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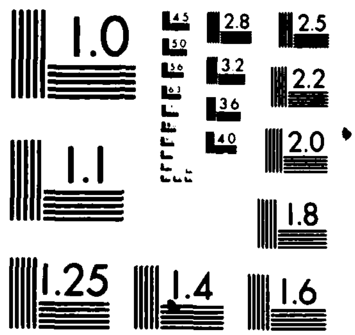

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A DECISION AID FOR RESTORATION OF

FORCE ENHANCEMENT SPACE SYSTEMS

THESIS

AFIT/GST/OS/86M-11 Calvin G. Hedgeman
Capt USAF

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A DECISION AID FOR RESTORATION OF FORCE ENHANCEMENT SPACE SYSTEMS

THESIS

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by

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Abstract

The goal of this research is to provide the Commander-in-Chief, United States Space Command with a prototype model he can use to make restoration management decisions for space systems. The model includes a data base of system attributes and provisions for varying mission priorities.

The study is limited to military space systems performing the communications, navigation and meteorological missions. This restriction simplifies the project without limiting the model's usefulness as a feasibility study. Other space systems and missions can be easily added to the data base as required.

The Analytic Hierarchy Process is used to assess CINCUSSPACECOM's mission priorities and technical preferences among space systems performing the same mission but providing different capabilities. Goal programming is used to develop a mathematical formulation of CINCUSSPACECOM's desire to restore preferred space systems and to specify a preferred configuration for each space system restored. Finally, resource changes resulting from wartime scenarios are used to validate the model.

The study concludes with a recommendation that USSPACECOM implement a restoration management system to realize the full value of force enhancement space systems during a conflict.

A DECISION AID FOR RESTORATION OF FORCE ENHANCEMENT SPACE SYSTEMS

I. Introduction

General Issue

Area Description. Military space systems have affected the entire operation of the Department of Defense. This impact was summarized in 1984 by then Chief of Naval Operations, Admiral James D. Watkins: "satellites make fleets out of ships" (2:89). Indeed, the satellite communications network is the vehicle for the US command and control system. Under Secretary of the Air Force Edward C. Aldridge noted in 1984 that the military depends extensively on space-based systems for "targeting, command and control, navigation and photo reconnaissance in support of arms control" (2:89). This dependence extends to the US strategic nuclear force. An attack on US satellites, for example, would affect the force since sea-launched ballistic submarines rely on satellites for launch point determination (17:41). Strategic forces will also rely on the Nuclear Detonation Detection System for surveillance (36:1-3).

The threat to the space capabilities of the US military has increased simultaneously with the US dependence on these systems. According to Col Robert A. Olivieri, (formerly a member of Mr. Aldridge's staff for space systems), "space operations will occur in a threat environment ... challenges to the US presence and capabilities can be expected" (27:17). The threat environment will increase after 1990 as Soviet military capabilities in space rise. Although the Soviets pose the only direct threat to the on-orbit components of US space systems, the ground-based segments are vulnerable to terrorism and acts of nature such as earthquakes. As Lt Gen Richard Henry, former commander of AFSC's Space Division, stated,

> ... a space system is sort of like a three legged milkstool. The three legs of the space system are the spacecraft, the bit-stream [communications link between the satellite and ground stations], and the terminals [satellite ground control stations]. Without any one of the three, a space system is totally worthless (1:40).

Situation. The ability of American satellites to perform their mission during a conflict has been studied for some time; indeed, new systems such as MILSTAR and NAVSTAR GPS, were designed with survivability and autonomy as major requirements (34:94). Other studies have considered ways to improve the survivability of the ground-based command and control segments, either by using mobile ground systems or deploying command and control systems aboard aircraft. Yet, equipment failures can occur at any time and limit mission accomplishment. Increased military dependence on American satellites raises the cost of such failures.

The creation of the United States Space Command

(USSPACECOM) and the Air Force's 2nd Space Wing offer planners a new opportunity to address the problem of recovering from space system failures. Previously, correcting these failures was the problem of each of the systems' operators. The consolidation of military space systems under the USSPACECOM and 2nd Space Wing now make it possible to consider a wide range of restoration actions potentially affecting the operation of several space systems in response to the failure of a single system. Thus, it may now be possible to make mission accomplishment insensitive to specific space systems. The decision maker will be CINCUSSPACECOM. Under his command, the Space Defense Operations Center (SPADOC) can direct restoration actions to take advantage of the synergistic nature of US space systems.

Problem Statement

The goal of this research project is to develop a prototype system to aid CINCUSSPACECOM in managing the restoration of US space systems throughout the spectrum of conflict.

Research Question

How should the US fleet of military space systems be reconfigured to best restore degraded mission capabilities caused by wartime failures?

Research Objective

An intermediate objective of this research is to identify the attributes and information required for a restoration management system. The data will be organized into three groups (space segment, ground segment, and data links), and will form a data base for the system. Intermediate questions include:

1. What information is the decision maker at the USSPACECOM likely to need for a restoration management decision?

2. How do priorities for mission accomplishment affect this decision?

3. To what depth should a space system's segments be modeled?

4. What are appropriate scenarios for evaluating restoration management systems?

5. How is performance of a restoration management system measured? Which attributes of space systems are important to performance?

6. How does the system perform under different sets of priorities in a wartime scenario?

Benefits

A restoration management system would improve mission accomplishment in any scenario involving space operations. Given a model that allows flexible prioritization of missions, operational planners could test different responses to hypothesized attacks. For example, the use of civilian communication satellites for military missions following an attack on military communication satellites could be evaluated (10).

A second benefit might be use of the model to evaluate future space system designs for commonality with current systems (10). The model specifies system attributes to the level of detail required to accomplish this. New multi-mission systems would improve restoration efforts and the value of the entire network (4).

Scope

Only force enhancement systems will be addressed in this study. Foreign cooperative programs and intelligence systems will not be considered. These restrictions are arbitrary but do not limit the model's usefulness as a feasibility study. The first restriction narrows the set of space systems to those under the direct control of the USSPACECOM. The second restriction also narrows the set by considering only systems for which obtaining unclassified information is feasible.

Since the goal of the research is a generic model of military space systems, identifying relevant attributes of space systems is more important than identifying all space systems. As long as the attributes can be modeled using unclassified systems, the goal will be achieved without classifying the study. Should the USSPACECOM accept the model and implement it on a secure computer system, classified systems can easily be added to the data base.

The study will focus on restoration management actions directed towards wartime failures. Although natural disasters are also a threat to space systems and can occur at any time, the model must function under the stress of a wartime environment to be useful to the USSPACECOM.

Literature Review

Meaningful restoration management for segments of space systems is now conceivable because of the establishment of the USSPACECOM. With the control of space systems under one commander, the opportunity to plan for restoration of military space systems has arrived. As a result however, there is little in the literature on this topic.

