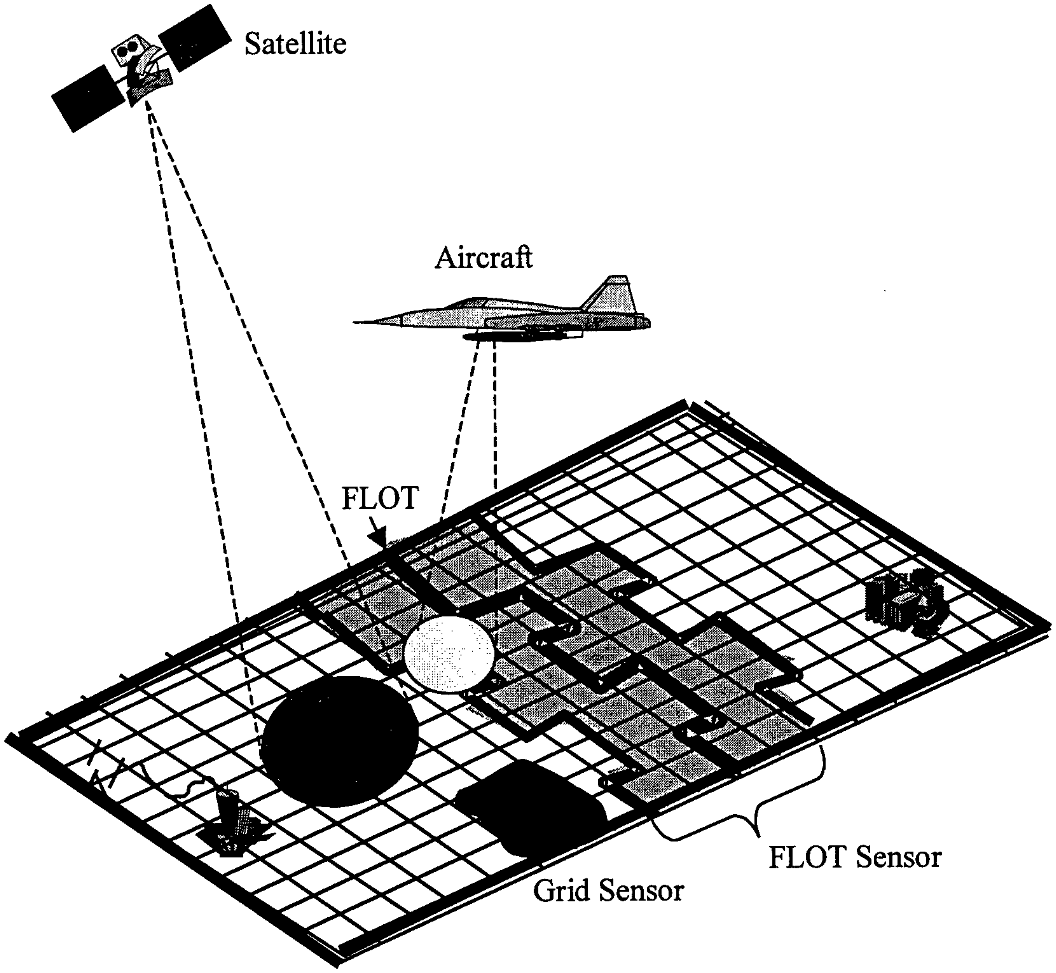


Figure 19. THUNDER ISR Platforms

5.4 Target Classes

THUNDER groups the targets in a scenario in three different ways for ISR: ISR target classes, planning classes, and perception classes.

Air-to-ground targets are given an ISR target class which categorizes that target according to characteristics such as whether it is fixed, mobile, engaged, moving, *etc.* Each class has a "Time vs. Probability of Movement Curve" and a "Time vs. 2-Sigma Location Latency Error Curve." These curves impact whether or not a flight group acquires a ground target. Recall, when a sensor observes a target, it already has a 2-sigma location error. When a flight group reaches the target area, whether or not the flight group acquires the target depends on the time since the last observation and curves defined for the ISR class containing the target. For example, when a sensor gathers data about a mobile target, it reports a location that has a random error, defined by the sensor, attached to it. When the flight group reaches the target area, the location it goes to has an additional error, defined by the target class, since the target has probably moved. See Figure 20 for graphical depiction.

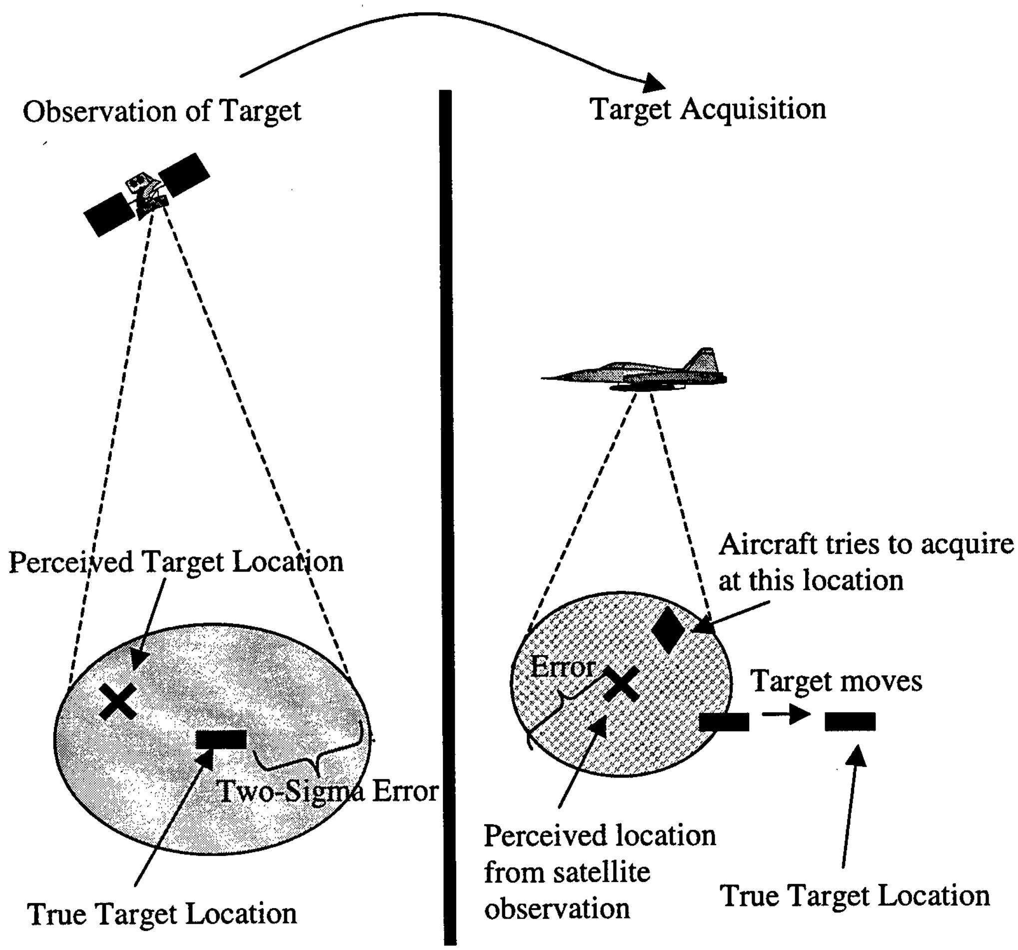


Figure 20. Impact of ISR Sensor Target Location Error on Target Acquisition

Standard targets are also assigned a planning class. Planning classes allow the user to impact how targets are prioritized for reconnaissance missions as well as influence nomination rules for air-to-ground attack. Figure 21 shows the process of prioritizing targets for collection. Targets that are assigned to a particular planning class have the following similar parameters for target prioritization.

- Options if BDA has not been accomplished for the target: 1) assume the target is still live and therefore use the previous perception, 2) assume the target has been damaged and use a degrade (multiplier also defined for each class), or 3) assume the target is dead and do not nominate for air-to-ground attack.

- Distinct priority multipliers for reconnaissance target nomination given that the target has been nominated for air-to-ground attack, has not been nominated, and has not been observed since it was last attacked.

- Minimum priority that the target can be assigned when planning for reconnaissance/surveillance missions.

- Confidence level curve that defines the reconnaissance priority multiplier as a function of the confidence level for the target. For example, one may want to ensure that we always have 80% for a target, and therefore, if the confidence is lower than 80%, the priority multiplier will increase the target's priority for a reconnaissance mission.

Targets are also assigned to an ISR perception class. This defines the probabilities that a live target is perceived as live. The perception class also defines default values for the confidence levels when an observation is made of the target, as well as the confidence degradation curve as a function of time since the observation. The Probability of Coverage is also defined in this class. The probability of coverage can be used to represent deception techniques such as targets being camouflaged.

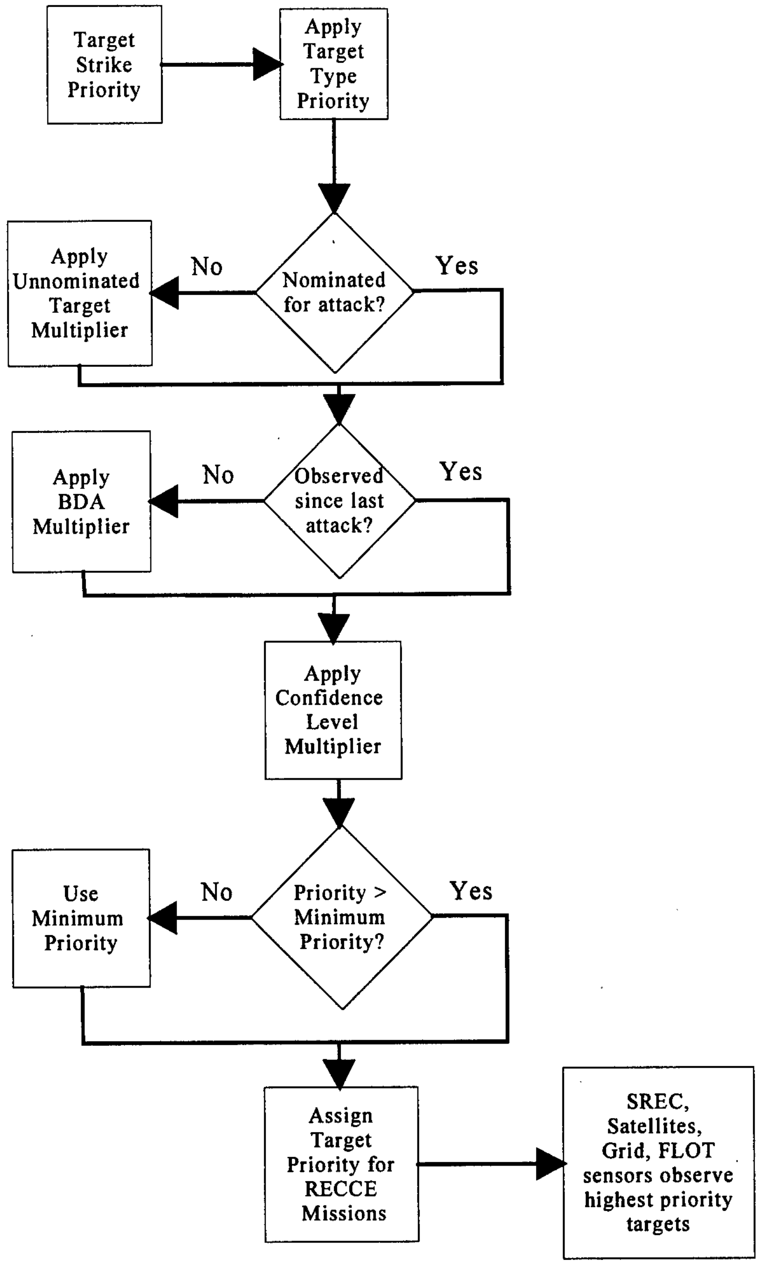


Figure 21. THUNDER ISR Target Prioritization

5.5 Intelligence Collection

Only aircraft reconnaissance (RECCE) and standoff reconnaissance (SREC) missions are automated in the intelligence collection process. The user must preplan any other type of collection, such as satellite observations or scripted observations. A satellite is assumed to always collect observations when the theater is in its view. Likewise, anything scripted by the user is collected during the scripted times.

A target's priority for a reconnaissance mission is based upon its priority for strike missions. The strike priority is adjusted using the multipliers in the planning class (see "Target Classes" above) to determine its reconnaissance priority. Reconnaissance missions are planned just as strike missions are planned.

Reconnaissance can also be obtained during an air-to-ground attack with aircraft carrying the appropriate sensors, representing either electronic or human reports. Figure 22 shows the collection process.

5.6 ISR Nodes

ISR nodes are entities in the ISR process that can affect the processing time of an observation, *e.g.* a communications center. The ISR sensors are grouped into sensor classes, and the sensors in a particular class share the same processing delay if ISR nodes are no longer functioning. They also specify the probability of an observation being lost if ISR nodes are damaged/destroyed. An example of a sensor's processing rules is shown in Figure 23. The Rule Sequence checks the status of the ISR Node, Blue_Comm_Center. If all of the Blue_Comm_Centers have been destroyed, the processing delay of the observation increases, and a probability that the observation is lost is also implemented. The processing delay can be adjusted, however, if a Blue AWACS is still live. The whole ISR observation process is depicted in Figure 24.

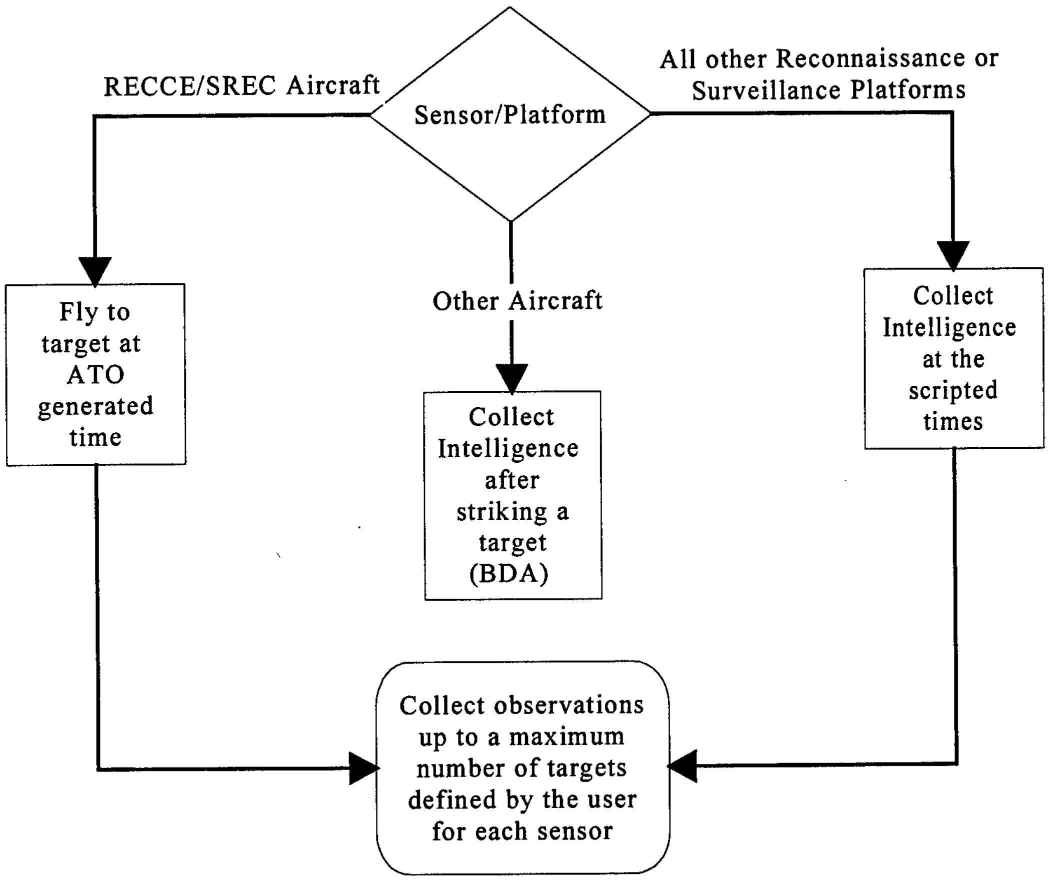


Figure 22. Intelligence Collection

```
@Grid and Flot Sensors
   10001
      BLUE
         BEGIN.ISR.PROCESSING.RULE.SEQUENCE
            IF COUNT(Blue_Comm_Center) = 0
            THEN
               LET PROCESSING.DELAY = 2.0 * PROCESSING.DELAY
               LET PROB.LOST.OBSERVATION = 0.25
            ENDIF
            IF COUNT(Blue_AWACS) > 0
            THEN
               LET PROCESSING.DELAY = PROCESSING.DELAY - 0.25
            ENDIF
            EXIT
    END.ISR.PROCESSING.RULE.SEQUENCE
```

Figure 23. ISR Processing Rules Example

5.7 Target Perceptions

ISR is used in THUNDER to generate perceptions of true target attributes. These perceptions affect mission planning and mission effectiveness.

> At the time of each sensor observation, random draws are made to generate a specific target perception with specific levels of confidence for each of the target attributes (size, location, velocity, *etc.*). The confidence levels for that observation are then degraded with the passage of time. At any point in time, the ISR view of a target will consist of a vector of target attribute perceptions built by 'fusing' the observations from reporting sensors. Fusion is modeled by taking, for each attribute, the highest degraded confidence level across sensors and using that confidence level to represent the level of perception [51:135].

Each time a sensor makes another observation on a target, its old perception is discarded.

The perceived status of each target includes the following parameters:

- Tons of supplies;
- Force ratio;
- Unit strength;
- Message processing capability;
- Number of spares;
- Numbers of aircraft (by type) at an airbase;
- Usable runway length;
- Locations;
- Velocities;
- Arc throughput;
- Air defense site status;
- Transshipment capacity;
- Logistics facility issue capacity;

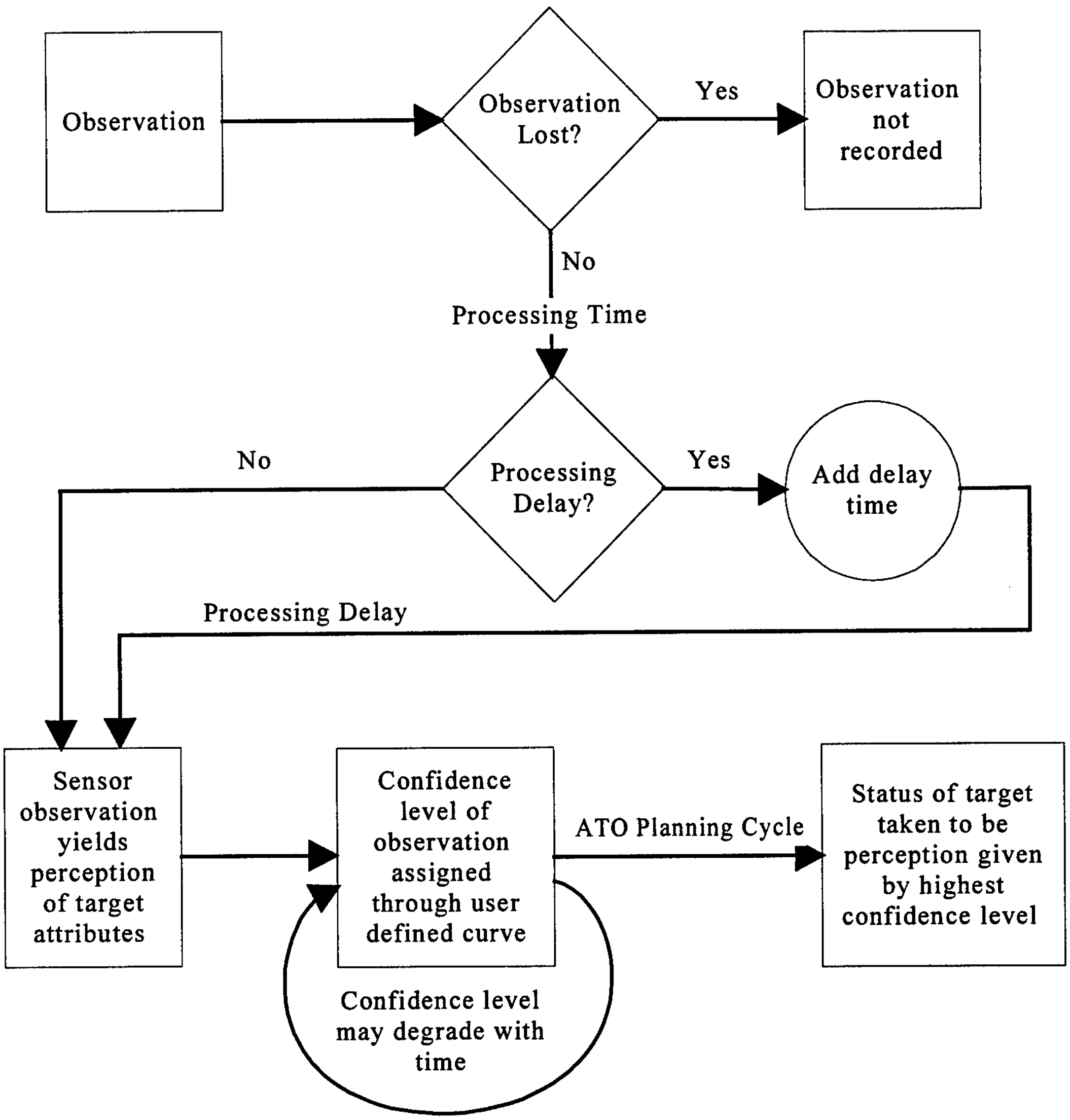


Figure 24. ISR Observation Processing

The perception is only updated after the processing time has passed. The processing time can be affected by the status of ISR nodes. Generally, as ISR nodes are degraded, processing time increases. This helps represent decreased bandwidth when an antenna is destroyed, as well as the extra time needed because of the reduced number of analysts deciphering the data. The ISR Processing Rule System also allows for a probability that an observation is lost, and therefore discarded. The probability of an observation being lost could model factors such as data not being received, data saturation of the receiver, or analyst oversight.