A significant study in the area was done by Flora (10) on communication satellites. He identified the attributes of many civilian communications satellites and noted the potential for converging architectures for civilian and military satellites. He also presented a plan for the integration of these satellites into the military organization. The plan calls for complete control of civilian satellites by the military however, an alternative that is possible but only for the most extreme case of restoration management.

The remaining studies by Lee and Cole provide peripheral information on restoration management. In his thesis, Lee (24) developed a decision analysis aid for command and control of resources. Using multiple attribute value theory, he developed and coded a decision analysis algorithm based on an additive worth assessment function. This algorithm, to be used by the SAC Warning and Control System with CINCSAC as the decision maker, maximizes the number of aircraft escaping an attack while minimizing the cost of maintaining the aircraft on alert. He also developed a sensitivity analysis program for the algorithm. Decision makers would use the software to determine the optimal status of alert aircraft based upon CINCSAC's preferences.

The restoration management problem is similar to Lee's because the decision maker, CINCUSSPACECOM, is a commander whose preferences are influenced by user priorities and a given scenario. Also, the attributes of the three segments are numerous and will be modeled separately because of the technical constraints. Although computerization is necessary to maintain the large data base, the timeliness of a restoration management decision is not as critical or complex: CINCSAC's decision must be made in seconds whereas CINCUSSPACECOM may have minutes to hours to make his decision. Furthermore, implementation of that decision may take days to accomplish.

Cole's (4) thesis determined and compared the costs of several uniquely-built satellites to a generic satellite. His main objective was determining the viability of generic spacecraft for military applications. The application of his work to restoration management is the identification of components of generic models. His efforts also allow grouping different satellites based on the attributes of the generic model. Finally, Cole suggested systems to use in modeling several missions, information useful when applying the restoration management system to space systems where information is not readily available. Cole's methodology - cost analysis - is not applicable to the restoration management problem.

Overview

Chapter II contains definitions of the variables of the decision process for restoration management and their relation to the problem (Appendix A contains a glossary and additional definitions of terms used in the study). The discussion concludes with a description of the data collected. Next, Chapter III presents alternative methodologies for modeling the restoration management decision process. The model for restoration management is formulated in Chapter IV. Chapter V describes the results for a specific scenario. Finally, the results are compared to restoration management decisions resulting from an alternative formulation of the problem.

II. The Decision Process for Restoration Management

Description of Decision Process

The decision aid provided to Space Command must be a dynamic tool that is oriented towards the users of satellite-generated data. CINCUSSPACECOM's perspective must encompass that of the users his systems support if he is to make effective decisions.

During a war these decisions will be made many times and most likely under dynamic demands for space system capabilities. For example, a central conflict involving a nuclear attack on the US might contain three phases. Missile launch detection satellites would have the highest priority for restoration prior to an attack on the US (phase 1). During the attack (phase 2), space systems providing information on the location of nuclear detonations might have the highest priority. Finally, space systems providing navigation would be most important during the US response (phase 3).

The phases described in this example reflect changes in combat objectives, rather than time periods. Since there will be uncertainty attached to the objectives of the enemy and in the subsequent response by the US, the variables of the decision process are multiperiod random variables. However, at the time CINCUSSPACECOM makes his decision, all random variables have been assigned a value.

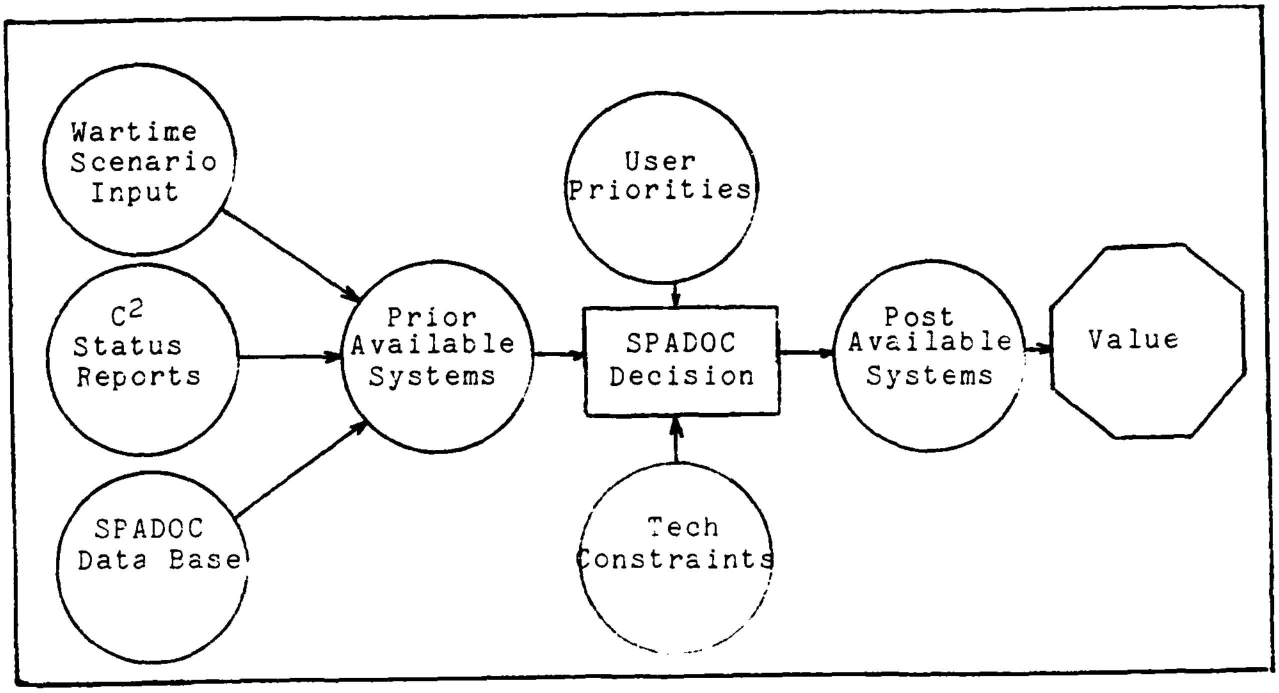

Figure 2.1 Influence Diagram

The influence diagram is a descriptive tool that can be used to formally describe a problem (18). According to Howard, the influence diagram can provide "a bridge between qualitative description and quantitative description" by showing the relationship of variables in a problem (18:721). Figure 2.1 shows the variables of one phase of a conflict and the resulting restoration management decision in an influence diagram. The single variable controlled by CINCUSSPACECOM, his decision, is represented by a square decision node. The remaining variables are chance events and are represented by circles. The value of the decision is represented by an octagon. The initial variables in each decision could be:

1. Status reports from the command and control centers of the space systems,

2. A data base of space system information stored at the SPADOC,

3. The wartime scenario.

The status reports are a situation picture of the space system, giving CINCUSSPACECOM the system's current ability to perform its mission and the subsystems used in operation of the system (23:10). Operational capability could be reported as color codes (green, yellow or red), as is currently done in many systems operated by Space Command today, or as percentages of total mission achieved. A SPADOC data base would describe the equipment used by each space system controlled by USSPACECOM reflecting the subsystems currently available in each segment of the system. The wartime scenario defines the nature of the attack, including enemy capabilities and objectives.

These three variables determine the systems available to CINCUSSPACECOM to accomplish his mission. When the currently available space systems provide wartime capabilities inconsistent with the wartime capabilities specified by user priorities, CINCUSSPACECOM must direct the modification of the overall system within the limits of the systems' technical constraints.

Each space system has a value - to its users - which can be measured by the wartime capabilities provided to those users. The value of the restoration management decision is then the sum of the values of the restored space systems.

Status Reports

To determine the current capability of each space system to perform its mission under normal or limited capability conditions, CINCUSSPACECOM needs a status report from each system (23:10). These reports may come directly from the command and control center of each space system or from an intermediate organization such as the Space Computational Center or Missile Warning Center (23:10). The report must include an assessment by each system's operator of the current capabilities of the system using pre-established criteria. The criteria for this assessment must show a deliberate orientation to system users because the focus of the restoration decision is always the optimization of wartime capabilities. Thus, the criteria become measures of achieving these capabilities. Examples of possible criteria are:

Navigation Coverage per Day (NCD). This criterion measures the amount of time per day coverage is available to users. This measure may be expressed as a percentage by dividing by 24 hours.

Navigation Coverage Area (NCA). This criterion measures the amount of coverage in terms of the earth's area. This measure may be expressed as a percentage by dividing by the earth's area, or by the conflict area.

Number of System Users (NSU). This criterion is expressed in terms of tons of weapons to be delivered during an operation divided by the total number of tons of weapons to be delivered. This criterion provides a direct link to the users. It is preferable to the number of system users measured directly because not all of those users may have a wartime mission or contribute anything to the current conflict. Users which do not contribute to mission objectives should not be considered in the restoration management decision. NSU measures direct contributions only.

Meteorological Coverage per Day (MCD). This criterion is similar to NCD.

Meteorological Coverage Area (MCA). This criterion is similar to NCA.

Communications Message per Day (CMD). This criterion is expressed in terms of the ratio of message traffic per day over a specific space system to total daily traffic.

Communications Number of Users (CNU). This criterion is expressed in terms of the ratio of the number of users of a specific system to total users.

Communications Encrypted (CE). This criterion measures the capability of a specific system to transmit encrypted communications. Unlike previous criteria where ratios were used, this is a yes or no capability. It is useful to consider this criterion since space systems may lose this capability due to sabotage, satellite attack or compromise of cryptologic material without losing total ability to transmit messages. In this degraded condition the space system is still capable of performing a mission, but may be unusable for certain types of messages.

Communications Delay Time (CDT). This criterion measures the delay in message receipt as calculated by the ratio of delay time to the difference between best and worst cases. This criterion reflects the usefulness of a space system for transmission of real-time messages related, perhaps, to flushing bombers away from targeted air bases or providing tactical warning.

Connectivity for Strategic Users (CSC). This criterion reflects the vital need to maintain communications between the National Command Authorities and the commanders of nuclear-capable commands. It may be assessed as either a discrete yes or no for the entire network or as a ratio reflecting the number of commanders connected. The latter is used here.

SPADOC Data Base

The Space Defense Operations Center (SPADOC), located in NORAD's Cheyenne Mountain Complex, monitors Soviet space activities that may indicate possible hostile Soviet activities on earth (5:56). The SPADOC is a "command post with computer consoles upon which can be displayed geographic and digital data on the ground network and condition of all spacecraft" controlled by NORAD (5:56). According to Covault, the center has completed agreements with the operators of space systems resulting in

> procedures on how the operators and SPADOC will exchange data on a day-to-day basis or in circumstances where a satellite malfunction or hostile act has occurred (5:57).

The USSPACECOM can thus use SPADOC as a focal point for tracking the status of American satellites.

For this mission, a SPADOC data base must describe the subsystems of each space system controlled by CINCUSSPACECOM. Ten space systems were initially considered for this study. After discussions with HQ SPACECOM/DOSC, the number of space systems was reduced to six:

1. Defense Meteorological Satellite Program (DMSP),
2. NROSS, a meteorological space system planned for the US Navy and designed to provide specialized information on sea conditions,
3. NAVSTAR Global Positioning System (GPS), a navigational system to be operational in the early 1990's,
4. Transit, an operational navigation system currently used by the US Navy's ballistic missile submarines for position fixing,
5. Defense Satellite Communications System (DSCS),
6. Military Strategic and Tactical Relay System (MILSTAR), a communications system to be operational in the mid 1990's.

These systems provide (or will provide by 1995) three major force enhancement capabilities: meteorological data (DMSP and NROSS), navigation (GPS and Transit) and communications (DSCS and MILSTAR). Each capability represents the mission of a specific space system for this study.

The six space systems were selected to study two forms of restoration management. First, specialized subsystems of each space system, such as the satellite payload, are limited in the way they can be replaced. For example, the DMSP payload cannot provide navigation information. Restoration for this specialized subsystem must occur from within the set of space systems providing meteorological data. Thus it is necessary to consider at least two space systems within each mission to study this form of restoration management.

The second form of restoration management involves support equipment. Ground based antennas are examples of this type of equipment. The Air Force Satellite Control Facility (AFSCF) operates a network of eleven antennas that can link operators of most US military space systems with their satellites. These antennas can backup the antennas owned by the space system operators. Restoration of these subsystems can span all six space systems since the equipment is not specialized.

The SPADOC data base must describe space systems to the subsystem level to allow both forms of restoration described above. The description used in this study was developed using the data sheets shown in Appendix B. These sheets were completed using information from USAF Fact Sheets (11, 12, 13, 14) and other references (22, 25, 26, 31, 32, 33). The data for NROSS' ground segment is similar to DMSP's because NROSS will be operated using DMSP's ground equipment. For this study however, it will be assumed that the NROSS space system has its own ground segment, similar to DMSP's but independent of that system. Additional research is needed to determine how to model subsystems shared by different space systems.

Finally, the data sheets were converted into a Subsystem Availability Table, shown in Table 2.1. Non-zero values indicate the number of subsystems available within the space system. The space segment values in this table are for a full satellite constellation and reflect operational subsystems. The resources of the AFSCF and the Consolidated Space Operations Center are listed under DSCS and GPS respectively. These resources include subsystems for telemetry and communications. These resources are not dedicated to any space system. As noted earlier, they are available to all space systems. This availability is modeled next.