5.8 ISR Effects on Mission Planning and Mission Effectiveness

Mission planning entails target nomination, prioritization, sortie allocation, and aircraft-munition configuration. THUNDER's air planning function uses target perceptions when formulating the target list. Nomination rules are set for each ISR target class. Targets must be nominated to be attacked. An example of this type of rule is, if an observation has been made of the target within the last 48 hours, then the target is nominated.

Different types of targets are prioritized using various formulas, but the parameters in these formulas, such as unit strength, *etc.*, are all based on their perceived values; therefore, the priorities of targets are based on the perceptions generated by the ISR sensors.

Once a prioritized target list is generated, aircraft sorties and their missions are assigned according to the perceived state of the targets. The aircraft/munition configuration for each sortie is selected based upon the forecasted weather, as well as the perceived state of the target.

Target acquisition depends on the sensor's target location error and how old the last observation is, since, for example, mobile targets may have moved. The probability of acquiring the target depends on the true distance between the aircraft and target. If the target exceeds a maximum distance, it is not acquired. However, an aircraft will have another chance to acquire the target is a standoff reconnaissance aircraft has the target in its view. The probability that the aircraft will acquire a target in this situation is given by a user-defined parameter.

Given target acquisition, the effectiveness of a strike depends on the munitions allocated to the mission. This mission-to-target allocation depends on target perception, which of course depends on the ISR observations.

5.9 Effects on Ground War

The ground war is deterministic and highly aggregated in THUNDER; individual battles do not actually occur.

> Ground units, usually of division or brigade size for on-line combat units, engage in combat along the Forward Line of [Own] Troops (FLOT) and combat is adjudicated by the USA CAA's Attrition Calibration (ATCAL) model…FLOT movement is based directly on the relative losses of both sides, the postures of the attacker and defender, and the terrain upon which the combat occurred [10:23].

Ground units in battle engagements move strictly back and forth within battlefield sectors. The ISR process influences ground battles and the movement of the FLOT through a multiplier on the lethality of indirect fire weapons and the target availability of direct fire weapons in equations used by ATCAL. This multiplier is activated whenever a standoff reconnaissance aircraft has coverage of an enemy unit. The user inputs a maximum multiplier indexed by weapon, target, and posture. "The actual multiplier is scaled according to a user input curve that relates SREC aircraft coverage (as a fraction of the ground combat cycle) to the maximum possible effect" [51:23].

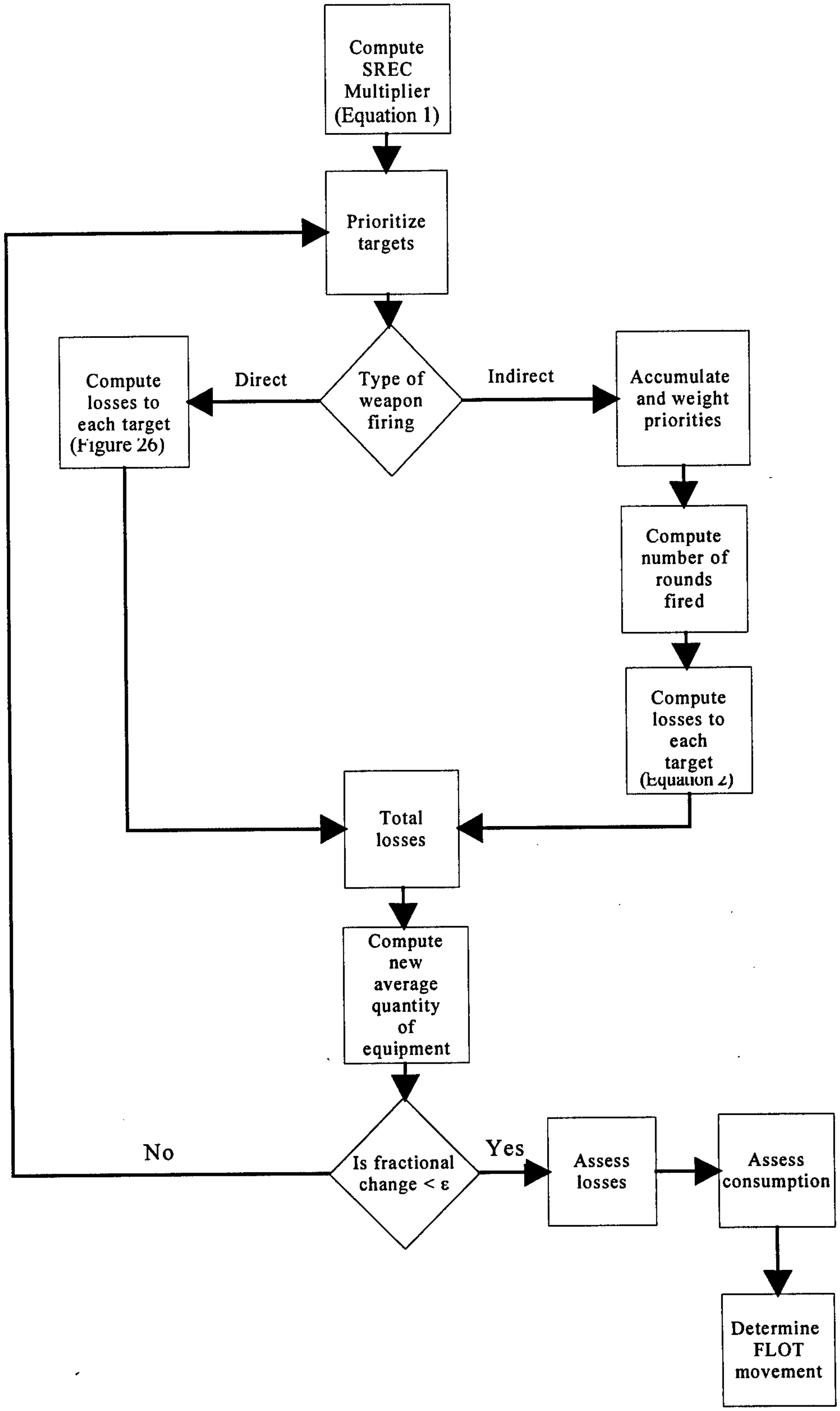


Figure 25. Attrition Calculation Process

To understand how this multiplier influences ground combat results and to get a better idea of its significance, we need to look at the ATCAL process used in THUNDER to determine battle outcomes. Figure 26 above shows the general process; individual elements of the process are further explained independently.

The SREC multiplier is computed in the following manner. First, the fraction of the ground combat cycle that the target was in SREC coverage is determined. Processing time and probability of an observation being lost are ignored in this calculation. Second, the user-input maximum multiplier for the appropriate weapon/target/posture combination is retrieved. The actual multiplier is then given by the following equation.

$$\text{SREC Multiplier} = 1 + [\text{SREC Coverage} * (\text{Maximum Multiplier} - 1)] \qquad (1)$$

Prioritizing the targets involves multiplying the probability of kill by its importance. No SREC effect is seen in this calculation.

For direct fire weapons, the effect of the SREC multiplier is seen in the availability of targets. It is a direct multiplier on availability, which in turn is used in computing losses. The procedure for computing losses for direct fire weapons is seen in Figure 27 where the "Availability" factor represents the availability with the SREC multiplier applied. Note that "Non-availability of higher priority targets" does not use this "Availability" factor, nor does the calculation for Shots Fired. We can see that as the Availability increases, the losses to each target will also increase.

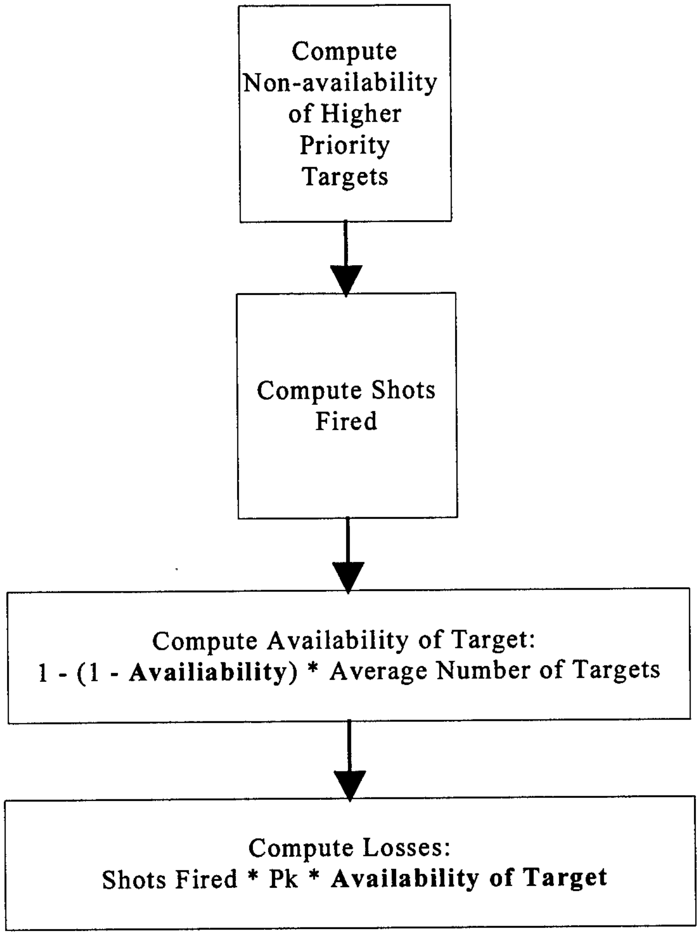


Figure 27. Computing Losses to Targets of Direct Fire Weapons

Figure 26 shows that the target priorities for indirect fire weapons are weighted. The number of rounds fired involves the weighted priorities and a bias factor, but that number is not affected by the SREC multiplier. The SREC multiplier only affects the lethality of the shooter, which is found in the computation of losses. Losses are calculated as:

$$\text{Losses} = \text{Rounds fired} \times \text{Lethality} \times \text{Adjusted Priority} \tag{2}$$

Note the Adjusted Priority is used to divide the effects of the rounds among the targets based on priority – it serves the same purpose of target availability for direct fire weapons.

All of the losses are then totaled, and averaged by equipment type. If the fractional change of each type of equipment is not less than a user-stated ε, re-compute (essentially, fight the war again for this cycle). Otherwise, assess losses, compute the consumption, and determine which way each FLOT segment should move.

FLOT movement depends on unit attrition, unit posture, terrain, POL, unit tactical march rates, and opposing command objectives. The SREC multiplier affects FLOT movement through the attrition of units.

The influence of ISR on the ground war presented above affects units actually in combat. ISR also influences reserve units, supplies, or any other support to combat units by influencing the air war and air interdiction efforts on lines of communication and resources, as well as targeting equipment and units involved in the ground war.

5.10 Summary

This chapter has presented the parameters and processes used by THUNDER to capture ISR elements and ISR effects. The parameters represent the uncertainty of intelligence data. The processes show the compounding effects of ISR by demonstrating its influence on air targeting and ground unit attrition, which impact mission effectiveness.

6. Analysis of the THUNDER ISR Module

6.1 Introduction

THUNDER has an ISR module because of the crucial impact of ISR to warfighting capabilities. Previous chapters have described the basic components of the ISR process and the design of the THUNDER ISR module. This chapter compares these two subjects, real versus modeled, in order to illustrate which ISR components have been captured, aggregated, or neglected by THUNDER.

Bear in mind that THUNDER is a campaign level model and aggregation of elements is something that is accepted and necessary in order to maintain reasonable run-times. So, although some elements of ISR may be identified as missing, or aggregated, that is not necessarily something undesirable. THUNDER justifiably does not attempt to model the detail of engagement or mission-level models. However, as technology advances, it may be possible, and maybe somewhat desirable, to implement more detail into campaign-level models, even if just for a few processes. Higher resolution processes allow for more flexibility, and for fewer, or maybe more valid, assumptions. Identifying the details of a process is a necessary step before an attempt at higher resolution can be accomplished. Also, knowing which elements of the ISR process have been aggregated, or dismissed, may allow for higher resolution models to either be identified, or built, in an effort to generate more accurate input data.

This chapter will present the comparison of the THUNDER ISR process and the "real" ISR process in an outline similar to chapter 4.

6.2 Implementation of ISR Purposes

The ISR portion in THUNDER has four basic applications, or purposes, each of which fit into the fundamental purposes of intelligence identified in Joint Pub 2-0. These applications are:

- Aid in aircraft/munition configuration decisions for striking targets
- Report target status after air strikes (BDA)
- Assist in real-time target location if strikers cannot locate the target
- Act as a force multiplier for ground units

Figure 28 maps THUNDER's ISR applications to the intelligence purposes identified in Joint Pub 2-0 (see p.19 for purpose descriptions). Further explanation of the comparison follows.

Supporting the commander is not necessarily a quantitative concept that can be reproduced in a model. ISR in THUNDER supports aircraft targeting decisions through target observations and BDA. Reconnaissance or stand-off reconnaissance missions are not scheduled by considering any effects on ground troops, although these missions can be scripted by the user. Knowledge of the situation for any other type of decision, such as air apportionment, are to some extent pre-set by the user through numerous input files when designing the scenario.

Identifying and determining objectives is primarily met through user inputs, and not as a result of process computations. Adherence to warfighting doctrine is accomplished through user inputs such as the force ratio needed for ground units to attack, or the strike priorities for targets. General strategic objectives are set before a war

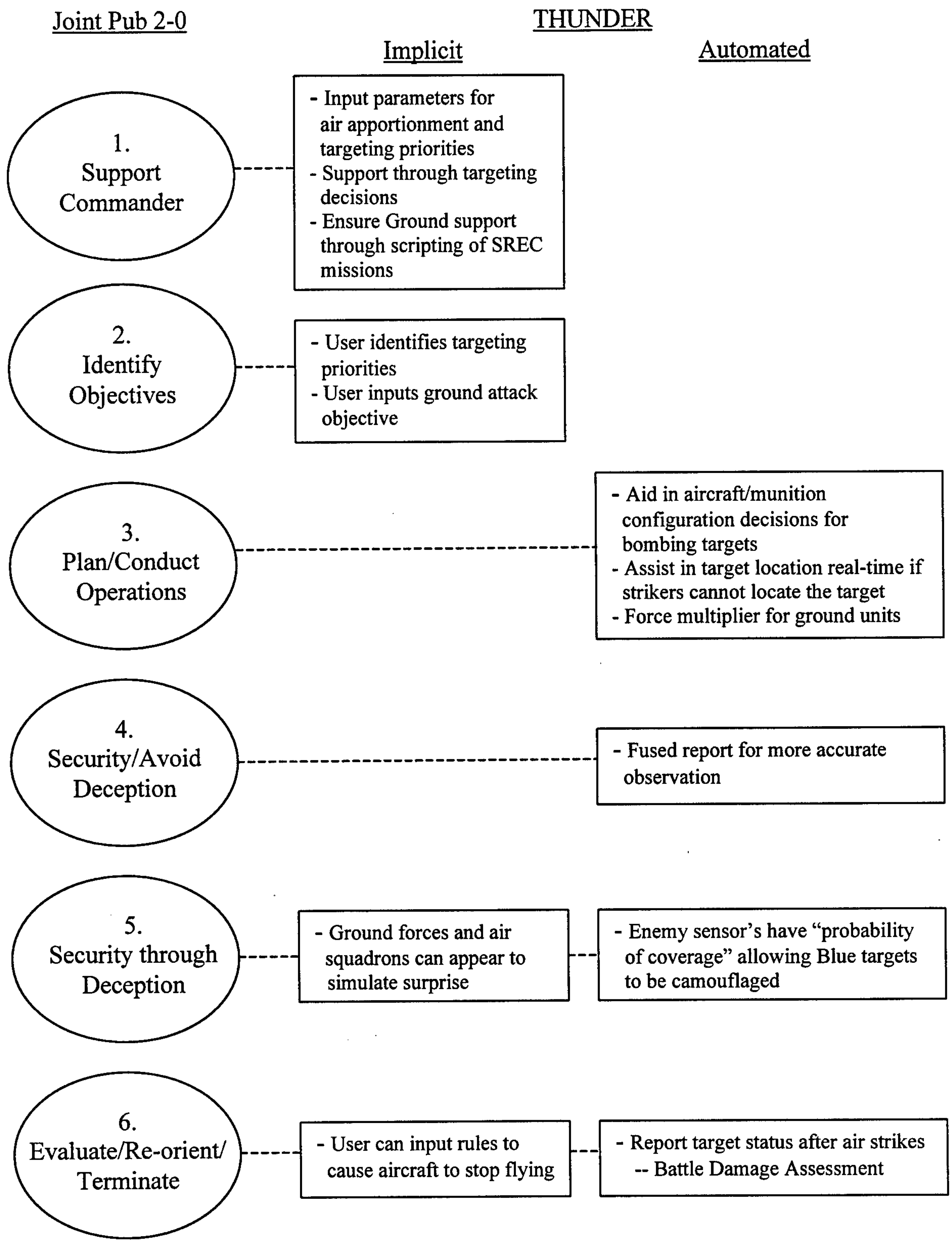


Figure 28. Comparison of ISR Purposes

begins and must be induced by the user via the input files. In reality, tactical and operational objectives are extremely dynamic and stem from the status and circumstances of the battle learned through ISR efforts. In THUNDER, however, these efforts are not used in determining objectives for operations.

Identifying enemy centers of gravity is a prime focus of intelligence activities. However, THUNDER primarily uses ISR to form weapon/aircraft assignments.

THUNDER's ISR does aid in planning which targets to strike in the air war, and can also help an aircraft locating a target.

Naval aircraft carriers and Tomahawk Land Attack Missile (TLAM) platforms are represented in THUNDER, although surface, subsurface, and anti-submarine warfare is not modeled. Aircraft on the carriers conduct operations just as any other aircraft based inland along with TLAM strikes.

The ground war is highly aggregated in THUNDER. Unit status and battle results are calculated deterministically through the ATCAL process. Ground units in battle engagements move strictly back and forth along pre-defined sectors. Therefore, these units do not decide where to move, since they always want to move forward. It is ultimately a question of 'if' they move, and which way. The ISR process influences the movement of units in combat and, therefore, the outcome of battles, by applying a multiplier to the lethality and target availability factors used in ATCAL equations as discussed previously. This multiplier is activated whenever a standoff reconnaissance aircraft has coverage of an enemy unit.

THUNDER's ground combat involves a myriad of variables including unit strength, supplies, equipment, lethality, rate of fire, shooter bias, flank degrade, target priority, and unit posture. Since the ground war is deterministic, ISR does not really have an impact on any ground unit planning. It may affect second echelon or reserve type forces as they may move along a network to carry out their duties. This seems to be a limited representation of the influence of intelligence on the ground war. In reality, ground units rely heavily on intelligence. Information about terrain, enemy reinforcements, second echelon forces, enemy supplies, *etc.* all influence operational and tactical decisions. Ground forces base decisions of when, where, and how to attack on the information they receive from their own reconnaissance equipment, as well as the intelligence from reconnaissance aircraft and satellites. However, since THUNDER's ground war is played deterministically, the implementation of the ISR effect through a multiplier seems to be a reasonable compromise. Although ISR does not aid in the planning or execution of operations in a true sense, an impact on battle outcomes can be realized.