The subsystems were then studied to determine which subsystems could be reallocated to meet changing priorities for wartime capabilities. This study yielded the Subsystem Allocation Tables shown in Tables 2.2 through 2.7. For each space system, the tables specify the minimum number of subsystems required to restore the subsystems by

TABLE 2.1

SUBSYSTEM AVAILABILITY TABLE

DMSP			GPS			MILSTAR		
Space Segment			**Space Segment**			**Space Segment**		
1.	Payload	2	1.	Payload	21	1.	Payload	378
2.	Comm	6	2.	Comm	42	2.	Comm	7
3.	Data Proc	4	3.	Data Proc	0	3.	Data Proc	7
Ground Segment			**Ground Segment**			**Ground Segment**		
4.	Telemetry	2	4.	Telemetry	2	4.	Telemetry	2
5.	CmdControl	2	5.	CmdControl	2	5.	CmdControl	3
6.	Comm	2	6.	Comm	6	6.	Comm	3
7.	Planning	2	7.	Planning	1	7.	Planning	1
8.	Antennas	2	8.	Antennas	6	8.	Antennas	1
Data Links			**Data Links**			**Data Links**		
9.	Space Link	2	9.	Space Link	7	9.	Space Link	0
10.	GroundLink	3	10.	GroundLink	6	10.	GroundLink	1
11.	Cross Link	0	11.	Cross Link	1	11.	Cross Link	1

NROSS			Transit			DSCS		
Space Segment			**Space Segment**			**Space Segment**		
1.	Payload	2	1.	Payload	3	1.	Payload	18
2.	Comm	6	2.	Comm	3	2.	Comm	3
3.	Data Proc	4	3.	Data Proc	3	3.	Data Proc	0
Ground Segment			**Ground Segment**			**Ground Segment**		
4.	Telemetry	2	4.	Telemetry	1	4.	Telemetry	7
5.	CmdControl	2	5.	CmdControl	1	5.	CmdControl	1
6.	Comm	2	6.	Comm	1	6.	Comm	1
7.	Planning	2	7.	Planning	1	7.	Planning	1
8.	Antennas	2	8.	Antennas	3	8.	Antennas	11
Data Links			**Data Links**			**Data Links**		
9.	Space Link	2	9.	Space Link	0	9.	Space Link	7
10.	GroundLink	3	10.	GroundLink	3	10.	GroundLink	2
11.	Cross Link	0	11.	Cross Link	0	11.	Cross Link	0

TABLE 2.2

SUBSYSTEM ALLOCATION FOR DMSP

Subsystem	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
Space Segment						
1. Payload	1	1	0	0	0	0
2. Comm	1	1	0	1	1	1
3. Data Proc	1	1	0	1	1	0
Ground Segment						
4. Telemetry	1	0	1	1	1	1
5. CmdControl	1	0	1	1	1	1
6. Comm	1	0	1	1	1	1
7. Planning	1	0	1	1	1	1
8. Antennas	1	0	1	1	1	1
Data Links						
9. Space Link	1	1	1	0	0	1
10. GroundLink	1	1	1	0	1	1
11. Cross Link	0	0	0	0	0	0

TABLE 2.3

SUBSYSTEM ALLOCATION FOR NROSS

Subsystem	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
Space Segment						
1. Payload	1	1	0	0	0	0
2. Comm	1	1	0	1	1	1
3. Data Proc	1	1	0	1	1	0
Ground Segment						
4. Telemetry	1	1	1	1	1	1
5. CmdControl	1	1	1	1	1	1
6. Comm	1	1	1	1	1	1
7. Planning	1	1	1	1	1	1
8. Antennas	1	1	1	1	1	1
Data Links						
9. Space Link	1	1	1	0	0	1
10. GroundLink	1	1	1	0	1	1
11. Cross Link	0	0	0	0	0	0

TAPLE 2.4

SUBSYSTEM ALLOCATION FOR GPS

Subsystem	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
Space Segment						
1. Payload	0	0	2	0	0	0
2. Comm	0	0	2	1	0	1
3. Data Proc	0	0	0	0	0	0
Ground Segment						
4. Telemetry	1	0	1	1	1	3
5. CmdControl	1	0	1	1	1	1
6. Comm	1	0	3	1	1	1
7. Planning	1	0	1	1	1	1
8. Antennas	0	0	3	1	1	3
Data Links						
9. Space Link	1	1	1	0	0	3
10. GroundLink	1	1	1	0	1	1
11. Cross Link	0	0	1	0	1	0

TABLE 2.5

SUBSYSTEM ALLOCATION FOR TRANSIT

Subsystem	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
Space Segment						
1. Payload	0	0	1	1	0	0
2. Comm	0	0	0	1	0	1
3. Data Proc	0	0	0	1	0	0
Ground Segment						
4. Telemetry	1	0	1	1	1	1
5. CmdControl	1	0	1	1	1	1
6. Comm	1	0	0	1	1	1
7. Planning	1	0	1	1	1	1
8. Antennas	0	0	0	1	1	1
Data Links						
9. Space Link	0	0	0	0	0	0
10. GroundLink	1	1	1	3	1	1
11. Cross Link	0	0	0	0	0	0

TABLE 2.6

SUBSYSTEM ALLOCATION FOR MILSTAR

Subsystem	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
Space Segment						
1. Payload	0	0	0	0	27	3
2. Comm	1	1	0	1	1	1
3. Data Proc	1	1	0	1	1	0
Ground Segment						
4. Telemetry	1	0	1	1	1	1
5. CmdControl	1	0	1	1	1	1
6. Comm	1	0	1	1	1	1
7. Planning	1	0	1	1	1	1
8. Antennas	0	0	1	1	1	1
Data Links						
9. Space Link	0	0	0	0	0	0
10. GroundLink	1	1	1	0	1	1
11. Cross Link	0	0	0	0	1	0

TABLE 2.7

SUBSYSTEM ALLOCATION FOR DSCS

Subsystem	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
Space Segment						
1. Payload	0	0	0	0	27	3
2. Comm	1	1	0	1	1	1
3. Data Proc	0	0	0	0	0	0
Ground Segment						
4. Telemetry	1	0	1	1	1	1
5. CmdControl	1	0	1	1	1	1
6. Comm	1	0	1	1	1	1
7. Planning	1	0	1	1	1	1
8. Antennas	0	0	1	1	1	1
Data Links						
9. Space Link	1	1	1	0	0	1
10. GroundLink	1	1	1	0	1	1
11. Cross Link	0	0	0	0	0	0

reallocating the subsystems of other space systems.

For example, Table 2.1 shows NROSS subsystem number 1 as the NROSS meteorological payload. According to the table, there are two payloads in the system - one payload per satellite, two satellites in the operational NROSS space system. Under Table 2.3, minimum restoration of the NROSS mission, collection of weather data, requires reallocation of one payload from either DMSP or NROSS, the two space systems in the model performing the meteorological mission. The zeros in Table 2.3 mean that the other four satellite payloads can not restore the meteorological mission of NROSS. Referring back to Table 2.1, reallocation of payloads cannot exceed the number available - two from DMSP and two from NROSS. Table 2.1 shows the resources available prior to a conflict. During a war, the number available may remain constant or be reduced by an attack. Constraints developed in the problem formulation in Chapter IV will indicate that NROSS cannot be restored if the number required exceeds the number of a particular subsystem available.