It is interesting to note that although the user can script observations as "Grid" or "FLOT" sensors to represent ground intelligence collection, these observations do not impact the ground war, except indirectly through air targeting of the enemy.

Security of operations and countering deception and surprise usually requires information from more than one source of intelligence since nearly every type of sensor is vulnerable to some type of deception. Fusing and comparing various sources of information allows analysts to increase their confidence in what they evaluate as truth. THUNDER does not compare reports from different sensors in its "fusing" process, but simply selects the report from the sensor that has the highest confidence level for the target. To obtain a reasonable outcome, the user must carefully assign the right confidence levels and degradations.

A crucial objective of intelligence collection is to prevent or counter surprise attacks, but THUNDER does not address this objective at all. Knowing where troops are massing and how many reinforcements are available builds knowledge of the enemy and aids in determining enemy intentions. Again, intelligence does not affect on-going operations of the ground war, but is only considered after the fact when calculating losses. A possible improvement might be to allow a unit to attack with a lower force ratio if it is believed the defender's reinforcements are delayed.

Deceiving the enemy and the element of surprise are highly dependent upon the use of intelligence. Knowing the command and control systems of the enemy and their intelligence systems facilitates deception. THUNDER's ATO generator can target these types of systems, but the ability to plan for surprise is generally lost. However, one way to accomplish this is through user input. For example, the user can order ground units to appear at a location at a designated time, but this really has no correlation with the status of the enemy's intelligence capability. Information superiority is a mission that is becoming increasingly important in today's world of technology. The ability to disable or deceive enemy ISR capabilities is vital to accomplishing this mission. THUNDER has implemented rule language that allows for ISR observations to be lost if certain structures, such as communication centers, are destroyed. Deception is hard to depict in a combat model because of the nature of deception activities. Planning for deception and ensuring that the enemy has not discovered the plan does not fit well with combat modeling quantitative limitations. The "probability of coverage" parameter does allow for a deception effect by not allowing the sensor to always see a target within its view.

The last purpose of ISR is evaluating effects of operations and re-orienting forces or terminating operations. Evaluating effects of operations is a BDA function. BDA is usually accomplished by more than one sensor because of the complexity of assessing the actual damage. BDA starts with aircrew debriefings or cockpit video, but is driven by imagery. In THUNDER, any aircraft defined with an ISR sensor can do BDA. This can be used to represent the aircrew report or cockpit video. It is important that the user configure the confidence of these reports appropriately, as generally they are given a lower confidence than something like satellite imagery.

In THUNDER, the nomination of a target for re-strike is influenced, through a priority multiplier, by whether or not BDA has been accomplished. This is a binary status, and does not take into account the confidence of a BDA report. The user inputs the perception of a target that has not had BDA accomplished. This tells THUNDER whether to consider the target live or dead. Targets considered dead are not nominated for re-strike. Again, only one sensor has to accomplish the BDA in order to trigger this perception, regardless of the confidence of that report. While BDA is performed on three levels – physical, functional, and system damage, THUNDER has incorporated just the physical and functional aspects. An ISR observation will report target characteristics, representing physical damage. The fact that ISR observations influence whether a target is considered live or dead can be seen as a functional aspect.

The usual termination criteria in THUNDER is a stated number of days of war completed or the annihilation of one side which leaves no targets to strike. The user may construct "rules" that stop aircraft from flying when a percentage of certain types of targets are destroyed. Therefore, ISR in THUNDER can influence the termination of operations through its impact on air targeting and the ability to destroy targets, as well as the perception it has of targets (live or dead).

6.3 Representation of ISR Principles

As previously stated in Chapter 4, there are numerous principles of ISR identified by military doctrine. THUNDER has captured some of the principles, while some are assumed. Again, assumptions are not necessarily inappropriate, as long as they are known, and can be applied validly. Table 5 summarizes the ISR principles-THUNDER relationship, with a discussion of each implemented principle following.

Table 5. ISR Principles

	Principle	Comments on THUNDER
√	Accuracy	Allows for location error and degrading confidence levels
√	Timeliness	Incurs processing time, delays, and probability of observation being lost
	Objectivity	Assumed
√	Unity of Effort/Interoperability	Cross-cueing essence in locating targets and ground force multiplier
	Relevance	Assumed
	Usability	Assumed
√	Completeness	Prioritization of targets given by multipliers
	Readiness	Not modeled. Demand-oriented tasking
√	Fusion	"Fuses" various sensor information by choosing the highest confidence level
	Accessibility	Assumed
	Security	Assumed
√	Survivability and Sustainability	Allows for redundancy through scripting (not through automated scheduling). Allows for processing delays and lost observations

Accuracy. This is implemented in THUNDER through the use of confidence levels, which may decrease over time. Each sensor is assigned a two-sigma location error applied to its target location estimate. An additional location error is applied at the time of strike based on the age of the report used for initial location.

Timeliness. Timeliness of ISR reports is based on a sensor's processing time, which may be a random variable. Processing delays can also be incurred when certain ISR nodes have been destroyed, as specified by user input. Also, the probability of an observation being "lost" is factored in when ISR nodes are destroyed (subject to user input). These processing delays and lost observations are used to represent a variety of occurrences such as interrupted or lost communications or analyst oversight.

Unity of Effort /Interoperability. The fact that the different military services, civilian organizations, and allied nations have interoperable systems and are unified in effort is assumed in THUNDER. One element in THUNDER where this has been implemented is through cross-cueing. This ability is demonstrated in THUNDER through the ability to "roll the dice" again if an AWACS (or J-STARS) type of aircraft is in reach, to aid in target location. The impact of cross-cueing can also be seen by the increase in lethality and target availability in the ground war.

Completeness. It is assumed that the "Commander" has all available and relevant information from an ISR observation to accomplish the mission. Prioritization for obtaining that information is seen through the prioritization of targets for intelligence collection. Targets are prioritized based on their strike priority, which is then multiplied by various ISR factors, such as a BDA multiplier.

Fusion. THUNDER "fuses" observations based on confidence level. This issue was discussed in Chapter 5.

Survivability and Sustainability. Mostly seen through the role of ISR nodes. As nodes are destroyed, delay time and probability of lost observation can be increased. Only ISR sensors attached to aircraft are vulnerable to attack. The user can simulate a satellite being "moved" or a new satellite being "launched" during the course of the war by using rules that set the probability of an observation being lost to 1.00 until the sensor should be used.

6.4 Types of Intelligence

Intelligence comes in different forms. In THUNDER, the user can script HUMINT and OSINT observations. Because any aircraft can carry a sensor, this sensor can be considered a HUMINT sensor if it is representing an aircrew debriefing. The type of intelligence explicitly accounted for in THUNDER is Imagery Intelligence. Analysts can "trick" the simulation to do other types, but it is laborious, and probably not desirable. THUNDER 6.6 will be able to model SIGINT. Since HUMINT and OSINT are scripted inputs, it is sufficient to explicitly model only IMINT and SIGINT; MASINT and TECHINT are probably not necessary.

6.5 Communications

Communication is a vital part of all military operations, including the ISR process. SATCOM, telephone, radio, fax, electronic message, *etc.* are just a few of the media to transmit information such as requirements, tasking orders, cross-cueing, and to permit dissemination of ISR. Communication systems and/or C4I systems are not explicitly modeled in THUNDER. Some communication problems and their effects are captured through various input parameters. For instance, a processing delay is incurred if ISR nodes are damaged or destroyed. Processing delays may decrease if an aircraft such as an AWACS is in the vicinity. The same rules can apply to the probability of an observation being lost. An observation may be lost for a variety of reasons such as a message being jammed or garbled or through saturation of a communications satellite. The sensor's defined processing time represents the time it takes to process and transmit the data. All of these parameters are highly aggregated measures, to which it seems rather difficult to assign "accurate" values. It may be desirable to explicitly model communications to some extent, or at least at a slightly higher resolution than currently employed.

6.6 Initial Preparation of th e Battlefield

In THUNDER, the Initial Preparation of the Battlefield is represented by a data file which includes the time since the last observation of each target based on a random draw and a confidence curve. This in turn translates to the confidence of intelligence data of targets, *i.e.* usually the more time that has passed since that last observation, the lower the confidence level. In reality, the initial assessment entails much more than just target status and contributes overwhelmingly to the timing of activities and courses of action considered by the commander. The way that the initial assessment must really be captured, aside from the data file, is through other inputs by the user. Obviously it is the user that decides how much is known about the enemy when the campaign begins.

6.7 ISR Process

So far this chapter has compared the ISR purposes, principles, and other ISR components in reality with those of THUNDER. The following section will compare the ISR process.

6.7.1 User Requirement

Although in reality, many factors drive ISR requirements, *e.g.* technological capabilities, enemy will, allied and foreign sentiments, and enemy centers of gravity, the ISR requirements in THUNDER are basically used for aircraft targeting. The air planning and mission generation processes within THUNDER attempt to model AF doctrine in that the JFC sets intelligence requirements, which the JFACC fulfills. The air planner accomplishes this primarily through the generation of target lists, which are then prioritized for reconnaissance/surveillance missions. The user can impose requirements through scripting or inputting planning parameters in such a way to obtain a desired outcome. For example, the air planner does not generate a surveillance mission to fulfill a requirement for real-time intelligence to aid in target location, but the user can either script or manipulate certain parameters to ensure that surveillance of targets is accomplished, thereby modeling the desired effect.

Although in reality ground units rely on intelligence inputs to determine their courses of action, these units do not generate requirements for intelligence in THUNDER. As discussed previously, the impact of intelligence on the ground war is mainly through the intelligence benefits to aircraft which can destroy ground units, equipment, supplies, *etc.* Ground units do receive a by-product of surveillance missions in that having surveillance of enemy units increases the lethality or target availability;

however, a ground unit cannot "request" this surveillance in THUNDER. Yet once again, the user can ensure that surveillance takes place through scripting or various other inputs.

Figure 29 summarizes how the JFC intelligence requirements of each of the component commanders are represented in THUNDER.

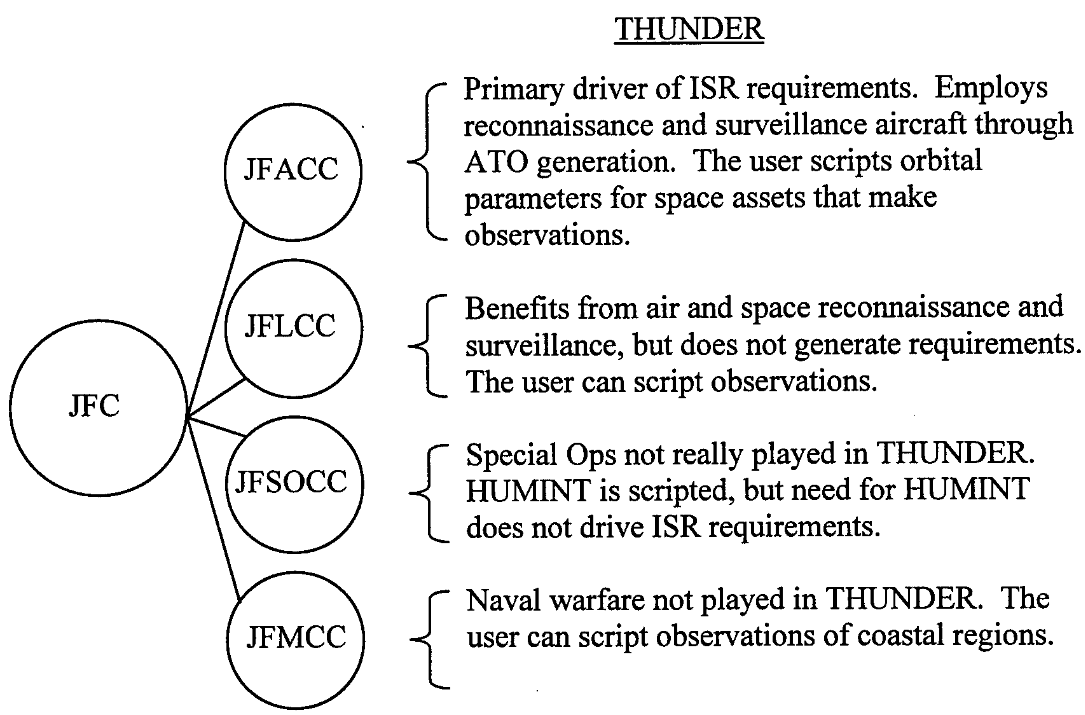


Figure 29. User Requirement Representations

6.7.2 Planning and Tasking

Figure 30 shows the Planning and Tasking Process in THUNDER. Figure 31 shows the Planning and Tasking Process during conflict.

THUNDER treats planning for intelligence collection and tasking intelligence collectors as one process. Actual planning for intelligence collection begins by prioritizing requests. THUNDER attempts to mimic this aspect by beginning with the

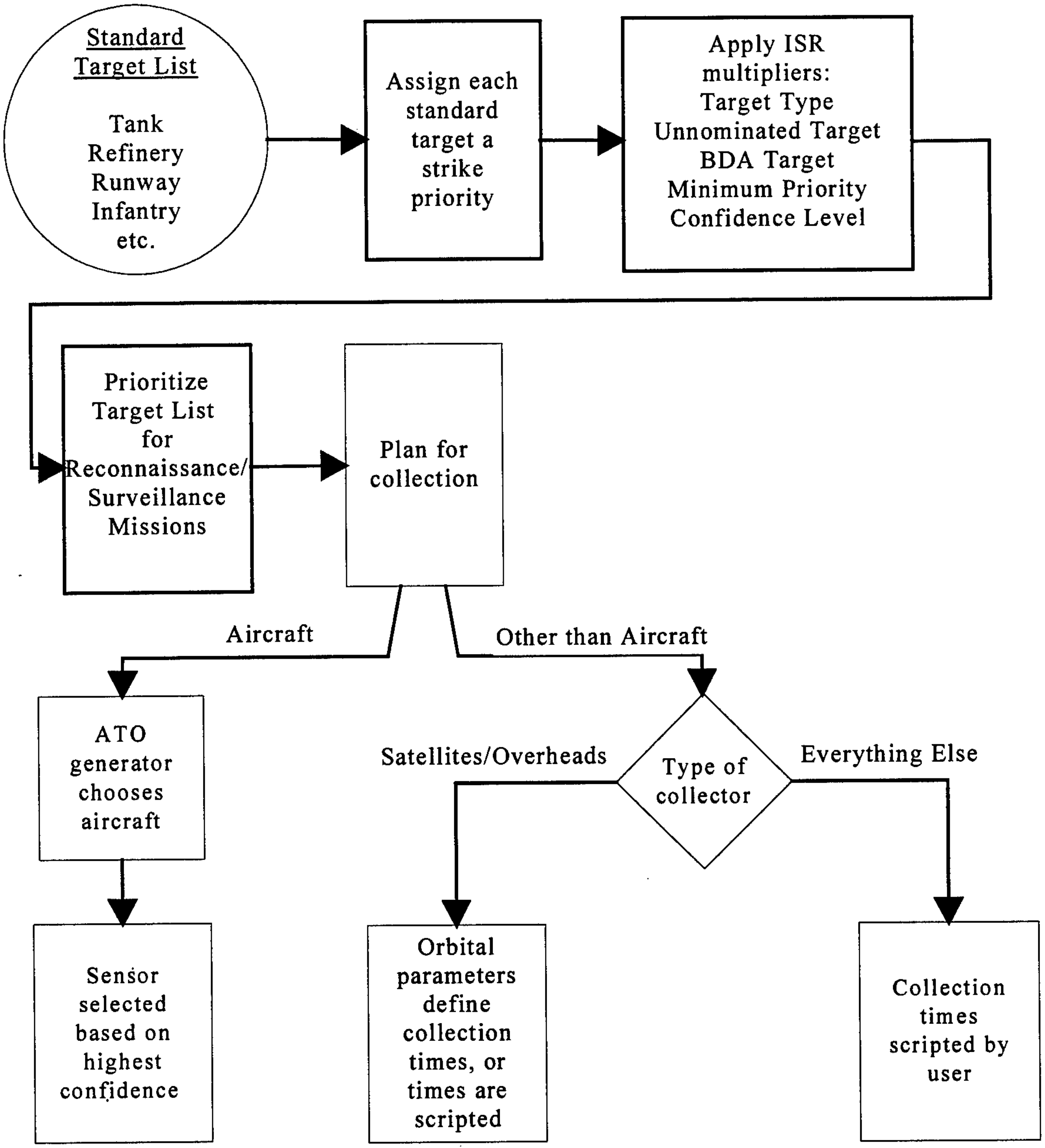


Figure 30. Planning and Tasking Intelligence Collection in THUNDER

standard target list and each target's strike priority. Standard targets are organized into ISR target planning classes that define the ISR multipliers to apply to each target's strike priority and therefore prioritize the target list for reconnaissance and surveillance (RECCE/SREC) missions. These multipliers allow considerable flexibility

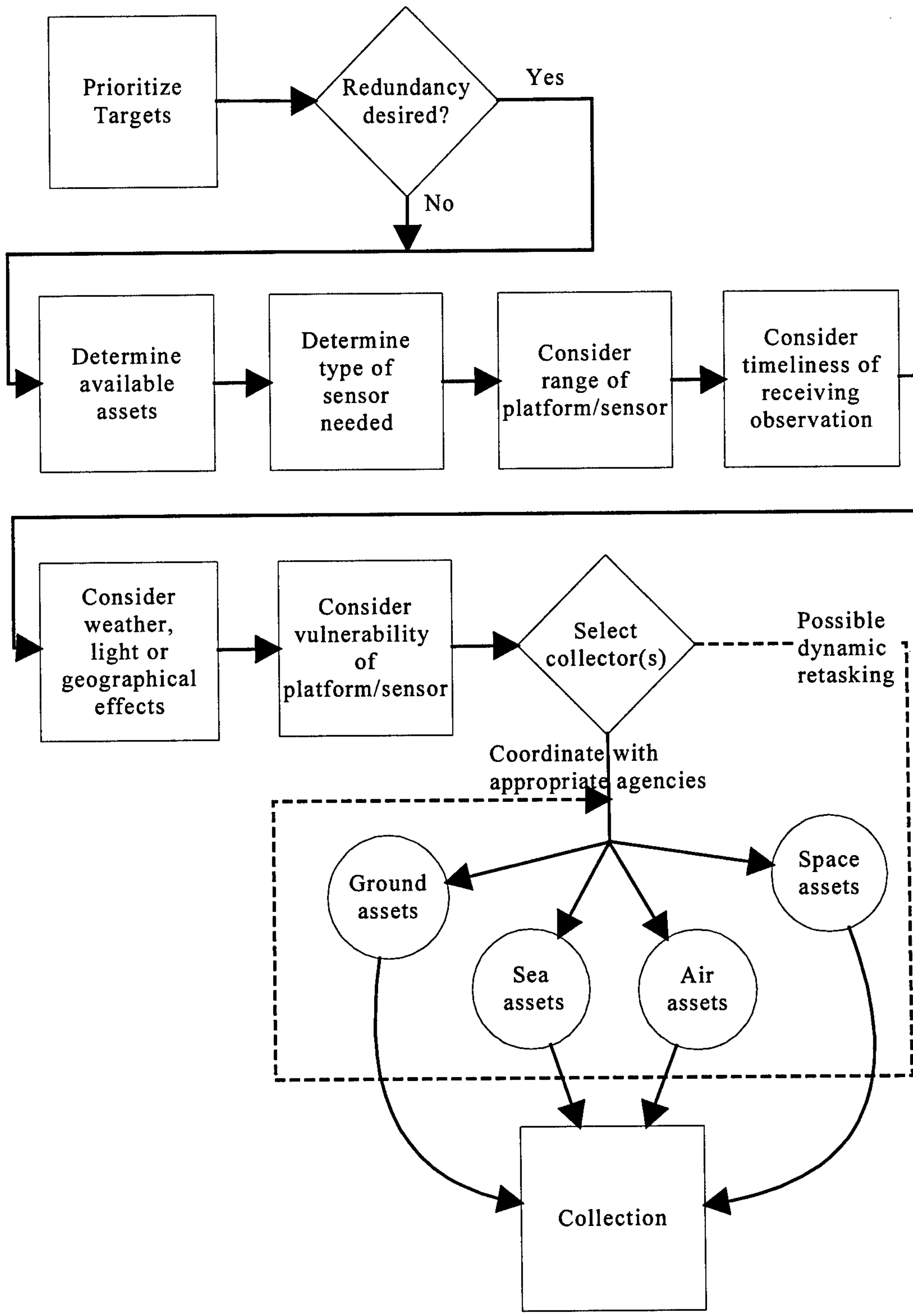


Figure 31. ISR Planning in Theater Level Conflict

for the user in planning for RECCE/SREC missions. Multipliers are applied if a target is not nominated for strike and if BDA has not been accomplished. A third multiplier allows the user to establish a minimum priority that the target may have for RECCE/SREC. These, once again, are good planning tools for quantitative items such as target status. Abstract information such as enemy intentions is something that the user must somehow manipulate when setting up initial parameters.

The THUNDER planning module lacks coordination between air and space assets. Air assets given RECCE or SREC missions are scheduled through the ATO generator. Space assets are planned for automatically through their specified orbital parameters. Of course, the user can script any other observations desired. The planning process in THUNDER shows the biggest divergence from reality. Figure 9 (page 39) shows that many factors are considered when deciding on the sensor/system for collection. In THUNDER, RECCE/SREC mission sorties are assigned to the aircraft/sensor combination that has the highest confidence for that particular target. Sensor capability in regard to weather and range to target are also considered. Aircraft can be tasked even if a space asset can make a collection, and vice versa. Although this does allow for possible redundancy, coordination between the two is desired to allow for maximum coverage of the greatest number of targets. In reality, all types of intelligence collectors (ground, air, space, and sea) should be considered when planning for collection.

Another factor to include in planning, related to timeliness, is sensor/system availability. The ATO generator automatically schedules RECCE/SREC aircraft. When integrating space assets, coverage times must be considered since the times that a space asset can view of a target is relatively fixed. Redundant coverage of some targets may be desirable, especially when conducting BDA. THUNDER does not schedule missions specifically based on the need for a redundant observation, but it does not prevent it either by integrating air, space, and scripted observations.

Tasking for reconnaissance aircraft in THUNDER takes place in the ATO generator at the same time as the planning. Similarly, satellite tasking is assumed through the defined orbital parameters. THUNDER assumes that the space assets are tasked every time they come into view, and perform the task 100% of the time. In reality, some sensors may not always be able to gather data on certain targets in their footprint due to various factors such as sun interference or other weather effects. Also, it is not necessarily a "given" that just because a satellite is overhead that it will be tasked to make collections.

Another departure from reality in the THUNDER ISR module is the lack of dynamic re-tasking. As situations change and new information becomes available, collection priorities may also change. In THUNDER, as with all of the aircraft sorties, dynamic re-tasking of aircraft is not possible. This is the same for all collections. Once the planning cycle has determined the RECCE/SREC priorities, these will not change until the next cycle.

Finally, tasking aircraft and satellites takes time, and relies upon the ability to communicate. Tasking national assets requires coordination through and with the appropriate agency. None of the tasking time or coordination is represented in THUNDER, and probably isn't necessary. The usual Planning Cycle in THUNDER is 12 hours, where in reality it is 48-72 hours. This extra time should ensure that at 12 hours out, the tasking has been ordered.

6.7.3 Collection

Collection is scheduled by the ATO generator for RECCE and SREC missions. Collection times by satellites are given by the orbital parameters of the satellite/overhead. Any aircraft equipped with a sensor may make observations after a strike. Sensors defined in THUNDER as "Grid" or "FLOT" sensors can be used to represent ground-based collection. The user must script all other types of collection. Scripting permits the user to define almost any type of collector. One limitation of THUNDER is that aircraft can only carry one sensor. In reality this is not the case. For example, a high altitude UAV, such as Global Hawk, can carry multiple sensors such as electro-optical, infra-red, and synthetic aperture radar.

Since THUNDER treats carriers as floating airbases, any naval aircraft that performs surveillance or reconnaissance missions can be modeled and scheduled just as any other land-based aircraft. However, intelligence of enemy naval assets normally gathered by naval platforms will not be captured in THUNDER. This has little impact on the theater level warfighting envisioned by THUNDER since it does not model open ocean, ship vs. ship warfare.

Army intelligence, or any ground-based intelligence, is not modeled explicitly in THUNDER. The user can mimic these type of collectors by using "Grid" or "FLOT" sensors. In reality, Army intelligence gathering capabilities depend to a large extent on the role of the unit, its proximity to the FLOT, and its status. (*i.e.,* engaged, recuperating, *etc.*) Numerous types of equipment can gather intelligence, whether purposely or as an important by-product of normal activities. These collections, in turn, aid in Army operations at both the tactical and operational level.

6.7.4 Analyze

Processing time is captured through random delays and user input. This also includes analysis time. Analyst error or oversight can be simulated through the probability that an observation is lost. Again, determining the number to be used for analysis time and probability of error is not an easy task. When fusing data from many sources, THUNDER uses the highest confidence level for each target; the confidence level considers the time since the observation was made. This "fusion" process is fairly realistic as long as the sensor confidence levels truly reflect the ability of the sensor. However, as with any model, THUNDER does not capture the human judgment often involved when human analysts face "special cases" and their experience and knowledge drive their actual decisions. For example, it is possible that specifications of a target found in open source material may be more useful than a report gathered by ISR assets, even though open source is generally considered less reliable. The integration of old data with new data to make better assessments is also lost in THUNDER. Old data is simply replaced by new observations. Also, since no other observation is considered, any dichotomy between sensors will not be realized. For example, if one sensor reports 10 tanks with 80% confidence, and another sensor reports 3 tanks with 75% confidence, only the 10 tanks will be considered, whereas in reality, the knowledge of another highly-confident sensor that produces a significantly different report may invoke the need to re-observe the target.

6.7.5 Dissemination

Dissemination in THUNDER can be represented by the sensor's processing time. Dissemination can be stopped through the "probability of lost observation" parameter.

6.7.6 Evaluate

In THUNDER, all observations are assumed to be relevant until an observation with higher confidence is reported, then the old observation is discarded. The end user of the product is assumed to be satisfied. The feedback loop is not modeled.

6.7.7 Apply

The ISR observations are applied by updating air-to-ground target statuses. Also, it is applied in its influence on the ground war.

6.8 Summary

This chapter has presented a comparison of the ISR purposes, principles, and processes involved in the real world and in THUNDER. Overall, THUNDER has captured most of the critical elements of the ISR process. Some assumptions that THUNDER makes in regard to ISR are:

- ISR and C4 systems within military services, among military services, among military and civilian organizations, and among nationalities are all interoperable.
- Observations are always analyzed objectively, and the same confidence level is always assigned to a particular sensor
- The observation from the sensor with the highest confidence level is always considered the best.
- Satellites always make observations whenever the theater is in view.
- Observations always fulfill the user's request.

- Only sensors attached to aircraft are vulnerable to attack.

Numerous parameters and algorithms are used within THUNDER to represent ISR. Many THUNDER ISR elements mimic the real world, or at least mimic the effects, in good fashion. Some of the better qualities of THUNDER's ISR module include:

- ISR sensors can be distinguished through capability and confidence level allowing for flexibility and ability to be adapted to a wide variety of scenarios.
- ISR sensors are modeled as real or batch; each has a processing time that can be adversely affected by the destruction of ISR nodes.
- Aging of ISR observations is taken into account when considering target nomination, confidence of the report, and target location error.
- ISR observations affect prioritization of targets.
- THUNDER makes an attempt to "fuse" ISR observations.

There are also some limitations to THUNDER's ISR module. Many of these limitations come in the interaction between ISR assets and the ground war. This is due in part to the fact that the ground war is played deterministically, limiting the ability of ISR to affect ground war decisions. Some of the most significant disadvantages of THUNDER's ISR module are:

- The ground war has no impact on ISR scheduling. Support of the ground war does not factor into RECCE/SREC mission scheduling.
- ISR has no impact on ground units' courses of action. Knowledge of enemy reserves or status of supplies is not considered.
- Grid, FLOT and Space sensors, as well as RECCE missions, do not aid the ground war.
- ISR collection is not coordinated among satellites, aircraft, and scripted events, resulting in less than the maximum number of targets being observed.

- In the target nomination rules, BDA is considered to be accomplished regardless of the confidence level of the sensor.

- Aircraft can only carry one ISR sensor.

- Dynamic re-tasking of ISR assets is not possible.

Because THUNDER is a campaign-level model, some parameters and process elements are aggregated to represent numerous possible effects. Some of the elements aggregated in THUNDER's ISR module are:

- Processing Time ⇐ Time to gather the intelligence, process it, relay it to the analyst, analyze the data, and disseminate the information to the user is aggregated into a randomized processing time.

- Processing Delay and Probability of Lost Observation ⇐ Problems such as interrupted communications, analyst errors, and the effect of information overflow are represented by a delay added to the processing time and a probability that the observation is lost and not used.

- Targeting Decisions ⇐ All user requirements are aggregated into decisions made about targeting.

- Air Planning Module ⇐ The Planning and Tasking processes for SREC/RECCE missions, and their coordination among military and civilian organizations, takes place when the ATO generator schedules the missions.

- Lethality and Target Availability ⇐ All ISR effects on ground units are seen only in the lethality and target availability factors used for attrition.

Although many ISR elements are represented in THUNDER, many of these rely on user input. Therefore, the user's knowledge and ability to input and script ISR parameters and elements correctly is critical to the process, and in effect, to the modeling capability of THUNDER itself. Some of the effects that rely upon user input or scripting are:

- Overall knowledge of the situation and enemy at the onset for air apportionment and target priority decisions

- Sensor capabilities – range, accuracy, confidence, perception of live targets as live and live targets as dead

- Impact of BDA on targeting decisions

- Maximum force multiplier of SREC on ground war

- Influence on processing time due to ISR nodes being destroyed

- Representation of ground-based and sea-based sensors through the scripting of Grid and FLOT sensor events

- Scripting of units to appear to simulate a surprise attack

- Launching or moving of satellites during the course of the war

Many of the real world ISR elements and effects are captured through THUNDER's automated processes or through user scripting. The next chapter will verify whether THUNDER's processes actually show ISR effects in battle outcomes.

7. Sensitivity Analysis of THUNDER ISR Module

7.1 Purpose

In order to evaluate the effectiveness of THUNDER's ISR implementation, an experiment examining the sensitivity of the quality, quantity, and timeliness of ISR observations on battle outcomes was performed. The purpose of the experiment was to verify that THUNDER is sensitive to ISR changes so it can validly be used for comparative analysis of competing ISR systems. For example, when trying to compare two systems, and one guarantees "faster" intelligence data, it must be established that THUNDER is sensitive to that difference in order to show the benefit of more timely intelligence. This experiment does not attempt to "quantify" the value of intelligence by concluding, for example, that if you have faster intelligence, you kill 1000 tanks versus 700 tanks, but it is merely interested in the fact that more tanks were killed. It is only these comparisons and sensitivities among ISR capabilities that are evaluated.

7.2 Scenario

A 30-day war using THUNDER's Middle East (ME) database was used for this experiment. The ME database is an unclassified scenario distributed with THUNDER in which the battlefield is oriented to resemble a Desert Storm scenario. One of the problems with this scenario, however, was the use of the ISR module. The scenario defaults to using "High" resolution for ISR. Many of the sensors defined in the scenario are never used, and only one reconnaissance aircraft, RF-4, is defined for the Blue side.

Because of the need for more reconnaissance aircraft, one squadron each of High-Altitude Endurance UAVs, U-2s, and RC-135s was added. The specifications for the aircraft were taken from unclassified, open literature sources [22, 28, 41, 48]. Absolute accuracy of system specifications was not as important as simply having more sensors available in the scenario.

The Blue side in the ME database is superior to the Red side. To avoid biasing battle outcomes due to this superiority, Blue capability was reduced and Red capability was increased. Some Blue squadrons were removed and all other Blue squadrons were reduced by 20-25%. In order to increase Red's ability and desire to push forward, the tactical march rate for the Red side was increased by 1000 and the objective of the Red side was increased from 0 to 1,000,000 meters. Finally, 40% of the Blue squadrons and 65% of Blue ground units were delayed from arriving at the theater anywhere from 1 to 7 days after combat had begun. Table 6 summarizes the modifications made to the ME database.

Table 6. Changes to ME database

	ME Database	Modified Database
Number of Blue squadrons	51	48
Number of Blue aircraft	1144	724
Number of Blue types of aircraft	19	22
Number of Red squadrons	19	19
Number of Red aircraft	454	454
Red tactical march rate		+1000 for each unit type
Red objective	0	1,000,000
Blue unit/squadron orders	None	Some arrive 1-7 days late

7.3 Design of Experiment

The design of the experiment was a face-centered central composite design (CCD) with 3 factors – quality, quantity, and timeliness. Central composite designs are widely used for second-order models. The CCD has three components: factorial points, axial points, and center runs.

> The factorial points represent a variance optimal design for a first-order model or a first-order + two-factor interaction type model. Center runs clearly provide information about the existence of curvature in the system. If curvature is found in the system, the addition of axial points allows for efficient estimation of the pure quadratic terms [36:298].

A graphical depiction of the face-centered CCD is shown in Figure 32.

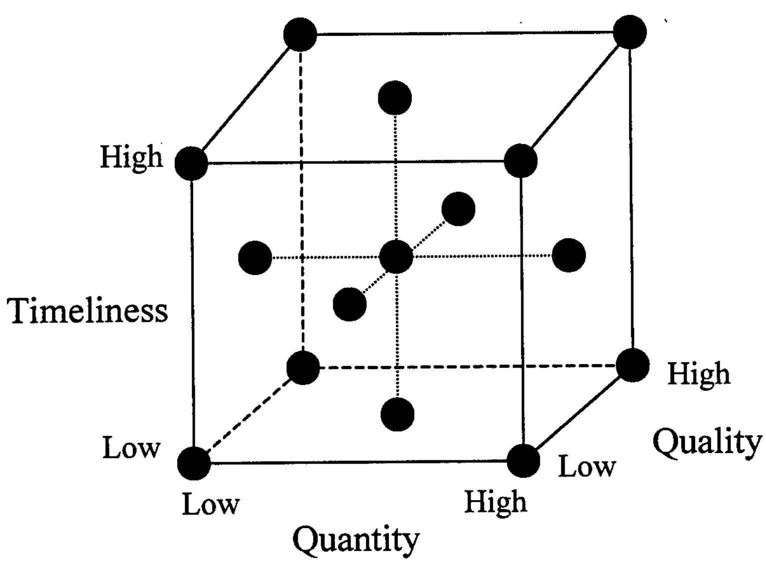


Figure 32. Face-centered Central Composite Design

The face-centered CCD was chosen so that the extreme values can be measured and a response surface can be generated within the bounds of the design space. It is desirable to include points that are at the extremes as this results in the most attractive scaled prediction variance [36:313]. The prediction variance will change depending on the position in the design space, and it reflects how well the model can predict the response. The traditional CCD could not be accomplished because the axial point design settings were infeasible.

As can be seen in Figure 32, the region defined by the face-centered CCD is cuboidal. The design is not rotatable, which would provide for a constant scaled prediction variance for any two points the same distance from the design center [36:306]. However, according to Meyers and Montgomery

> ...rotatability or near-rotatability is not an important priority when the region of interest is clearly cuboidal. Rotatability (or near-rotatability) is a useful option that comes from spherical or near-spherical designs; these designs are certainly appropriate for spherical regions of interest or regions of operability, and they are less appropriate with cuboidal regions [36:313].

The design matrix for the face-centered CCD is shown in Equation (3), where each row in the transposed matrix denotes a factor. The top row represents timeliness, the second row is quantity, and the bottom row signifies quality. A setting of -1 represents the "Low" setting, 1 represents the "High" setting, and 0 represents the center point.

$$\overrightarrow{\text{Response}} = \begin{bmatrix} -1 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & 1 & 1 & -1 & -1 & 1 & 1 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & -1 & 1 & 1 & 1 & 1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{3}$$

Note that the matrix includes 6 center point replications (seen in the last 6 columns of (3) above). For cuboidal designs, two center runs will suffice to stabilize the scaled prediction variance [36:313]. However, doing additional center runs allows for more degrees of freedom when estimating the error [36:113].

Since THUNDER is a stochastic model, 30 replications were performed at the first eight design points, which represent the full-factorial portion of the design, and 20 replications were performed at the six axial design points. For the center runs, 4 replications at each center point in the design matrix were completed for a total of 24 replications at the center point. The mean response over all replications was calculated, and this mean was used in the response vector for the design matrix.

Every run was independent. No attempt was made to correlate the runs at the various design points due to the large number of stochastic processes in THUNDER. Synchronization of random numbers in THUNDER is difficult, if not impossible, to achieve. An attempt to use common random numbers may correlate and synchronize processes at the start of a run, but this would soon diverge and synchronization would cease. Banks, Carson, and Nelson suggest that "If synchronization is not possible…, use independent streams of random numbers…" [3:483].

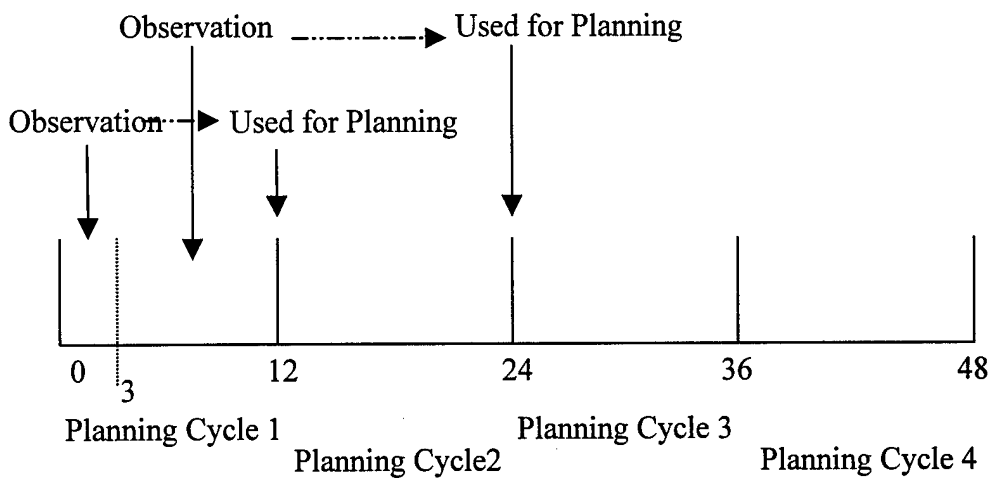
7.4 Parameters

Table 7 summarizes the parameter settings used corresponding to the face-centered CCD matrix of Equation (3). Each factor - quantity, quality, and timeliness - contains parameters within THUNDER varied together for each setting of low, center, and high. Only the Blue side's parameters were changed for the experiment, Red capabilities were left untouched.