Since some subsystems are mission specific, these values must be considered relative to the space system that will use the subsystem. These tables were reviewed by HQ SPACECOM/DOSC for validity. Although they may not be exact in some cases, the values are reliable enough for this study. For example, the number of satellites in the NROSS operational system may be very different from the two satellites assumed in this study. These differences would affect the restoration management decision but would not affect how the decision is made.

Wartime Scenario

The wartime scenario is an input to the restoration management decision because it changes the values in the Subsystem Availability Table. The scenario is also a means of testing the restoration management system. The following procedure was used to build scenarios:

1. Select the time period for the scenario,
2. Define enemy capabilities in this time period,
3. Define Soviet objectives,
4. Calculate subsystem changes and modify the Subsystem Availability Table.

Select The Time Period. The 1995 time period is the time period used in the study. This time period is used because it is consistent with the projected initial operational capability for GPS, MILSTAR and NROSS.

Define Enemy Capabilities. By 1995 the USSR will have enhanced their current weapon systems and added new means to attack US space systems. Among current weapons is the Soviet antisatellite (ASAT) weapon which is already a threat to all US space systems but primarily intended for space systems positioned in low earth orbits below 500 nautical miles (8:34). The same rocket booster used to place the ASAT in orbit can also deliver nuclear weapons to low earth orbits for a point in space attack. The radiation emitted when these weapons are detonated can be deadly to any space system passing through the radiation. These systems could be capable of attacking US space systems in higher orbits by 1995 (15:29). A new USSR weapon that may be available by 1995 is the ground-based laser (8:35-36).

Sabotage and direct attack on the ground segments will remain useful weapons for the Soviets, particularly against space systems with ground segments located outside the US (9). Also, the effects of attacks directed against US weapon systems based near the ground segments of space systems (collateral damage) must be considered a threat to these systems.

<u>Define Soviet Objectives</u>. Although Soviet doctrine provides some information on their objectives, the precise nature of an attack may not be clear until the attack has begun. One way to overcome this problem is to select scenarios from the range of the conflict spectrum and use the phases of each scenario to determine the space systems which are most likely to be attacked. According to Lange,

> the conflict spectrum is the basic group of scenarios presently in use in a number of DOD and space operations studies, including peacetime, local crises, theater war/non-nuclear, theater war/nuclear, central conflict/initial phase and central war/reconstitution phase (23:2).

Three scenarios were selected from this spectrum: limited war, major war and central war.

Limited War. In a limited war, US space systems could be attacked to prevent employment of US forces. This would be the case in a conventional war where nuclear weapons are used sparingly, perhaps only to demonstrate resolve. Soviet emphasis on surprise suggests only an attack directed against navigation and meteorological systems supporting US forces deployed in the conflict area. Collateral damage from attacks on weapon systems located near ground segments is not expected since these segments are located primarily in the US. Attacking US-based ICBMs and bombers would not be consistent with the limited use of nuclear weapons assumed for this type of conflict. Instead it implies the first strike objectives of a central conflict.

Major War. Soviet objectives in a major war would be limitation of US force employment and deterrence of escalation to central war. Thus, the space systems attacked during a limited war would also be attacked in this war. Also, early warning and communication space systems supporting forces in the conflict area would also be attacked. However, the phasing of the attacks would depend on the conflict level. Assuming that space systems would be attacked according to the level of conflict, the first systems attacked during a major conflict might be weather and navigation systems. Loss of these capabilities would contribute to the Soviet objective of preventing the employment of US forces. As the level of conflict increased, strategic systems including DSCS, MILSTAR and tactical warning systems might be attacked to forestall the employment of US strategic (nuclear) forces. Thus the order of attack during a major conflict would likely be opposite that of a central conflict. Finally, CONUS-based systems would not be attacked and collateral damage would not occur.

Central War. A central war involves employment of forces against the enemy's homeland. Soviet objectives in a central war would be disruption of US command and control systems and destruction of US strategic weapons systems. Thus the Soviets would be expected to attack communication and early warning space systems initially to surprise and blind the US, followed in later phases, by destruction of navigation and meteorological systems. The attacks would include both CONUS-based and overseas ground segments of space systems to degrade the capabilities of the overall systems. Finally, collateral damage would also affect space systems.

Figure 2.2 summarizes the characteristics of the three scenarios.

Calculate Subsystem Changes. The last step in building the wartime scenarios is to convert the characteristics of the Soviet attack into changes to the Subsystem Availability Table. This was done by creating a new table for each phase of each scenario and changing the values to reflect the

	Limited	Major	Central
number of phases	1	2	3
targets:			
low altitude	yes	yes	yes
high altitude	no	no	yes
CONUS systems attacked	no	no	yes
overseas systems attacked	yes	yes	yes
collateral damage	no	yes	yes

Figure 2.2 Summary of Scenario Characteristics

attack characteristics. This procedure is based on the influence diagram, Figure 2.1, since each phase of the attack represents a new restoration management environment to be handled by CINCUSSPACECOM. The tables for each scenario are shown in Appendix C. Changed values are identified by an asterisk.

This chapter introduced the influence diagram as a means of developing the decision process for restoration management of space systems. The initial inputs to the influence diagram, status reports from command and control centers, SPADOC data base and wartime scenarios, were then derived. In Chapter III alternative methodologies for modeling this decision process are described.

III. Methodology

Introduction

This chapter uses the influence diagram and decision process presented in Chapter II to select a methodology that can be used to determine user priorities and make restoration decisions. Using the influence diagram of Chapter II, CINCUSSPACECOM "knows" both the environment and his alternatives at the time of decision. So it is assumed that CINCUSSPACECOM works in a "certain" environment.

Selecting A Methodology

Preemptive Priorities. One approach to resolving the restoration management decision is to look at each space system's subsystems as resources which may be reallocated to the mission of highest priority. Since technical constraints limit the reallocation process, it is possible that a space system's resources will not be reallocated, no matter how high or low the system's priority. The priorities then provide direction for optimizing the architecture under a given set of resources.

In the restoral process described above, it is assumed that several possible architectures are available for restoring space systems of a given priority. When this is true, restoration of lower priority space systems can affect the restoration management decision. When alternate solutions do not exist, there is no choice. This approach is called lexicographic optimization. Here, the highest priority mission is restored first. Then restoration of the second highest priority is attempted if alternate solutions exist. Each time a system is restored, CINCUSSPACECOM has moved closer to final optimization of the wartime capabilities of the space systems. When alternate solutions no longer exist, his decision process has been completed.

Weighted Priorities for Restoration. A second approach to the restoration management decision is the use of the priorities as simple weights for comparing alternative solutions. Each alternative represents a different architecture of available systems. The priorities are applied to these architectures to derive a value for that architecture. For example, suppose DMSP (space system 1) has priority 1 ($p_{1,t}$), NROSS priority 2 ($p_{2,t}$), GPS priority 3 ($p_{3,t}$), Transit priority 4 ($p_{4,t}$), MILSTAR priority 5 ($p_{5,t}$), and DSCS priority 6 ($p_{6,t}$) for restoration during some time period t (t = 1, 2, 3) of the conflict. Suppose architecture A restores DMSP, GPS, DSCS and architecture B restores space systems NROSS, Transit and MILSTAR. The priorities are applied and summed:

$$\text{Value(Architecture A)} = V_A = p_{1,t} + p_{3,t} + p_{5,t} \qquad (3.1)$$

$$\text{Value(Architecture B)} = V_B = p_{2,t} + p_{4,t} + p_{6,t} \qquad (3.2)$$

Then the architectures are compared on the basis of V_A and V_B.