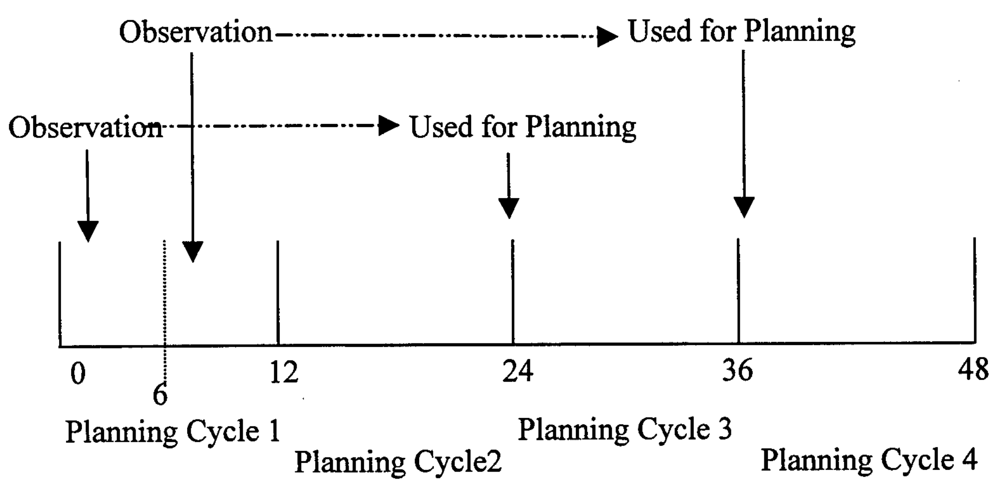
Table 7. Parameter Settings for each Factor Level

Factor	Parameters	Low	Center	High
Quality	Perception (Live as Live)	0.25	0.5	0.75
	Two-Sigma Target Location Error	5000	2550	100
	Ground War Multiplier (Lethality and Availability)	1.5	2.25	3.0
	SREC Air-to-Ground Update	.25	.5	.75
Timeliness	Processing Time	18	13.5	9
Quantity	Probability In Coverage	0.25	0.5	0.75
	Probability of Initial Coverage	0.25	0.5	0.75
	Probability of Lost Observation	0.75	0.5	0.25

The "Low" setting represents the study's worst ISR capability, with "High" being the best. "Center" represents the center point. Some preliminary results from an AFSAA study [52] indicate little difference in some battle outcomes between the absolute extremes (such as 0 and 1.0) for the above parameters. Therefore, 0.25 and 0.75 are used as the extremes. The Two-Sigma Target Location Error setting was used in the AFSAA study as was the Processing Time. The Processing Time was set at 9 and 18 so that the effect wouldn't just be to shift the effects to the next Air Planning Cycle (the usual Air Planning Cycle in THUNDER is 12 hours). By choosing 9 as the "High" setting, any observation taken before hour 3 of the Cycle is available for planning the next Cycle. Anything taken after hour 3 is not available until the next Cycle has already been planned (Figure 33a). By choosing 18 as the "Low" setting, nothing is available for the next Planning Cycle, but if the observation is made before hour 6, it is available to plan for the third Planning Cycle. Anything after hour 6 is not available until the fourth Planning Cycle (Figure 33b). Choosing these settings adds randomness in that the availability may be similar at both settings, or it may be two Cycles apart, but it will not just shift the planning over a cycle.



a) Processing Time set to 9



b) Processing Time set to 18

Figure 33. Processing Time Parameters Impact on Air Planning Cycle

7.5 Measures of Outcome (MOO)/Measures of Effectiveness (MOE)

Five MOO/MOEs were chosen corresponding to battle outcomes expected to demonstrate sensitivity to ISR capabilities. These measures are:

- Total Red ground equipment killed. Equipment includes tanks, infantry vehicles, armored personnel carriers, trucks, and artillery.
- Red equipment killed in ground battle.
- Red equipment killed by air missions.
- Air Loss Exchange Ratio: Ratio of Red air losses to Blue air losses. Air Losses include air-to-air losses, surface-to-air losses, and aircraft lost on the ground.
- Percentage of Red strategic targets killed. Strategic targets include Nuclear, Biological, Chemical (NBC) facilities, communication centers, command bunkers, refineries, power plants, and air defense radars.

7.6 Statistical Analysis Methods

To illustrate the responsiveness of THUNDER to ISR input parameters, a combination of statistical methods was used based upon least squares linear regression and determining the difference between two means.

7.6.1 Least Squares Linear Regression

Linear regression involves using independent predictor variables to estimate a model, or function, that can be used to predict a response. A first-order model is represented by the following equation:

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \qquad (4)$$

where y is the response variable, x_i are the independent variables (or factors), β_i are the regression coefficients which represent the expected change in response y per unit change in x_i when all remaining independent variables x_j ($i \neq j$) are held constant. ε is the error term which is assumed to be independent and identically normally distributed with a mean of zero and constant variance.

The term "linear" regression is used because the model is linear in the parameters of β_i. Often, first order models (first order referring to the independent x variables) are not adequate in representing the model relationships. If curvature exists or interaction terms are significant, second order models must be used. This study uses second order models to fit the responses. An example of a second order model is shown below:

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \varepsilon \tag{5}$$

The method of least squares calculates the β's such that the sum of the squares of the errors, ε's, are minimized. An error is the difference between the observed value and the corresponding value predicted by the fitted model.

7.6.2 Testing for Significance of Individual Regression Coefficients

Variables that are not important to the model can cause the mean square error to increase and therefore decrease the usefulness of the model [36:31]. To ensure that only significant variables are included, a t-test is used. The null hypothesis is H_o: $\beta_j = 0$, with the alternative of H_A: $\beta_j \neq 0$. If the null hypothesis is not rejected, the coefficient, β_j, for the x_j variable is not significant, and x_j is removed from the model. The test statistic is given by

$$t_0 = \frac{b_j}{\sqrt{\hat{\sigma}^2 C_{jj}}} \tag{6}$$

where b_j is the estimate of β_j, and C_{jj} is the diagonal element of $(\mathbf{X'X})^{-1}$ corresponding to b_j, where **X** represents the matrix of independent x variables. The null hypothesis is rejected if $|t_0| > t_{\alpha/2,n-k-1}$, where n is sample size and k is the number of independent variables. The t-test was used in this study during the "screening" phase to determine which variables to include in the model. A p-value was computed to determine whether or not to accept or reject the null hypothesis. A p-value is the smallest value of α for which the null hypothesis can be rejected [35:432]. For this study, a variable with a p-value of greater than 0.10 was considered insignificant.

7.6.3 Testing for Significance of Regression

Testing for significance of regression determines whether any of the β_j coefficients are significant. The null hypothesis is H_o: $\beta_1 = \beta_2 = \ldots = \beta_k = 0$, with an alternative of H_a: Not all β_i equal zero. Rejecting the null hypothesis implies that at least one of the independent variables is significant to the model. The test statistic is

$$F_o = \frac{SS_R / k}{SS_E /(n-k-1)} = \frac{MS_R}{MS_E} \tag{7}$$

where SS_R is the sum of squares due to the model (or regression) and SS_E is the sum of squares due to the residual (or error). The formulas for these estimates are

$$SS_R = b'X'y - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n} \tag{8}$$

$$SS_E = y'y - b'X'y \tag{9}$$

H_o is rejected if $F_o > F_{\alpha, k, n-k-1}$. A p-value is computed for this test statistic to determine whether or not the model is significant. In this study, the model was considered significant if the p-value is less than 0.05.

The coefficient of multiple determination, R^2, is another estimate that implies the appropriateness of the model. R^2 is the measure of the amount of reduction in the variability of the response obtained from the independent variables used [36:30].

$$R^2 = \frac{SS_R}{SS_R + SS_E} \tag{10}$$

However, adding an independent variable will always increase R^2, so a better measure is given by an adjusted R^2, which does not always increase with the addition of a variable.

$$R^2{}_{adj} = 1 - \frac{SS_E/(n-p)}{(SS_R + SS_E)/(n-1)} \tag{11}$$

where p is the number of β_i's. Higher $R^2{}_{adj}$ values indicate a better fit to the data.

To verify that model assumptions are not violated, residual analysis is performed. This involves verifying that the error terms, ε_i's, are independent and identically normally distributed with mean zero and constant variance. For this study, a scatter plot of the residuals against the predicted vales was used to visually verify independence and constant variance. The Shapiro Wilk test was used to verify normality. The null hypothesis of the test is that the distribution is normal. For this study, residuals with a p-value of less than 0.05 were considered non-normal.

7.6.4 Testing for Significant Differences in Mean/Median Response

Ninety-percent confidence intervals were constructed between each of the first eight design points to test for differences in mean/median response. For design points that had normally distributed data, 90% two-sample-t confidence intervals, assuming unequal variances, were constructed. Law and Kelton [33:319] state that constructing confidence intervals to test for differences in mean response is preferable to testing the hypothesis that the mean responses are equal for the following two reasons:

1. Since the model is only an approximation to the system, (the hypothesis) will clearly be false in almost all cases [33:319].

2. A confidence interval provides more information than the corresponding hypothesis test. If the hypothesis test indicates that (the means are not equal), then the confidence interval will provide this information and also give an indication of the magnitude by which (the mean of the first system) differs from (the mean of the second system) [33:319].

Because the replications between design points were independent, and equal variances could not be assumed, the two-sample-t confidence interval first introduced by Welch in 1938 was used [33:589]. The confidence intervals were formed in the following manner. Let X_1 and X_2 be the average of the responses for two design points, and X_{1j} and X_{2j} be the j^{th} response in the corresponding design point. Calculate the following equations:

$$X_i = \sum_{j=1}^{30} X_{ij} \tag{12}$$

$$S^2{}_i = \frac{\sum_{j=1}^{30} \left[X_{ij} - X_i\right]^2}{29} \tag{13}$$

for i=1,2. Degrees of freedom are estimated as:

$$f = \frac{\left[S^2{}_1 / 30 + S^2{}_2 / 30\right]^2}{\left[S^2{}_1 / 30\right]^2 / 29 + \left[S^2{}_2 / 30\right]^2 / 29} \tag{14}$$

The 90% confidence interval is given by:

$$X_1 - X_2 \pm t_{f,.95} \sqrt{\frac{S^2{}_1}{30} + \frac{S^2{}_2}{30}} \tag{15}$$

The "f" value was rounded down to the nearest integer to find the t-value. There is a significant difference in mean response between design points if the confidence interval does not contain zero.

For the design points that did not have normally distributed data, a non-parametric test based on the Wilcoxon Rank Sum test (also called the Mann-Whitney test) was used to construct the 90% confidence intervals for difference in median response. This non-parametric test does not assume normality of the data. The assumptions that must be met are:

1. Both samples are random samples from their respective populations [6:216].
2. In addition to independence within each sample, there is mutual independence between the two samples [6:216].
3. The measurement scale is at least ordinal [6:216].

The procedure for calculating a 90% confidence interval for difference in the median is as follows. Obtain ordered values, $U^{(1)} \leq \ldots \leq U^{(mn)}$ of $X_{1i} - X_{2j}$ for i=1…m and j=1….n, with m and n being the sample sizes. The lower bound for the 90% confidence interval is $U^{(C)}$, and the upper bound is $U^{(mn+1-C)}$. For a 90%

confidence interval, C can be approximated [25:79] by

$$C_{.9} \approx \frac{mn}{2} - z_{(.05)}\left[\frac{mn(m+n+1)}{12}\right]^{1/2} \qquad (16)$$

A significant difference in median response between design points is concluded if the confidence interval does not contain zero.

7.7 Results

For each MOO/MOE, a screening experiment was performed to determine significant variables to include in the model. The t-test for significant coefficents was used, as well as a graphical look at the influence of quality, quantity, and timeliness. The model was then constructed and verified with the F-test for linear significance. All models proposed in this study passed the model assumptions for the residuals. The model yields a response function that was used to form a surface plot. For each MOO/MOE, three surfaces plots are shown, each corresponding to timeliness set at either the low, center, or high level; Air Loss Exchange Ratio has quality at the various settings. Each surface has quantity and quality plotted on the two horizontal axes, with the response of the MOO/MOE on the z-axis; Air Loss Exchange Ratio has quantity and timeliness plotted on the axes. Twenty-five coordinates, corresponding to quantity and quality set at -1, -0.5, 0, .5, and 1 were used to construct the surface plots; the rest of the points were interpolated by Mathcad software. Finally, a table indicating differences in mean/median response among the first eight design points is shown. The 90% confidence intervals for each MOO/MOE can be found in Appendix B.

Table 8 shows the results of the experiments for each design point and each MOO/MOE. Analysis of each MOO/MOE follows.

Table 8. Design Matrix and Mean Responses for each MOO/MOE

	FACTORS			MOO/MOEs				
Design Point	**Quality**	**Quantity**	**Timeliness**	**Equipment Killed**	**Equipment Killed by Ground**	**Equipment Killed Per Mission**	**Red/Blue Air Losses**	**% Strat Tgts Killed**
1	-1	-1	-1	7121.50	6323.93	49.45	1.23	0.67
2	-1	-1	1	7142.27	6266.53	59.42	1.19	0.67
3	-1	1	-1	7209.23	6085.30	105.60	1.62	0.77
4	-1	1	1	7253.63	6092.73	112.98	1.57	0.79
5	1	-1	-1	7925.76	7028.03	108.01	1.28	0.80
6	1	-1	1	8131.47	7399.70	87.94	1.15	0.80
7	1	1	-1	8140.70	7265.13	88.17	1.53	0.88
8	1	1	1	8253.07	7283.47	89.22	1.55	0.88
9	-1	0	0	7201.95	6211.00	103.95	1.61	0.73
10	1	0	0	8269.70	7245.00	94.38	1.55	0.82
11	0	-1	0	7809.60	7172.00	87.85	1.33	0.87
12	0	1	0	7848.80	6942.00	111.78	1.64	0.85
13	0	0	-1	7790.05	7028.00	94.23	1.47	0.85
14	0	0	1	7823.60	6913.00	96.89	1.58	0.85
15	0	0	0	7775.75	6931.25	104.98	1.64	0.89
16	0	0	0	7926.25	6995.50	139.87	1.68	0.86
17	0	0	0	7866.25	6932.00	153.59	1.74	0.86
18	0	0	0	7834.75	6916.00	172.69	1.63	0.87
19	0	0	0	7857.50	6943.75	128.60	1.62	0.87
20	0	0	0	7836.50	6903.00	104.06	1.47	0.86

7.7.1 Total Red Equipment Killed

7.7.1.1 Screening Experiment

Table 9 and Figure 34 summarize the results of the screening experiment for Total Red Equipment Killed. Significant factors are indicated by a Prob > |t| of less than 0.10 in Table 9. Figure 34 graphically shows the relative sensitivity of the main factors. For this MOO/MOE, the significant factors are Quality, Quantity, Timeliness and Quality^2.

Table 9. Screening Fit for Total Red Equipment Killed

	Parameter Estimates			
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	7853.230	17.753	442.37	<.0001
Quality	479.211	16.330	29.35	**<.0001**
Quantity	57.484	16.330	3.52	**0.0055**
Timeliness	41.679	16.330	2.55	**0.0288**
Quality*Quality	-123.001	31.140	-3.95	**0.0027**
Quantity*Quality	17.180	18.258	0.94	0.3689
Quantity*Quantity	-29.626	31.140	-0.95	0.3638
Timeliness*Quality	31.614	18.258	1.73	0.114
Timeliness*Quantity	-8.714	18.258	-0.48	0.6434
Timeliness*Timeliness	-52.001	31.140	-1.67	0.1259

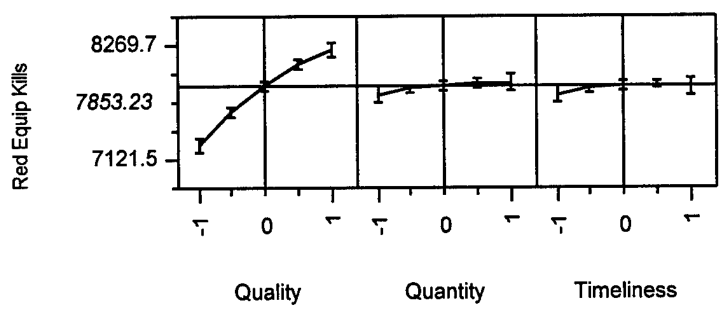


Figure 34. Total Red Equipment Killed Prediction Profile

7.7.1.2 Model

The response model is:

$$\hat{y} = 7836.905 + 479.211 \times Quality + 57.484 \times Quantity + 41.679 \times Timeliness - 171.978 \times Quality^2 \quad (17)$$

The model parameter estimates are shown in Table 10.

Table 10. Total Red Equipment Killed Model Parameter Estimates

Parameter Estimates				
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	7836.905	18.760	417.75	<.0001
Quality	479.211	18.760	25.54	<.0001
Quantity	57.484	18.760	3.06	0.0079
Timeliness	41.679	18.760	2.22	0.0421
Quality*Quality	-171.978	26.531	-6.48	<.0001

The R^2_{Adj} for the model is high (Table 11), and the model is significant (Table 12).

Table 11. Total Red Equipment Model Summary of Fit

RSquare	0.97928
RSquare Adj	**0.97375**
Root Mean Square Error	59.3242
Mean of Response	7750.92
Observations (or Sum Wgts)	20

Table 12. Total Red Equipment Killed Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	2494727.5	623682	177.215
Error	15	52790.4	3519	Prob>F
C Total	19	2547517.9		**<.0001**

7.7.1.3 Response Surface

The response surfaces for Total Red Equipment Killed are seen in Figure 35. These indicate that Total Red Equipment Killed is very sensitive to the Quality factor. As Quality increases, there are relatively large increases in Total Red Equipment killed.

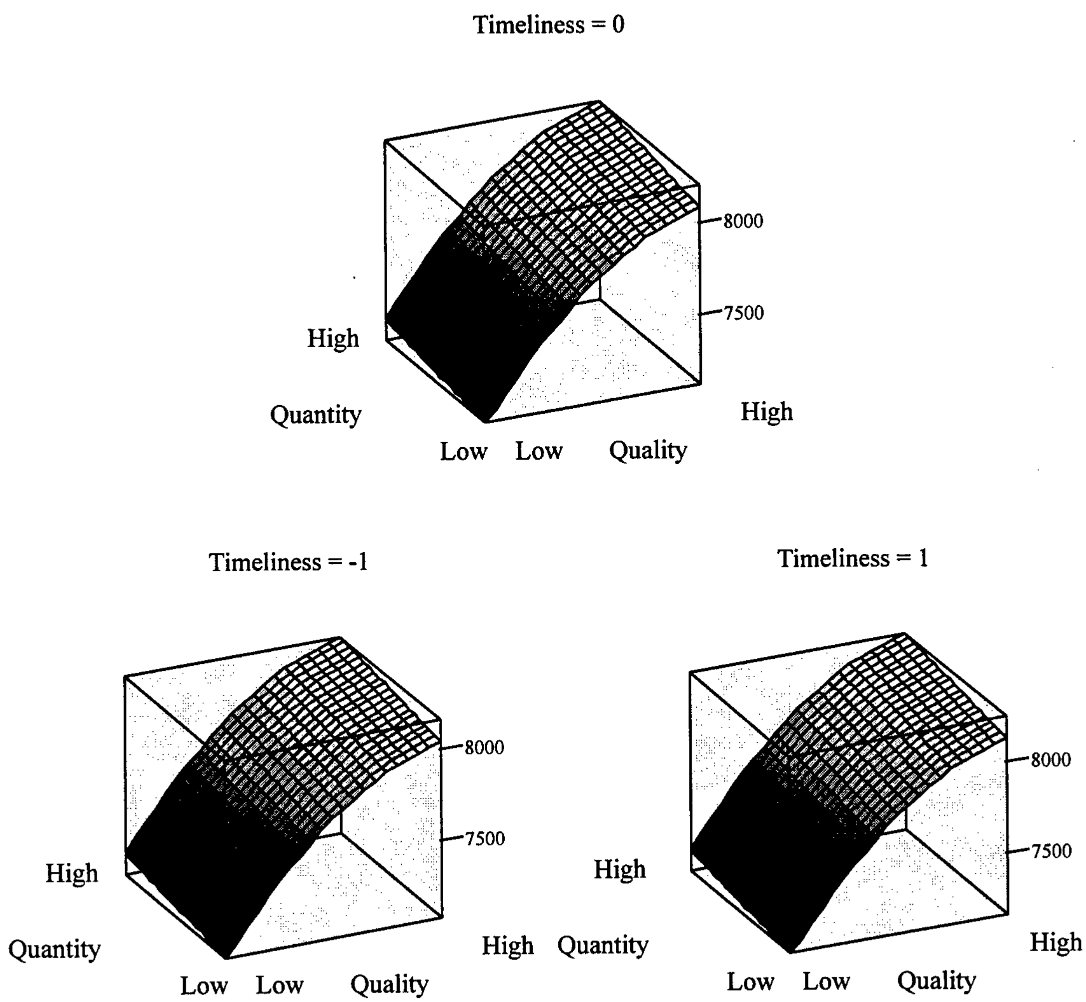


Figure 35. Response Surfaces for Total Red Equipment Killed Model

The Quantity factor plays a slight role in increasing the number of equipment killed as it moves to the "high" setting. Timeliness has even less of an effect than Quantity.

7.7.1.4 Significant Differences

Table 13 indicates significant differences in mean/median response among the first eight design points. Since the table is symmetric, only the upper half has been filled. Referring back to Equation (3), Design Points 1-4 have Quality set at "low", and Design Points 5-8 have Quality set at "high". Whenever Quality changes from "low" to "high", there is a significant difference, as is evidenced by the upper right 16 blocks. Within Design Points 1-4, there is a difference when Quality changes. Within Design Points 5-8, differences mainly exist with Design Point 8. Referring to Appendix B, we see that the differences within Design Points 1-4 and 5-8 are an order of magnitude lower than the differences between the groups. This indicates, and confirms, that Quality is the most important factor for Total Red Equipment Killed.