Additional criteria may be required to select an architecture if $V_A = V_B$. One approach to tie-breaking is simply to select the architecture containing the highest priority system. If $p_{3,t}$ was the highest priority in the previous example, then DMSP, GPS and DSCS would be restored. The justification for this procedure resembles the lexicographic approach, lending support to that approach.

A second approach to tie-breaking is to look at the number of space systems restored. In the last example, this would not be useful. Indeed, the number of space systems restored cannot be substituted for important missions. For example, in a conventional war navigation may be more important than systems that locate nuclear detonations. It must be understood that "priorities" means the order of wartime capabilities needed by battlefield commanders. Priorities thus represent the order in which restoration must be attempted. So the highest restoration priority is given to the system that restores the highest priority wartime capability. As the problem of tie-breaking indicates, applying the priorities as weights does not model this restoral requirement without assistance from the lexicographic approach. Thus the priorities cannot be used to derive the value of the architecture. Their only purpose is to allow ranking of wartime capabilities or missions.

Optimum Configuration

In the restoration process described above, partial restoration solutions can be obtained by reallocating subsystems from other space systems. This may occur even when the original subsystems are still available. In addition, the restoration solution may include the first available subsystems found in the data base. Thus, there may be more than one way to restore a space system. However, the subsystems used to restore the space system may allow or prevent the restoration of other space systems.

From the viewpoint of efficiency and capability, an architecture which uses the original subsystems for restoration is preferable to an architecture of reallocated subsystems. The original system is efficient because the subsystems are engineered for compatibility and collocated. Thus, the time required to produce a specified wartime capability is minimized. The original system has more capability than alternative architectures because all original capabilities are achieved using this configuration. Alternative architectures which introduce some degree of incompatibility (beyond that of different payloads) may not have the equipment or capacity to produce all of the capabilities of the original equipment. If the capacity exists, operators may have to trade off efficiency to achieve these capabilities.

Thus, for efficiency and capability, the original configuration may be considered the optimal configuration for the space system. Achieving this optimal configuration can be a goal of the restoration management decision, within the limits of the available subsystems.

Space System Restoration

Restoral management can be considered a problem where restoring each space system during a specific phase of a conflict represents an objective. The problem is trivial when only the initial Subsystem Availability Table is used since each space system can be "restored" using its own subsystems. However, the restoral objectives can conflict with each other once a war begins and subsystems are removed from the table.

It is preferable to view the restoral management problem as a multiple, rather than single, objective problem since conversion to a single objective by treating one space system's restoral as the objective while holding the others as constraints would "force rather severe assumptions" on the problem (19:280). This characterization of the problem using multiple, conflicting objectives suggests Goal Programming as a methodology for system restoration.

According to Ignizio (19:278), there is "no universal agreement as to the definition of either goal programming or generalized goal programming." However, goal programming may be distinguished from single objective linear programming by its use of goals, priorities or weights, deviation variables and "minimization of weighted sums of deviation variables" to optimize goals (29:220). Thus, the idea of goal programming is to establish a aspiration level of achievement for each criterion and then use that level as a target for optimization of the goals. Goal programming is ideal for criteria with respect to which target (or threshold) values of achievement are of significance (29:220).

Determining User Priorities

User priorities for space system restoral represent a subjective judgment by a decision maker of the wartime capabilities needed most in a particular phase of a conflict. Whether done by the National Command Authorities, the Joint Chiefs of Staff or by CINCUSSPACECOM, this judgment must be timely and related to clearly measurable criteria such as those presented in status reports from the command and control centers. Methodologies suggested by these requirements include Worth Assessment, Delphi Method and Analytic Hierarchy Process (AHP).

Worth Assessment. Worth Assessment is a "decision analysis procedure that finds the worth or value for each possible course of action (alternative) in a problem" (24:11). The procedure uses the attributes of an alternative to measure the alternative's worth. Implicit in this procedure is a hierarchy (an objectives tree) of criteria flowing from the initial problem through the alternatives to their attributes. Worth Assessment is useful because it can be used to "solve multiple conflicting objectives that have noncommensuratble units" to produce a ranking of the alternatives (24:9). However, developing the value functions and weights make Worth Assessment unusable in time-critical situations (24:10).

Delphi Method. The Delphi method is an iterative procedure for obtaining weights from a group of experts (28). The procedure refines the opinions of panel members by repeatedly challenging extreme opinions until a consensus is developed. Quade lists four criticisms of the procedure (28:342):

1. It is useful when the "experts are all of the same specialty,"

2. It is "cumbersome: several weeks may elapse before questionnaires are returned or an interviewer can poll the panel,"

3. "The amount of material each respondent must process for each round may be considerable,"

4. The experts "may have difficulty reproducing earlier reasoning" on the problem.

Although these criticisms indicate the Delphi Method may not be useful for obtaining subjective judgments once a conflict has begun, it may be applied prior to the start of a conflict. For example, military planners developing OPLANs could apply the procedure when establishing criteria for the restoration decision. These criteria would then determine the data reported in the status reports.

Analytic Hierarchy Process. This process is similar to

Worth Assessment since a hierarchy of criteria is used to determine weights. Here, however, the hierarchy is derived explicitly and is the first of three steps in the process. The remaining steps, pairwise comparison of criteria and calculation of weights, are derived from the hierarchy (30). According to Saaty (30:12), using AHP:

> enables decision makers to represent the simultaneous interaction of many factors in complex, unstructured situations. It helps them to identify and set priorities on the basis of their objectives and their knowledge and experience of each problem.

Thus, AHP may a useful tool as experienced commanders, aware of combat objectives, determine their requirements for each phase of a conflict. Unlike the Delphi Method, AHP provides techniques for testing the sensitivity of final decisions and for reducing the inconsistency inherent in subjective judgments. This is possible since AHP uses matrix mathematics to process weighted value assessments, thereby increasing computational speed while providing structure to the commander's subjective logic. Finally, the time required to convert subjective judgments into numerical weights is decreased through the use of computer programs. Saaty provides a listing for a FORTRAN computer program that can generate these values (30). The program was modified for use on the Aeronautical Systems Division's Cyber computer in support of an available zero-one integer programming computer program. For these reasons, AHP was selected as the methodology for determining User Priorities.

Goal programming's use of priorities and weights complements AHP in its support of the User Priorities. Ignizio states (19:281) that goal programming is based on the belief that:

> while it may be either impossible or impractical to determine a decision maker's utility function, a real world decision maker can usually at least cite (initial) estimates of his or her aspiration levels for objectives.

Thus, when AHP is used to synthesize priorities and weights for space system restoral, goal programming can determine a restoral plan that maximizes the wartime capabilities desired. This solution is found using the priorities developed in AHP to determine a lexicographic optimization of the solution. This lexicographic procedure is consistent with the restoral management process described at the beginning of the chapter.

This chapter discussed the requirements and possible methodologies for solving the restoral management problem. Chapter IV develops goal programming and AHP formulations.

IV. Problem Formulation

Introduction

This chapter provides the problem formulation. The format follows the Generalized Goal Programming model of Ignizio (19). Following the goal programming formulation, AHP is applied to determine weights and priorities for restoration management.

Goal Programming Formulation

Definitions. The following indices have already been used implicitly in describing the restoration management decision and the environment for a model containing six space systems and eleven subsystems per space system:

1. time periods: $t = 0, 1, 2, 3$;
2. space system missions: $m = 1, 2, 3$;
3. space systems: $i, j = 1, 2, 3, 4, 5, 6$;
4. subsystems: $k = 1, 2, \ldots, 11$;

where the values are shown in Table 4.1. The index i will normally denote the space system providing a reallocated subsystem. The index j will normally denote the space system using a reallocated space system.

Decision Variables. Let $x_{i,t}$ be the decision variable representing the decision to make space system i available in time period t. The range of $x_{i,t}$ is:

1, if space system i is available in time period t
0, if system i is not available in time period t

TABLE 4.1

MODEL INDICES AND VALUES

Mission Type	m	Space System Type	i, j
Weather	1	DMSP	1
		NROSS	2
Navigation	2	NAVSTAR GPS	3
		Transit	4
Communications	3	MILSTAR	5
		DSCS	6

Let $\overline{X}_t$ be the vector of decision variables at time period t. Then:

$$\overline{X}_t = (x_{1,t}, x_{2,t}, x_{3,t}, x_{4,t}, x_{5,t}, x_{6,t}) \qquad t = 1, 2, 3. \quad (4.1)$$

So $\overline{X}_t$ represents the restoration management decision at the beginning of time period t.

Let $y_{i,j,k,t}$ be the decision variable representing the use of subsystem k from space system i by space system j in time period t. The range of $y_{i,j,k,t}$ is:

1, if space system j uses subsystem k from space system i n time period t
0, otherwise

For example, $y_{1,2,1,3} = 1$ indicates that a number of payloads ($k = 1$) originally belonging to DMSP ($i = 1$) have been reallocated to the NROSS ($j = 2$) mission during the third time period ($t = 3$) of a conflict.

Let $\overline{Y}_t$ be the matrix of decision variables $y_{i,j,k,t}$ for time period t. Then $\overline{Y}_t$ is a 6 X 6 X 11 array representing individual decisions about the use of available subsystems.

Parameters. Let $b_{i,k,t}$ be the resource parameter representing the number of k subsystems of space system i available at the beginning of time period t. Then

$$\overline{B}_t = (b_{1,1,t}, \ldots, b_{6,11,t}) \qquad t = 1, 2, 3. \qquad (4.2)$$

is a 6 X 11 array as shown (transposed) in Table 2.1 for $t = 0$ or as modified for a specific scenario in Appendix C. Table 2.1 shows the subsystems available when the six space systems are fully operational. As noted in Chapter II, these are the initial values only and may change due to the wartime scenario.

Let $c_{i,j,k}$ be the resource usage parameter representing the minimum number of subsystems k from space system i required to restore subsystem k of space sytem j in time period t. In this formulation, Tables 2.2 through 2.7 are technology matrices for the restored space systems ($j = 1,\ldots,6$). The columns in each table show the minimum number of subsystems k of space system i required for restoration of space system j. If space system j cannot use subsystem k during the specified time period, then $c_{i,j,k} = 0$. The parameter $c_{i,j,k}$ is assumed to be constant with respect to the time period so the index t is not used.

Goal Programming Variables. There are two sets of goals in the model: restoration goals and configuration goals. The restoration goals for each time period t are:

goal 1:	$x_{1,t} \geq 1$	Restore DMSP	(4.3)
goal 2:	$x_{2,t} \geq 1$	Restore NROSS	(4.4)
goal 3:	$x_{3,t} \geq 1$	Restore NAVSTAR GPS	(4.5)
goal 4:	$x_{4,t} \geq 1$	Restore Transit	(4.6)
goal 5:	$x_{5,t} \geq 1$	Restore MILSTAR	(4.7)
goal 6:	$x_{6,t} \geq 1$	Restore DSCS	(4.8)

These goals state the desire to make each space system available in time period t. When restoration goal i is achieved, $x_{i,t} = 1$, so the aspiration level for each goal is 1. The goals are converted to equalities by considering the nonachievement of each goal (19:282). Let $d_{i,t}$ equal the deviation of goal i from its aspiration level in time period t:

$$d_{i,t} = 1 - x_{i,t} \tag{4.9}$$

Since the deviation may be positive (representing underachievement) or negative (overachievement), let

$$d_{i,t} = p_{i,t} + n_{i,t} \tag{4.10}$$

where

$$p_{i,t} * n_{i,t} = 0 \tag{4.11}$$

and

$$p_{i,t},\ n_{i,t} \geq 0. \tag{4.12}$$

However, the upper bound on the $x_{i,t}$ decision variables equals to the aspiration level for each goal, so the restoration goals cannot be overachieved. That is, $p_{i,t} = 0$ for all values of $x_{i,t}$ and $n_{i,t}$. Thus the variable $p_{i,t}$ may be removed from the goal equations, yielding:

$$\text{goal 1:} \quad x_{1,t} + n_{1,t} = 1 \tag{4.13}$$

$$\text{goal 2:} \quad x_{2,t} + n_{2,t} = 1 \tag{4.14}$$

$$\text{goal 3:} \quad x_{3,t} + n_{3,t} = 1 \tag{4.15}$$

$$\text{goal 4:} \quad x_{4,t} + n_{4,t} = 1 \tag{4.16}$$

$$\text{goal 5:} \quad x_{5,t} + n_{5,t} = 1 \tag{4.17}$$

$$\text{goal 6:} \quad x_{6,t} + n_{6,t} = 1 \tag{4.18}$$

In this formulation, the deviation variables are associated with the space systems. Other formulations of the restoration management problem may be developed where the deviation variables are associated with the mission.

The mathematical formulation of the configuration goals is based on the $c_{i,j,k}$ values listed in Tables 2.2 through 2.7. Each table contains the minimal number of each specific subsystem required to restore each subsystem of a given space system. For example, Table 2.6 describes the restoration requirements for MILSTAR. Due, perhaps, to efficiency or compatibility, the $c_{i,j,k}$, value for a specific subsystem may vary as different space systems are considered as the source for a replacement subsystem. So the value of $c_{i,j,k}$ must be considered relative to the source space system and to the destination space system.