Table 13. Significant Differences in Total Red Equipment Killed

Design Point	1	2	3	4	5	6	7	8
1	■	■	■	□	□	□	□	□
2	■	■	■	□	□	□	□	□
3	■	■	■	■	□	□	□	□
4	■	■	■	■	□	□	□	□
5	■	■	■	■	■	■	■	□
6	■	■	■	■	■	■	■	□
7	■	■	■	■	■	■	■	□
8	■	■	■	■	■	■	■	■

□ = Significant Difference
■ = No Significant Difference

7.7.2 Red Equipment Killed in Ground Battle

7.7.2.1 Screening Experiment

The screening experiment for Red Equipment Killed in Ground Battle, shown in Table 14 and Figure 36, calculated the significant factors to be Quality, Quantity, Timeliness, Quality^2, Quantity*Quality, and Timeliness*Quality. Note that Timeliness was not significant by itself, but was included because the interaction term, Timeliness*Quality, was significant.

Table 14. Screening Fit for Red Equipment Killed in Ground Battle

Parameter Estimates				
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	6960.708	27.643	251.81	<.0001
Quality	524.183	25.428	20.61	**<.0001**
Quantity	-52.157	25.428	-2.05	**0.0674**
Timeliness	22.503	25.428	0.88	**0.3969**
Quality*Quality	-268.394	48.489	-5.54	**0.0002**
Quantity*Quality	66.663	28.429	2.34	**0.041**
Quantity*Quantity	60.606	48.489	1.25	0.2398
Timeliness*Quality	54.996	28.429	1.93	**0.0818**
Timeliness*Quantity	-36.063	28.429	-1.27	0.2334
Timeliness*Timeliness	-25.894	48.489	-0.53	0.605

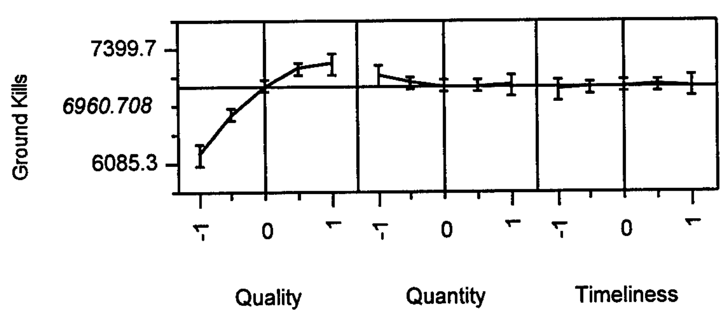


Figure 36. Red Equipment Killed in Ground Battle Prediction Profile

7.7.2.2 Model

The response model is:

$$\hat{y} = 6967.65 + 524.183 \times Quality - 52.157 \times Quantity + 22.503 \times Timeliness$$
$$- 247.567 \times Quality^2 + 66.663 \times Quality \times Quantity \qquad (18)$$
$$+ 54.996 \times Quality \times Timeliness$$

The model parameters are shown in Table 15.

Table 15. Red Equipment Killed in Ground Battle Parameter Estimates

	Parameter Estimates			
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	6967.650	25.600	272.18	<.0001
Quality	524.183	25.600	20.48	<.0001
Quality*Quality	-247.567	36.204	-6.84	<.0001
Quantity	-52.157	25.600	-2.04	0.0625
Timeliness	22.503	25.600	0.88	0.3953
Quality*Quantity	66.663	28.621	2.33	0.0366
Quality*Timeliness	54.996	28.621	1.92	0.0769

The R^2_{Adj} (Table 16) is high, and the model is significant as seen in Table 17.

Table 16. Red Equipment Killed in Ground Battle Model Summary of Fit

RSquare	0.97364
RSquare Adj	**0.96147**
Root Mean Square Error	80.9536
Mean of Response	6843.87
Observations (or Sum Wgts)	20

Table 17. Red Equipment Killed in Ground Battle Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	3146142.6	524357	80.0119
Error	13	85195.3	6553	Prob>F
C Total	19	3231337.9		**<.0001**

7.7.2.3 Response Surface

The response surfaces for Red Equipment Killed in Ground Battle are shown in Figure 37. The Quality factor is again the most influential on the model response, with Quantity at a distant second. When Quality is set at "low", Equipment Killed actually decreases slightly as Quantity increases.

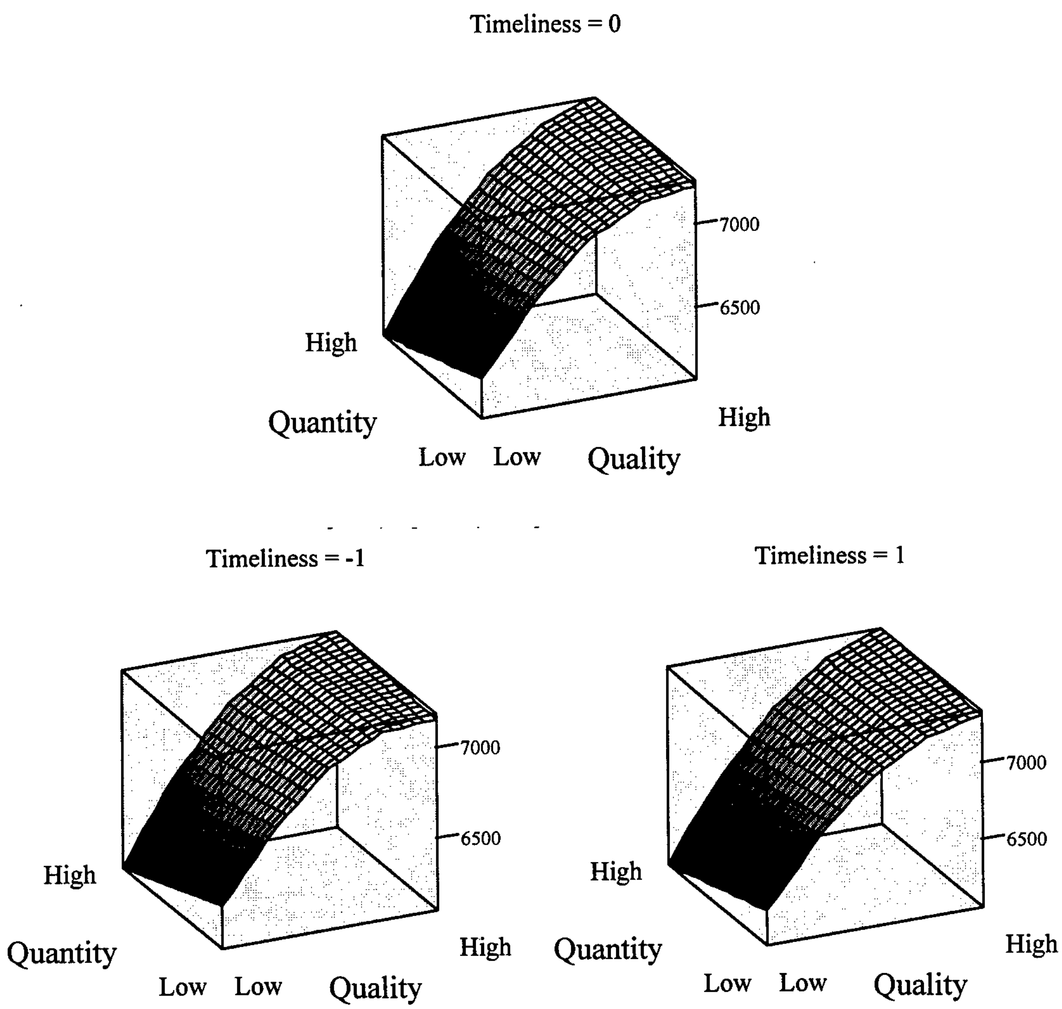


Figure 37. Response Surfaces for Red Equipment Killed in Ground Battle Model

7.7.2.4 Significant Differences

Table 18 indicates if there is a significant difference in mean/median response among the first eight design points. Again, there are always differences when Quality moves from "low" to "high". No differences exist when only Timeliness changes.

Table 18. Significant Differences in Red Equipment Killed in Ground Battle

Design Point	1	2	3	4	5	6	7	8
1								
2								
3								
4								
5								
6								
7								
8								

= Significant Difference
= No Significant Difference

7.7.3 Red Equipment Killed by Air Missions

7.7.3.1 Screening Experiment

The following factors are significant for Red Equipment Killed by Air Missions as shown in Table 19 and Figure 38: Quality, Quantity, Timeliness, Quality^2, Quantity^2, and Quantity * Quality.

Table 19. Screening Fit for Red Equipment Killed by Air Missions

Parameter Estimates				
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	914.920	12.499	73.2	<.0001
Quality	-87.150	11.497	-7.58	**<.0001**
Quantity	124.880	11.497	10.86	**<.0001**
Timeliness	31.505	11.497	2.74	**0.0208**
Quality*Quality	70.650	21.924	3.22	**0.0091**
Quantity*Quality	-25.731	12.854	-2	**0.0732**
Quantity*Quantity	-48.850	21.924	-2.23	**0.05**
Timeliness*Quality	-2.394	12.854	-0.19	0.856
Timeliness*Quantity	1.556	12.854	0.12	0.906
Timeliness*Timeliness	-18.375	21.924	-0.84	0.4215

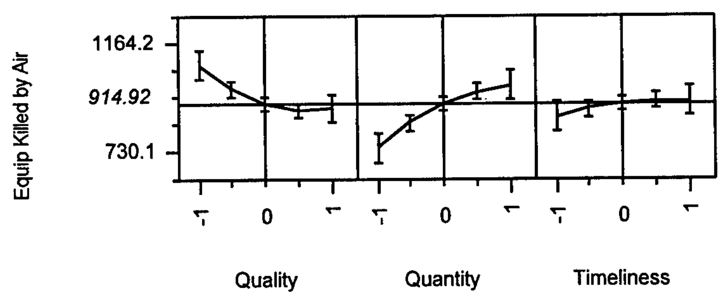


Figure 38. Red Equipment Killed by Air Missions Prediction Profile

7.7.3.2 Model

The response model is:

$$\hat{y} = 912.623 - 87.150 \times Quality + 124.880 \times Quantity + 31.505 \times Timeliness$$
$$+ 63.759 \times Quality^2 - 55.741 \times Quantity^2 - 25.731 \times Quantity \times Quality \quad (19)$$

The model parameter estimates are summarized in Table 20.

Table 20. Red Equipment Killed by Air Missions Parameter Estimates

Parameter Estimates				
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	912.623	11.090	82.29	<.0001
Quality	-87.150	10.456	-8.34	<.0001
Quantity	124.880	10.456	11.94	<.0001
Timeliness	31.505	10.456	3.01	0.01
Quality*Quality	63.759	18.484	3.45	0.0043
Quantity*Quality	-25.731	11.690	-2.2	0.0464
Quantity*Quantity	-55.741	18.484	-3.02	0.0099

The R^2_{Adj} is fairly high for this model as seen in Table 21. The model is significant as can be seen in Table 22.

Table 21. Red Equipment Killed by Air Missions Model Summary of Fit

RSquare	0.94848
RSquare Adj	**0.92471**
Root Mean Square Error	33.0644
Mean of Response	916.633
Observations (or Sum Wgts)	20

Table 22. Red Equipment Killed by Air Missions Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	261661.25	43610.2	39.8902
Error	13	14212.33	1093.3	Prob>F
C Total	19	275873.58		**<.0001**

7.7.3.3 Response Surface

The response surfaces for Red Equipment Killed by Air Missions are seen in Figure 39. Unlike previous models, Quantity has the biggest effect on the responses, with Quality also causing changes. Timelines has a small impact as evidenced by the surface shifting down when it is set to “low”.

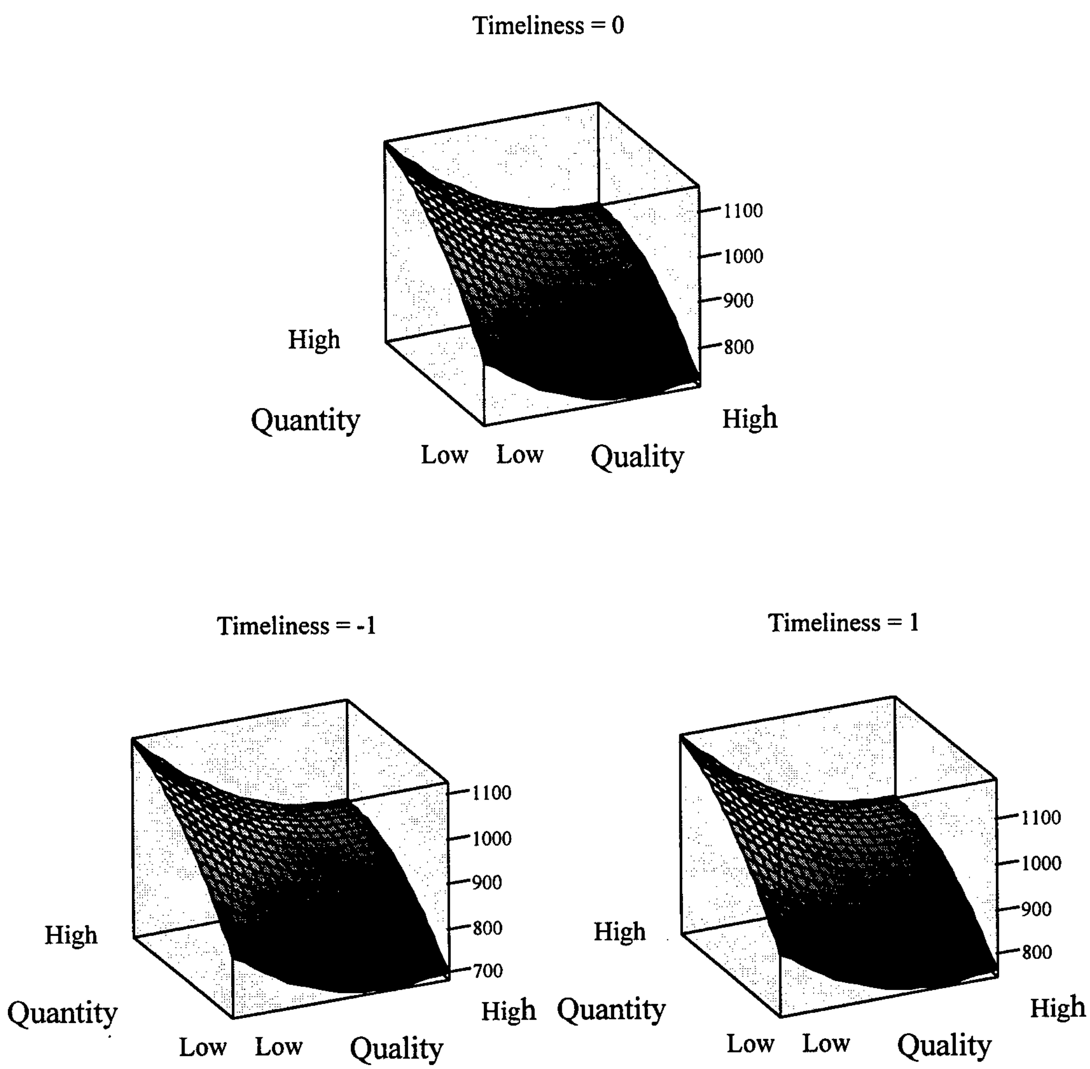
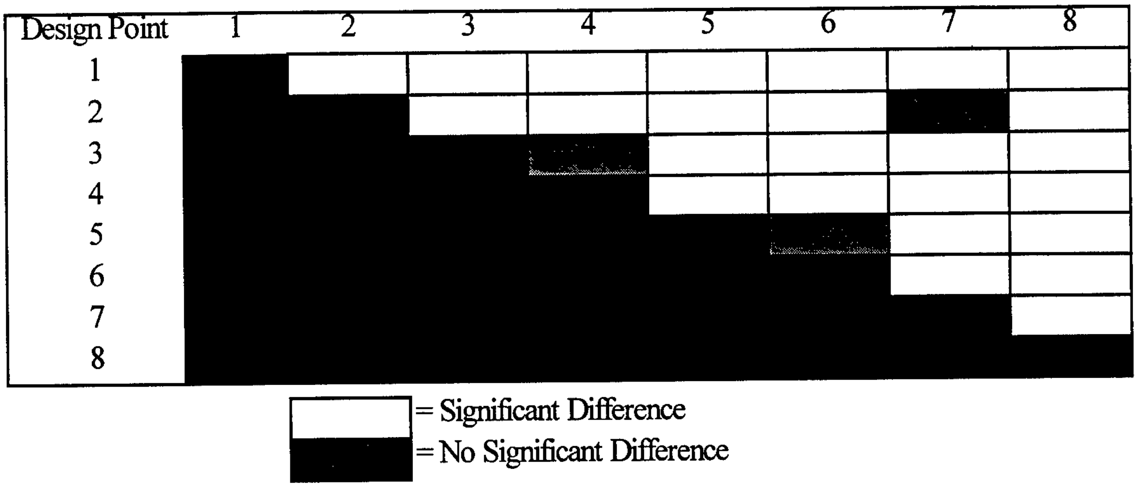


Figure 39. Response Surfaces for Red Equipment Killed by Air Missions

7.7.3.4 Significant Differences

Table 23 indicates if there is a significant difference in mean/median response among the first eight design points. Design Point pairs 3 & 4 , and 5 & 6 differ only by Timeliness. This MOE has the most significant differences among the Design Points.

Table 23. Significant Differences in Red Equipment Killed by Air Missions



7.7.4 Air Loss Exchange Ratio

7.7.4.1 Screening Experiment

Table 24 and Figure 40 summarize the significant factors for Air Loss Exchange Ratio found through the screening experiment to be Quantity, Timeliness, Quantity^2, and Timeliness^2. Timeliness was included because Timeliness^2 was significant.

Table 24. Screening Fit for Air Loss Exchange Ratio

Parameter Estimates				
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	1.620	0.026	63.06	<.0001
Quality	-0.016	0.024	-0.67	0.5156
Quantity	0.173	0.024	7.3	**<.0001**
Timeliness	-0.010	0.024	-0.42	**0.68**
Quality*Quality	-0.029	0.045	-0.64	0.5372
Quantity*Quality	-0.014	0.026	-0.54	0.6016
Quantity*Quantity	-0.122	0.045	-2.71	**0.0221**
Timeliness*Quality	-0.001	0.026	-0.05	0.9625
Timeliness*Quantity	0.016	0.026	0.61	0.5529
Timeliness*Timeliness	-0.081	0.045	-1.8	**0.1014**

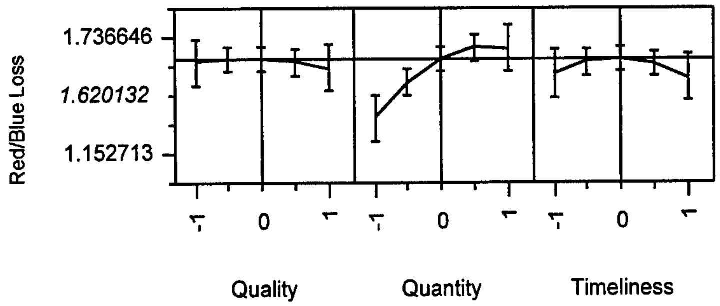


Figure 40. Air Loss Exchange Ratio Prediction Profile

7.7.4.2 Model

The response model is:

$$\hat{y} = 1.617 + 0.173 \times Quantity - 0.010 \times Timeliness - 0.133 \times Quantity^2 - 0.092 \times Timeliness^2 \quad (20)$$

The model parameters are shown in Table 25.

Table 25. Air Loss Exchange Ratio Model Parameter Estimates

Parameter Estimates				
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	1.617	0.02198	73.55	<.0001
Quantity	0.173	0.02072	8.33	<.0001
Timeliness	-0.010	0.02072	-0.48	0.6351
Quantity*Quantity	-0.133	0.03663	-3.62	0.0025
Timeliness*Timeliness	-0.092	0.03663	-2.51	0.0238

The R^2_{Adj} (Table 26) is fairly high, and the model is significant (Table 27).

Table 26. Air Loss Exchange Ratio Model Summary of Fit

RSquare	0.88646
RSquare Adj	**0.85618**
Root Mean Square Error	0.06553
Mean of Response	1.50412
Observations (or Sum Wgts)	20

Table 27. Air Loss Exchange Ratio Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	0.503	0.126	29.2767
Error	15	0.064	0.004	Prob>F
C Total	19	0.567		**<.0001**

7.7.4.3 Response Surface

The response surfaces for the Air Loss Exchange Ratio are seen in Figure 41. Note that the axes are Quantity and Timeliness since Quality is not in the model. Quantity has the largest effect on the response. The highest response is when Timeliness is near the "Center". Quality has no effect.

7.7.4.4 Significant Differences

Table 28 indicates if there is a significant difference in mean/median response among the first eight design points. This MOE has the fewest number of significant differences among Design Points. In fact, except for the pair 3 & 8, the only significant differences are present when Quantity is different between the Design Points. Referring to Appendix B, the difference between 3 & 8 is barely significant, with a lower bound at 0.02.

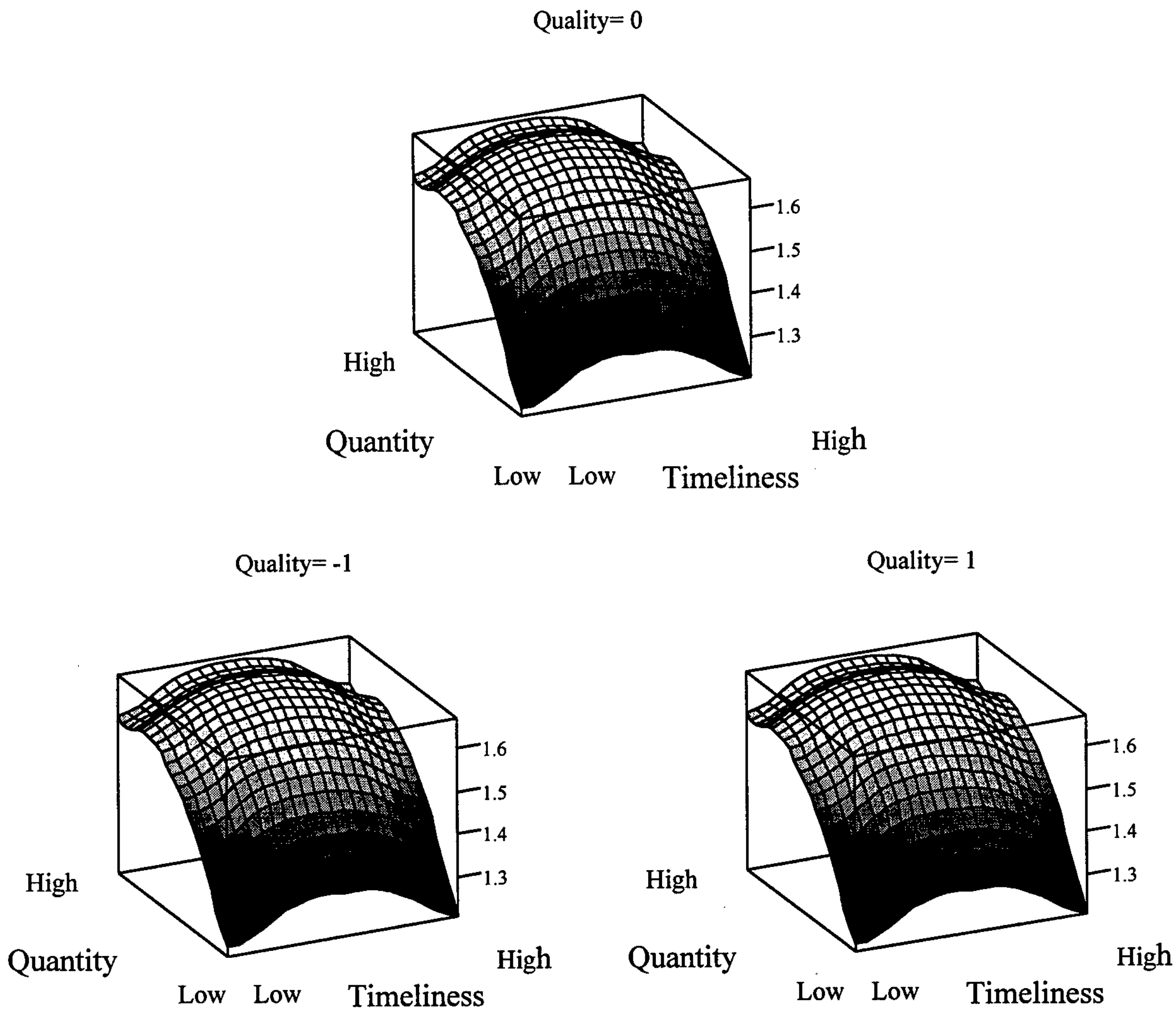
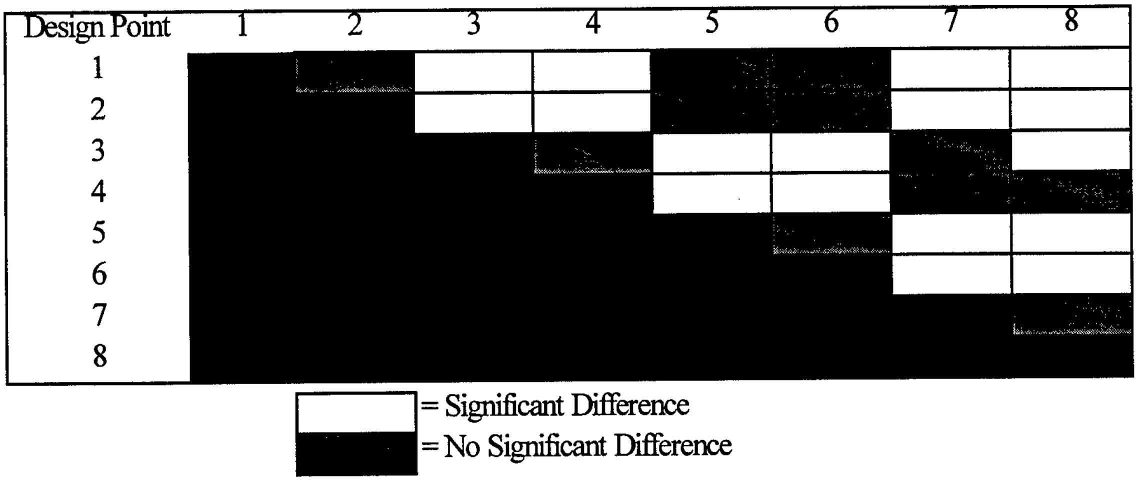


Figure 41. Response Surfaces for Air Loss Exchange Ratio Model

Table 28. Significant Differences in Air Loss Exchange Ratio



7.7.5 Percentage of Red Strategic Targets Killed

7.7.5.1 Screening Experiment

The significant factors for the Percentage of Red Strategic Targets Killed are Quality, Quantity, and Quality^2 (shown in Table 29 and Figure 42).

Table 29. Screening Fit for Percentage of Red Strategic Targets Killed

Parameter Estimates				
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	0.863	0.008	103.06	<.0001
Quality	0.056	0.008	7.21	**<.0001**
Quantity	0.036	0.008	4.64	**0.0009**
Timeliness	0.002	0.008	0.21	0.8358
Quality*Quality	-0.082	0.015	-5.61	**0.0002**
Quantity*Quality	-0.007	0.009	-0.87	0.4049
Quantity*Quantity	0.006	0.015	0.42	0.6814
Timeliness*Quality	-0.001	0.009	-0.11	0.9182
Timeliness*Quantity	0.001	0.009	0.11	0.9122
Timeliness*Timeliness	-0.006	0.015	-0.4	0.6973

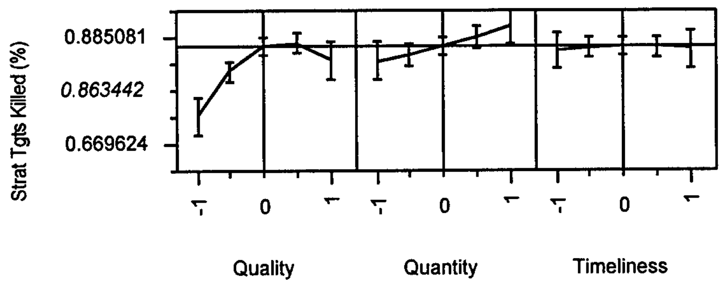


Figure 42. Percentage of Strategic Targets Killed Prediction Profile

7.7.5.2 Model

The response model is:

$$\hat{y} = 0.864 + 0.056 \times Quality + 0.036 \times Quantity - 0.082 \times Quality^2 \qquad (21)$$

The model parameter estimates are shown in Table 30.

Table 30. Percentage of Strategic Targets Killed Model Parameter Estimates

	Parameter Estimates			
Term	Estimate	Std Err	t Ratio	Prob > |t|
Intercept	0.864	0.006	134.69	<.0001
Quality	0.056	0.006	8.67	<.0001
Quality*Quality	-0.082	0.009	-9.08	<.0001
Quantity	0.036	0.006	5.58	<.0001

The R^2_{Adj} (Table 31) is fairly high, and the model is significant as seen in Table 32.

Table 31. Percentage of Red Strategic Targets Killed Model Summary of Fit

RSquare	0.92182
RSquare Adj	**0.90717**
Root Mean Square Error	0.02027
Mean of Response	0.82236

Table 32. Percentage of Red Strategic Targets Killed Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.078	0.026	62.8883
Error	16	0.007	0.000	Prob>F
C Total	19	0.084		**<.0001**

7.7.5.3 Response Surface

The response surfaces for Percentage of Red Strategic Targets Killed are seen in Figure 43. Quality has the largest effect, although Quantity also causes a change in response.

7.7.5.4 Significant Differences

Table 33 indicates if there are significant differences in mean/median response among the first eight design points. Since Timeliness has no impact, there are no significant differences when only Timeliness is changed. This is evidenced in Design Point pairs 1 & 2, 3 & 4, 5 & 6, and 7 & 8.

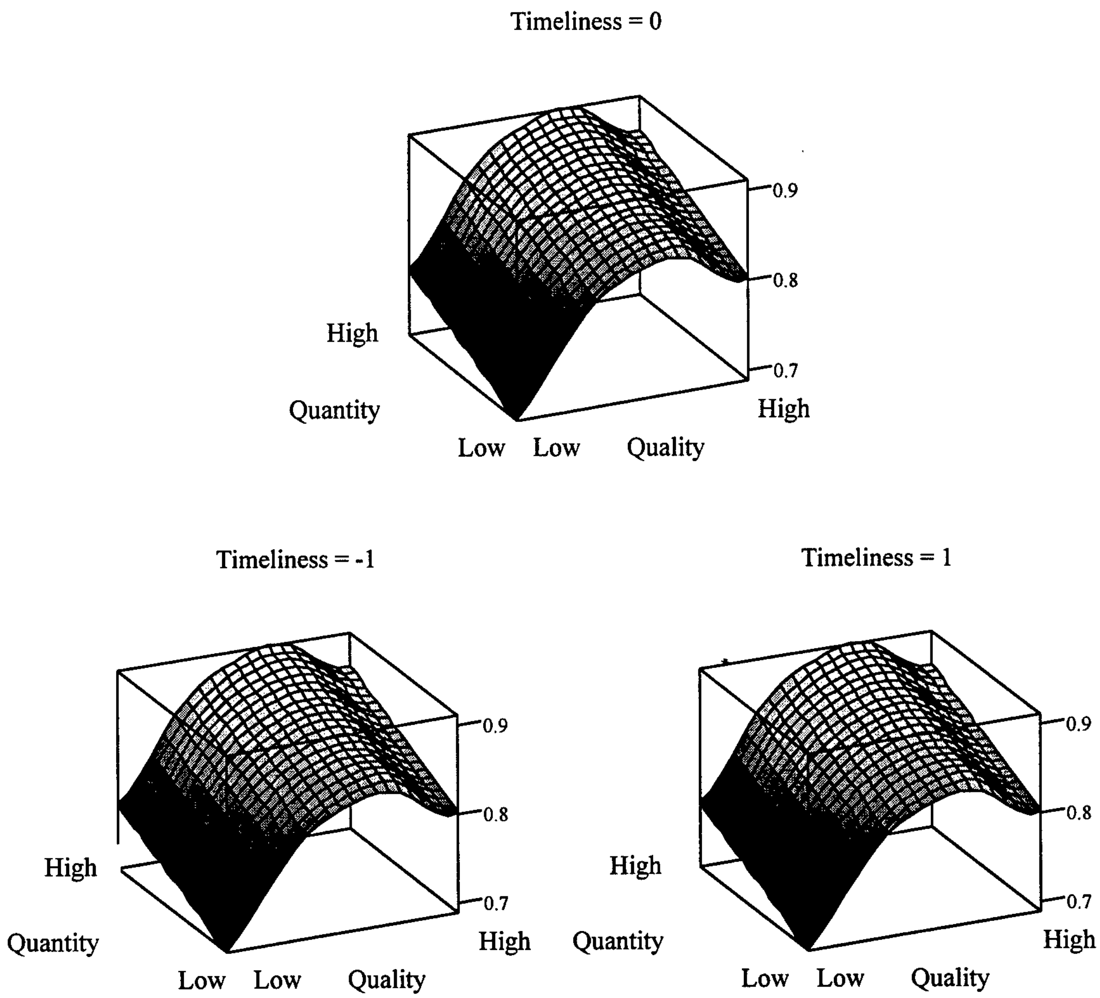
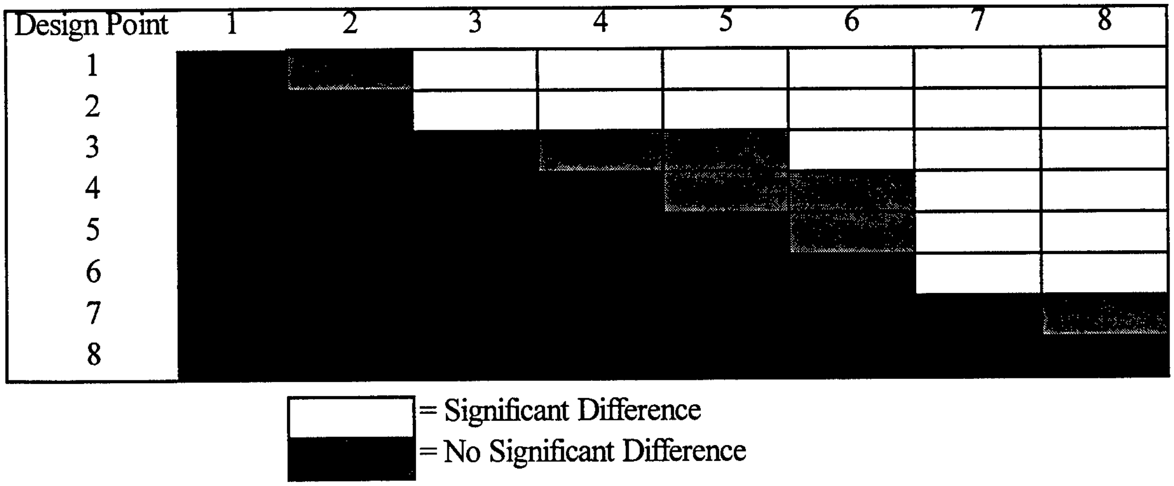


Figure 43. Response Surfaces for Percentage of Red Strategic Targets Killed Model

Table 33. Significant Differences in Percentage of Red Strategic Targets Killed



7.8 Summary and Conclusion

Table 34 summarizes which variables were considered significant in each of the MOO/MOEs, as well as which of the three main factors – Quality, Quantity, or Timeliness – was the most influential. Quality and Quantity had the most influence on the selected MOO/MOEs. Timeliness did not play a very significant role. This is not overly surprising since Timeliness is represented by only one parameter, and if observations are delayed, it is at most for two planning cycles.

Table 35 summarizes the significant differences in mean/median response among the first eight design points. The number in each square is the number of times the two design points were significantly different, across the five MOO/MOEs. From this table we see that Design Point pairs 1and 2, 3 and 4, 5 and 6, and 7 and 8 were rarely significantly different in response. Referring back to the design matrix in Equation (3), these pairs only differ in the Timeliness parameter, again confirming that Timeliness did not play a significant role in battle outcomes.

Table 34. Summary of Significant Factors Over All MOO/MOEs

	MOO/MOEs				
Parameters	Equipment Killed	Equipment Killed by Ground	Equipment Killed by Air	Air Loss Exchange Ratio	% Strat Tgts Killed
Quality	**XXX**	**XXX**	X		**XXX**
Quantity	X	X	**XXX**	**XXX**	X
Timeliness	X	X	X	X	
Quality*Quality	X	X	X		X
Quantity*Quality		X	X		
Quantity*Quantity			X	X	
Timeliness*Quality		X			
Timeliness*Quantity					
Timeliness*Timeliness				X	

X = Included in the Model
XXX = Most Influential among Quality, Quantity, Timeliness

Table 35. Summary of Significant Differences in Mean/Median Response

Design Point	1	2	3	4	5	6	7	8
1		1	4	5	4	4	5	5
2			4	5	4	4	4	5
3				0	4	5	4	5
4					4	4	4	4
5						0	3	4
6							4	5
7								2
8								

Based on the results shown in this chapter, the battle outcomes are responsive to changes in the ISR parameters in THUNDER, with Quality and Quantity parameters causing the most responsiveness. This confirms that THUNDER can be used as a tool for comparative analysis between competing ISR systems.

8. Conclusions and Recommendations

8.1 Validation Assessment of THUNDER's ISR Module

THUNDER is a vital tool for Air Force acquisition and operational planning decisions. With the ever-increasing impact of intelligence on information superiority and battlefield success, THUNDER must represent the ISR aspect of combat with a high degree of fidelity. To neglect this aspect of THUNDER would result in inaccurate assessments and false assumptions about ISR systems and their ability to influence combat outcomes.

The comparison between the real world process and THUNDER's ISR process presented in this study indicates that THUNDER's ISR module has implemented the ISR process with a considerable degree of fidelity, although improvements can be made. Although the processes do involve some aggregation and rely heavily on user input, they do reasonably represent the real world processes, especially in regard to the air war. THUNDER does not capture abstract information and the human decision-making process. It focuses more on winning the battle instead of winning the war. Strategic uses of ISR such as deciding when to strike and where to attack are lost. It is possible to artificially capture some of these aspects through user input, but that makes the already user-intensive input process even more laborious, and somewhat defeats the purpose of having a model to enact the process. These elements are often neglected in campaign-level models, and although they are extremely important issues in the real world, they are not a major degradation of the validity of THUNDER's ISR module.

The experiment performed in this study demonstrated that the battle outcomes of THUNDER reflect the importance of ISR capabilities through their responsiveness to differences in the quality, quantity, and timeliness of ISR. This validates THUNDER's use for comparative analysis between competing ISR systems. It also demonstrates the compounding effects of ISR in THUNDER. Poor ISR results in poor prioritization of targets and poor aircraft/munition selection, which results in low mission effectiveness. Low mission effectiveness results in fewer targets being hit, more missions needed, more Blue targets being hit, more aircraft endangered, *etc*. Because THUNDER reflects these compounding effects, it is that much more important that the processes implemented in THUNDER closely represent the real world process.

The importance of user input in THUNDER cannot be overemphasized. The real flexibility, and some of the resulting validity, of the ISR module comes from the fact that the user can script or influence so many different aspects to capture ISR effects. The capabilities of the sensors, the degradations of their observations over time, and the target prioritization rules must be carefully input as the confidence levels and perception levels of the sensors, and the rules set for target nomination, greatly influence the perceptions of targets and targeting decisions.

8.2 Recommendations

Improvements are possible to increase the precision of THUNDER's ISR module. The goal of improving THUNDER's ISR module is not to make it an explicit, high resolution module, but the following suggestions should help to improve the fidelity of the model bearing in mind the purpose of campaign-level models. Recommendations for improvement are:

- Coordinate among air, satellite, and scripted events to avoid unnecessary redundancy and/or to ensure desired redundancy.
  -- Planning must consider availability of assets.

- Aid in determining ground unit posture through adjustment on force ratio. Allow unit to attack, or not to attack, based on perception of enemy's support status.

- Adjust fusion algorithm to incorporate previous knowledge and other observations available.

- Consider the confidence level of the sensor performing BDA for the target perception and target nomination rules.

- Allow Grid and FLOT sensors to impact the ground war.

- Allow aircraft to carry more than one sensor. Also, more than one sensor can be available for all ISR assets with the best one or two selected depending on target type.

A final recommendation is to ensure that the results found in the experiment conducted in this study are consistent with results that would be found using classified, or more realistic data.

8.3 Final Thought

THUNDER's ISR module is definitely a useful and necessary element. The ISR module has evolved over the past few years and is continually being improved. The recommendations presented above will only enhance THUNDER's utility and capability beyond that which it has already.

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Appendix A: Glossary of Acronyms

ACC	Air Combat Command
AF	Air Force
AFSAA	Air Force Studies and Analyses Agency
AFSATCOM	Air Force Satellite Communications
ASAS	All-Source Analysis System
ATARS	Advanced Tactical Air Reconnaissance Systems
ATCAL	Attrition Calibration
ATO	Air Tasking Order
AUV	Autonomous Underwater Vehicles
AWACS	Airborne Warning and Control System
BAI	Battlefield Air Interdiction
BDA	Battle Damage Assessment
C4I	Command, Control, Communications, Computer, and Intelligence
CAS	Close Air Support
CASCOM	Combined Arms Support Command
CCD	Central Composite Design
CEM	Concept Evaluation Model
CHATS	CI/HUMINT Automated Tool Set
CI	Counterintelligence
CIA	Central Intelligence Agency
CINC	Commander-in-Chief
CNES	Centre National d'Etudes Spatiales
COMINT	Communications Intelligence
COMSEC	Communications Security
COSAGE	Concepts and Analysis Agency's Combat Sample Generator
COSPO	Community Open Source Program Office
DAMA	Demand Assigned Multiple Access
DEA	Drug Enforcement Agency
DIA	Defense Intelligence Agency
DIDS	Defense Intelligence Dissemination System
DISN	Defense Information System Network
DO	Directorate for Intelligence Operations
DoD	Department of Defense
DoDIIS	DoD Intelligence Information System
DSCS	Defense Satellite Communications System
DSP	Defense Support Program

EA	Electronic Attack
ECM	Electronic Countermeasures
EHF	Extremely-High Frequency
ELINT	Electronic Intelligence
ENSCE	Enemy Situation Correlation Element
ESAMS	Enhanced Surface to Air Missile Simulation
FAX	Facsimile
FBI	Federal Bureau of Investigation
FISINT	Foreign Instrumentation Signals Intelligence
FLOT	Forward Line of Troops
GBCS	Ground-Based Common Sensor
GBS	Global Broadcast Service
GCCS	Global Command and Control System
GPS	Global Positioning System
HQ	Headquarters
HUMINT	Human Intelligence
ICBM	Intercontinental Ballistic Missile
IDHS	Intelligence Data Handling Systems
IMINT	Imagery Intelligence
INF	Intermediate-Range Nuclear Forces
INFOSEC	Information Security
INMARSAT	International Maritime Satellite
INSCOM	Intelligence and Security Command
IPB	Intelligence Preparation of the Battlefield
INTELSAT	International Telecommunications Satellite
ISR	Intelligence, Surveillance, and Reconnaissance
JAOC	Joint Air Operations Center
JC2WC	Joint Command and Control Warfare Center
JDISS	Joint Deployable Intelligence Support System
JFACC	Joint Force Air Component Commander
JFC	Joint Force Commander
JFLCC	Joint Land Component Commander
JFSOCC	Joint Force Special Ops Component Commander
JIC	Joint Intelligence Center
JISE	Joint Intelligence Support Element
JSIPS	Joint Service Imagery Processing System
J-STARS	Joint Surveillance Target Attack Radar System
JTF	Joint Task Force
JWICS	Joint Worldwide Intelligence Communications System

MASINT	Measurement and Signature Intelligence
MCIA	Marine Corps Intelligence Activity
ME	Middle East
MILSATCOM	Military Satellite Communications
MOE	Measure of Effectiveness
MOO	Measure of Outcome
MSE	Mean Square Error
MSR	Mean Square Regression
NAIC	National Air Intelligence Center
NATO	North Atlantic Treaty Organization
NBC	Nuclear, Biological, Chemical
NCA	National Command Authority
NIMA	National Imagery and Mapping Agency
NIST	National Intelligence Support Team
NMIC	National Maritime Intelligence Center
NMJIC	National Military Joint Intelligence Center
NRO	National Reconnaissance Office
NSA	National Security Agency
OPSEC	Operations Security
OSINT	Open Source Intelligence
Pk	Probability of Kill
RADGUNS	Radar-Directed Gun System Simulation
RADINT	Radar Intelligence
RAF	Royal Air Force
RCS	Radar Cross Section
RECCE	Reconnaissance
S3I	System Simulation Solutions, Inc.
SAAI	Information Superiority Branch (within AFSAA)
SAAW	Wargaming Branch (within AFSAA)
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar
SBIRS	Space-Based Infrared System
SCI	Sensitive Compartmented Information
SEAD	Suppression of Enemy Air Defenses
SHF	Super-High Frequency
SIGINT	Signals Intelligence
SLBM	Submarine Launched Ballistic Missile
SOF	Special Operations Forces
SREC	Standoff Reconnaissance
SSE	Sum of Squares for Error

SSR	Sum of Squares for Regression
START	Strategic Arms Reduction Treaty
TACS	Tactical Air Control System
TADIX-B	Tactical Data Information Exchange System-Broadcast
TBM	Tactical Ballistic Missile
TDRSS	Tracking and Data Relay Satellite System
TECHINT	Technical Intelligence
TEG	Tactical Exploitation Group
TELINT	Telemetry Intelligence
TIBS	Tactical Information Broadcast System
TLAM	Tomahawk Land Attack Missile
TRAP	Tactical Receive Equipment and Related Applications
UAV	Uninhabited Aerial Vehicle
UHF F/O	Ultra-High Frequency Follow-on
UHF	Ultra-High Frequency
US	United States
USMC	United States Marine Corp
USN	United States Navy

Appendix B: Confidence Interval Summaries

90% Confidence Intervals for Total Red Equipment Killed

Mean/Median of Design Point 1 - Mean/Median of Design Point i							
Design Point i	2	3	4	5	6	7	8
Lower Bound	-126.46	-196.72	-213.00	-1049.00	-1112.99	-1118.94	-1231.16
Upper Bound	84.93	21.25	-70.00	-755.00	-906.94	-919.46	-1031.97
Significant?	No	No	Yes	Yes	Yes	Yes	Yes

Mean/Median of Design Point 2 - Mean/Median of Design Point i							
Design Point i	1	3	4	5	6	7	8
Lower Bound	-84.93	-174.02	-182.00	-1019.00	-1090.18	-1095.99	-1208.21
Upper Bound	126.46	40.09	-43.00	-737.00	-888.22	-900.87	-1013.39
Significant?	No	No	Yes	Yes	Yes	Yes	Yes

Mean/Median of Design Point 3 - Mean/Median of Design Point i							
Design Point i	1	2	4	5	6	7	8
Lower Bound	-21.25	-40.09	-107.00	-967.00	-1026.65	-1032.65	-1144.87
Upper Bound	196.72	174.02	34.00	-657.00	-817.81	-830.28	-942.79
Significant?	No	No	No	Yes	Yes	Yes	Yes

Mean/Median of Design Point 4 - Mean/Median of Design Point i							
Design Point i	1	2	3	5	6	7	8
Lower Bound	70.00	43.00	-34.00	-924.00	-918.00	-940.00	-1057.00
Upper Bound	213.00	182.00	107.00	-647.00	-790.00	-796.00	-926.00
Significant?	Yes	Yes	No	Yes	Yes	Yes	Yes

Mean/Median of Design Point 5 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	6	7	8
Lower Bound	755.00	737.00	657.00	647.00	-261.00	-269.00	-372.00
Upper Bound	1049.00	1019.00	967.00	924.00	64.00	35.00	-77.00
Significant?	Yes	Yes	Yes	Yes	No	No	Yes

Mean/Median of Design Point 6 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	7	8
Lower Bound	1112.99	888.22	817.81	790.00	-64.00	-103.90	-216.11
Upper Bound	906.94	1090.18	1026.65	918.00	261.00	85.43	-27.09
Significant?	Yes	Yes	Yes	Yes	No	No	Yes

Mean/Median of Design Point 7 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	8
Lower Bound	919.46	900.87	830.28	796.00	-35.00	-85.43	-203.21
Upper Bound	1118.94	1095.99	1032.65	940.00	269.00	103.90	-21.52
Significant?	Yes	Yes	Yes	Yes	No	No	Yes

Mean/Median of Design Point 8 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	7
Lower Bound	1031.97	1013.39	942.79	926.00	77.00	27.09	21.52
Upper Bound	1231.16	1208.21	1144.87	1057.00	372.00	216.11	203.21
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes

90% Confidence Intervals for Red Equipment Killed in Ground Battle

Mean/Median of Design Point 1 - Mean/Median of Design Point i							
Design Point i	2	3	4	5	6	7	8
Lower Bound	-42.35	161.00	158.00	-1118.00	-1175.43	-1027.64	-1051.32
Upper Bound	157.15	298.00	286.00	-799.00	-976.10	-854.76	-867.75
Significant?	No	Yes	Yes	Yes	Yes	Yes	Yes

Mean/Median of Design Point 2 - Mean/Median of Design Point i							
Design Point i	1	3	4	5	6	7	8
Lower Bound	-157.15	109.00	106.00	-1176.00	-1230.91	-1082.73	-1106.63
Upper Bound	42.35	241.00	234.00	-876.00	-1035.42	-914.47	-927.24
Significant?	No	Yes	Yes	Yes	Yes	Yes	Yes

Mean/Median of Design Point 3 - Mean/Median of Design Point i							
Design Point i	1	2	4	5	6	7	8
Lower Bound	-298.00	-241.00	-51.00	-1344.00	-1346.00	-1204.00	-1240.00
Upper Bound	-161.00	-109.00	41.00	-1091.00	-1225.00	-1089.00	-1110.00
Significant?	Yes	Yes	No	Yes	Yes	Yes	Yes

Mean/Median of Design Point 4 - Mean/Median of Design Point i							
Design Point i	1	2	3	5	6	7	8
Lower Bound	-286.00	-234.00	-41.00	-1340.00	-1336.00	-1192.00	-1223.00
Upper Bound	-158.00	-106.00	51.00	-1088.00	-1216.00	-1082.00	-1105.00
Significant?	Yes	Yes	No	Yes	Yes	Yes	Yes

Mean/Median of Design Point 5 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	6	7	8
Lower Bound	799.00	876.00	1091.00	1088.00	-293.00	-100.00	-135.00
Upper Bound	1118.00	1176.00	1344.00	1340.00	46.00	186.00	167.00
Significant?	Yes	Yes	Yes	Yes	No	No	No

Mean/Median of Design Point 6 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	7	8
Lower Bound	1175.43	1035.42	1225.00	1216.00	-46.00	50.54	26.64
Upper Bound	976.10	1230.91	1346.00	1336.00	293.00	218.59	205.83
Significant?	Yes	Yes	Yes	Yes	No	Yes	Yes

Mean/Median of Design Point 7 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	8
Lower Bound	854.76	914.47	1089.00	1082.00	1082.00	-218.59	-92.51
Upper Bound	1027.64	1082.73	1204.00	1192.00	-186.00	-50.54	55.85
Significant?	Yes	Yes	Yes	Yes	No	Yes	No

Mean/Median of Design Point 8 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	7
Lower Bound	867.75	927.24	1110.00	1105.00	-167.00	-205.83	-55.85
Upper Bound	1051.32	1106.63	1240.00	1223.00	135.00	-26.64	92.51
Significant?	Yes	Yes	Yes	Yes	No	Yes	No

90% Confidence Intervals for Red Equipment Killed by Air Missions

Mean/Median of Design Point 1 - Mean/Median of Design Point i							
Design Point i	2	3	4	5	6	7	8
Lower Bound	-154.32	-397.94	-426.21	12.03	10.68	-145.34	-251.09
Upper Bound	-47.35	-295.33	-307.06	122.91	115.86	-33.02	-142.07
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Mean/Median of Design Point 2 - Mean/Median of Design Point i							
Design Point i	1	3	4	5	6	7	8
Lower Bound	47.35	-291.20	-320.52	118.15	117.21	-39.29	-144.87
Upper Bound	154.32	-200.40	-211.08	218.45	210.99	62.59	-46.63
Significant?	Yes	Yes	Yes	Yes	Yes	No	Yes

Mean/Median of Design Point 3 - Mean/Median of Design Point i							
Design Point i	1	2	4	5	6	7	8
Lower Bound	295.33	200.40	-72.60	366.33	365.60	208.85	103.40
Upper Bound	397.94	291.20	32.60	461.87	454.20	306.05	196.70
Significant?	Yes	Yes	No	Yes	Yes	Yes	Yes

Mean/Median of Design Point 4 - Mean/Median of Design Point i							
Design Point i	1	2	3	5	6	7	8
Lower Bound	307.06	211.08	-32.60	377.47	376.05	220.11	114.29
Upper Bound	426.21	320.52	72.60	490.73	483.75	334.79	225.81
Significant?	Yes	Yes	No	Yes	Yes	Yes	Yes

Mean/Median of Design Point 5 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	6	7	8
Lower Bound	-122.91	-218.45	-461.87	-490.73	-53.35	-209.68	-315.33
Upper Bound	-12.03	-118.15	-366.33	-377.47	44.95	-103.62	-212.77
Significant?	Yes	Yes	Yes	Yes	No	Yes	Yes

Mean/Median of Design Point 6 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	7	8
Lower Bound	-10.68	-210.99	-454.20	-483.75	-44.95	-202.41	-307.95
Upper Bound	-115.86	-117.21	-365.60	-376.05	53.35	-102.49	-211.75
Significant?	Yes	Yes	Yes	Yes	No	Yes	Yes

Mean/Median of Design Point 7 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	8
Lower Bound	33.02	-62.59	-306.05	-334.79	103.62	102.49	-159.46
Upper Bound	145.34	39.29	-208.85	-220.11	209.68	202.41	-55.34
Significant?	Yes	No	Yes	Yes	Yes	Yes	Yes

Mean/Median of Design Point 8 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	7
Lower Bound	142.07	46.63	-196.70	-225.81	212.77	211.75	55.34
Upper Bound	251.09	144.87	-103.40	-114.29	315.33	307.95	159.46
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	Yes

90% Confidence Intervals for Air Loss Exchange Ratio

Mean/Median of Design Point 1 - Mean/Median of Design Point i							
Design Point i	2	3	4	5	6	7	8
Lower Bound	-0.09	-0.48	-0.47	-0.15	-0.03	-0.44	-0.38
Upper Bound	0.12	-0.30	-0.26	0.09	0.16	-0.22	-0.16
Significant?	No	Yes	Yes	No	No	Yes	Yes

Mean/Median of Design Point 2 - Mean/Median of Design Point i							
Design Point i	1	3	4	5	6	7	8
Lower Bound	-0.12	-0.51	-0.51	-0.19	-0.10	-0.48	-0.40
Upper Bound	0.09	-0.32	-0.24	0.06	0.18	-0.21	-0.18
Significant?	No	Yes	Yes	No	No	Yes	Yes

Mean/Median of Design Point 3 - Mean/Median of Design Point i							
Design Point i	1	2	4	5	6	7	8
Lower Bound	0.30	0.32	-0.08	0.24	0.35	-0.04	0.02
Upper Bound	0.48	0.51	0.12	0.47	0.54	0.17	0.22
Significant?	Yes	Yes	No	Yes	Yes	No	Yes

Mean/Median of Design Point 4 - Mean/Median of Design Point i							
Design Point i	1	2	3	5	6	7	8
Lower Bound	0.26	0.24	-0.12	0.20	0.28	-0.10	-0.02
Upper Bound	0.47	0.51	0.08	0.45	0.55	0.17	0.21
Significant?	Yes	Yes	No	Yes	Yes	No	No

Mean/Median of Design Point 5 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	6	7	8
Lower Bound	-0.09	-0.06	-0.47	-0.45	-0.02	-0.40	-0.33
Upper Bound	0.15	0.19	-0.24	-0.20	0.24	-0.17	-0.12
Significant?	No	No	Yes	Yes	No	Yes	Yes

Mean/Median of Design Point 6 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	7	8
Lower Bound	0.03	-0.18	-0.54	-0.55	-0.24	-0.52	-0.44
Upper Bound	-0.16	0.10	-0.35	-0.28	0.02	-0.24	-0.22
Significant?	No	No	Yes	Yes	No	Yes	Yes

Mean/Median of Design Point 7 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	8
Lower Bound	0.22	0.21	-0.17	-0.17	0.17	0.24	-0.05
Upper Bound	0.44	0.48	0.04	0.10	0.40	0.52	0.16
Significant?	Yes	Yes	No	No	Yes	Yes	No

Mean/Median of Design Point 8 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	7
Lower Bound	0.16	0.18	-0.22	-0.21	0.12	0.22	-0.16
Upper Bound	0.38	0.40	-0.02	0.02	0.33	0.44	0.05
Significant?	Yes	Yes	Yes	No	Yes	Yes	No

90% Confidence Intervals for Percentage of Red Strategic Targets Killed

Mean/Median of Design Point 1 - Mean/Median of Design Point i							
Design Point i	2	3	4	5	6	7	8
Lower Bound	-0.02	-0.12	-0.14	-0.16	-0.15	-0.23	-0.23
Upper Bound	0.01	-0.08	-0.09	-0.12	-0.12	-0.20	-0.21
Significant?	No	Yes	Yes	Yes	Yes	Yes	Yes

Mean/Median of Design Point 2 - Mean/Median of Design Point i							
Design Point i	1	3	4	5	6	7	8
Lower Bound	-0.01	-0.12	-0.14	-0.15	-0.15	-0.23	-0.23
Upper Bound	0.02	-0.07	-0.08	-0.11	-0.12	-0.19	-0.20
Significant?	No	Yes	Yes	Yes	Yes	Yes	Yes

Mean/Median of Design Point 3 - Mean/Median of Design Point i							
Design Point i	1	2	4	5	6	7	8
Lower Bound	0.08	0.07	-0.05	-0.06	-0.06	-0.13	-0.14
Upper Bound	0.12	0.12	0.02	0.01	-0.02	-0.08	-0.08
Significant?	Yes	Yes	No	No	Yes	Yes	Yes

Mean/Median of Design Point 4 - Mean/Median of Design Point i							
Design Point i	1	2	3	5	6	7	8
Lower Bound	0.09	0.08	-0.02	-0.05	-0.05	-0.12	-0.13
Upper Bound	0.14	0.14	0.05	0.02	0.00	-0.06	-0.07
Significant?	Yes	Yes	No	No	Yes	Yes	Yes

Mean/Median of Design Point 5 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	6	7	8
Lower Bound	0.12	0.11	-0.01	-0.02	-0.02	-0.10	-0.11
Upper Bound	0.16	0.15	0.06	0.05	0.02	-0.05	-0.06
Significant?	Yes	Yes	No	No	No	Yes	Yes

Mean/Median of Design Point 6 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	7	8
Lower Bound	0.15	0.12	0.02	0.00	-0.02	-0.09	-0.10
Upper Bound	0.12	0.15	0.06	0.05	0.02	-0.06	-0.06
Significant?	Yes	Yes	Yes	Yes	No	Yes	Yes

Mean/Median of Design Point 7 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	8
Lower Bound	0.20	0.19	0.08	0.06	0.05	0.06	-0.02
Upper Bound	0.23	0.23	0.13	0.12	0.10	0.09	0.01
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	No

Mean/Median of Design Point 8 - Mean/Median of Design Point i							
Design Point i	1	2	3	4	5	6	7
Lower Bound	0.21	0.20	0.08	0.07	0.06	0.06	-0.01
Upper Bound	0.23	0.23	0.14	0.13	0.11	0.10	0.02
Significant?	Yes	Yes	Yes	Yes	Yes	Yes	No

Vita

Capt Francine Nelson was born on 14 July 1971 in Davenport, IA. She grew up in Inwood, IA and graduated from West Lyon High School in 1989. In May 1993, she graduated from Boston University with a Bachelor of Arts degree in Mathematics and Economics, and was commissioned through the Air Force ROTC program. She attended Undergraduate Space Training at Vandenberg AFB and arrived at her first assignment at Cheyenne Mountain Air Station in 1994. She worked in the Missile Warning Center as a Deputy Crew Commander and held a staff position as Deputy of the Missile Operations Branch. In August 1997, she entered the School of Engineering, Air Force Institute of Technology. Upon graduation she will be assigned to the National Reconnaissance Office.

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13. ABSTRACT *(Maximum 200 words)*
A validation assessment of THUNDER 6.5's Intelligence, Surveillance, and Reconnaissance (ISR) module is accomplished using formulational and experimental validation techniques. A comparison of ISR purposes and processes according to military doctrine is made with the purposes and processes of ISR implemented within THUNDER 6.5. This comparison provides an overview of the process, an understanding of the level of aggregation within THUNDER, insight into possible problem areas in THUNDER, and a basis for improving THUNDER ISR processes. Sensitivity analysis of the ISR parameters as they relate to the Quality, Quantity, and Timeliness of ISR is also presented to provide insight into the responsiveness of THUNDER to changes in ISR capability for selected battle outcomes. Linear Regression and a Face-Centered Central Composite Design were used to generate a response surface. Ninety-percent confidence intervals were used to determine differences in mean response among the full factorial design points.

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