In most cases, no one space system contains all the subsystems required to restore another space system. For example, DMSP lacks the communications payload needed to restore MILSTAR since the former space system performs the meteorological mission. This is indicated in the DMSP column of Table 2.6 by a zero in the payload row. However, the MILSTAR column of Table 2.6 contains only one zero, in the space link row, because the original system does not have a space link (from Table 2.1). This column therefore depicts the minimal number of subsystems required to keep MILSTAR operational without reallocation of subsystems from other space systems.

In general, the minimal configuration column for space system $x_{j,t}$ can be denoted by $c_{j,j,k}$, for $k = 1,\ldots,11$. The time period is not specified since the parameter $c_{j,j,k}$ is assumed to be independent of time. Achieving the optimal configuration for MILSTAR can be described as the restoration of this minimal configuration. This occurs when the $y_{j,j,k,t}$ decision variables associated with this column of Table 2.6 are set to one. Thus:

$$\sum_{k=1}^{11} y_{5,5,k,t} \geq 10 \tag{4.19}$$

represents the goal of achieving the restoration of the minimal configuration for MILSTAR in time period t, where 10 is the number of different types of subsystems required to make MILSTAR available and the value of the equation when $y_{5,5,k,t} = 1$ for all values of k. So 10 is the aspiration level for the goal. From the $c_{j,j,k}$ columns in Tables 2.2 through 2.7, the aspiration level is ten for all space systems except Transit and DSC where the value is nine. To simplify modeling this difference in aspiration levels, let g_i represent the aspiration level for space system i. Then $g_i = 9$ for $i = 4, 6$ and $g_i = 10$ otherwise.

Since the aspiration levels are sought as a minimum value, underachievement must be avoided. Underachievement of the configuration goals is measured by the value of the deviation variable $n_{1i,t}$ (19:282). The notation $n_{1i,t}$ is used to distinguish these variables from the deviation variables associated with the restoration goals. In general, $n_{1i,t}$ is the deviation variable associated with space system i in the configuration goals. The range of these deviation variables is:

$$0 \leq n_{1i,t} \leq g_i \qquad i = 1,\ldots,6 \tag{4.20}$$

where only integer values are assumed.

The configuration goals then become equalities:

$$\sum_{k=1}^{11} y_{i,i,k,t} + n_{1i,t} = g_i \qquad \begin{array}{l} i = 1,\ldots,6 \\ t = 1, 2, 3 \end{array} \qquad (4.21)$$

$P_{m,t}$ is an integer parameter representing the priority of mission m in time period t. Upper case P is used to distinguish between the preemptive priority used here and the weighted priority system discussed in Chapter III and designated by a lower case p. Space systems having similar mission capabilities are assumed to be comparable (or commensurable) and thus have the same priority for restoration. This grouping allows the decision maker to plan system availability in terms of missions rather than specific space systems. This is a more natural approach to the problem, particularly when more than one system can provide some degree of mission accomplishment. The values for $P_{m,t}$ are determined by the decision maker. The range of $P_{m,t}$ is:

$$P_{m,t} = 1, 2, 3 \qquad t = 1, 2, 3. \qquad (4.22)$$

where $P_{m,t} = 1$ if mission m has the highest priority for restoration in time period t.

According to Ignizio (20), a fourth priority should be added to this formulation. This priority is the requirement that all absolute constraints in the model be satisfied by any problem solution. This requirement is usually designated priority zero, indicating it must be satisfied before a solution to lower priority goals is sought.

Parameter $w_{i,t}$ represents the weight given to space system i in time period t. The weights sum to one for each mission. For example, MILSTAR and DSCS III share the communications mission, thus:

$$w_{5,t} + w_{6,t} = 1 \qquad t = 1, 2, 3. \qquad (4.23)$$

These weights are considered penalties, since the deviation from goal achievement is being minimized in the goal programming formulation. Thus if $w_{i,t} > w_{j,t}$, then space system i is preferred to space system j in time period t. Space systems are assumed to have different weights dependent on the mission and time period but independent of the priority. Values for the weights may be determined by technical experts in a space mission using AHP or a similar method.

Variable $a_{s,t}$ is the sum of the weighted deviations of all goals of priority $s = P_{m,t}$ during time period t. That is:

$$a_{s,t} = (w_{i,t} * n_{i,t}) + (w_{i,t} * n_{1i,t}) \qquad (4.24)$$

where index i ranges over the set of space systems having priority s in time period t. The first term in the sum is the deviation from system restoration while the second is the deviation from the minimal configuration using a system's own subsystems for restoration. The achievement vector for time period t is:

$$\bar{A}_t = (a_{0,t}, a_{1,t}, a_{2,t}, a_{3,t}) \qquad (4.25)$$

Formulation of the Objective Function. The starting point for formulating the objective function is maximization of the wartime capabilities provided by those space systems made available during time period t of a conflict. This is done by restoring the space system missions in the order specified by the user priorities. So the deviation from the restoration and configuration goals is minimized. Then the objective function for time period t is to lexicographically minimize:

$$\bar{A}_t = (a_{0,t}, a_{1,t}, a_{2,t}, a_{3,t}) \qquad t = 1, 2, 3. \quad (4.26)$$

Formulation of Constraints. There are three sets of constraints. Formulation of the restoration and configuration goals (4.3 - 4.8, 4.21) above yielded the first set, containing 36 equations for the full three time period model. The remaining two sets of constraints are the rigid or absolute constraints of the goal programming problem and are treated like normal constraints in a linear programming problem (19:279).

The second set of constraints sets the upper bound on the number of subsystems of each system available at the beginning of each time period. These constraints state that the total use of each subsystem in the time period must be less than or equal to the number available ($b_{i,k,t}$). Thus, these equations select a time period (t), source space system (i), and subsystem (k) and then sum the subsystem's use over all six space systems (j).

The first step in writing these constraints was to determine the values of $b_{i,k,0}$ which represent the number of subsystems available prior to the start of a conflict where all space systems are in their original configuration. Time period t = 0 may be considered as the time period prior to the start of a conflict. These values are shown in Table 2.1. Next, the values of $c_{i,j,k}$ which represent minimal numbers of subsystems required for system availability were determined. The values of $c_{i,j,k}$ are based on the mission and requirements of space system i. With 11 subsystems in each space system and 6 space systems in each time period of the model, there are 198 system technical requirement constraints.

The inequalities are formed by summing the product of the resource usage parameter, $c_{i,j,k}$, and the decision variable $y_{i,j,k,t}$ over the using space systems j and setting the sum less than or equal to the resource availability parameter $b_{i,k,t}$:

$$\sum_{j=1}^{6} (c_{i,j,k} * y_{i,j,k,t}) \leq b_{i,k,t} \qquad \begin{array}{l} t = 1, 2, 3 \\ i = 1,\ldots,6 \\ k = 1,\ldots,11. \end{array} \qquad (4.27)$$

An example of these constraints is the use of the eleven AFSCF ground antennas which support all six space systems in this study. In Chapter II, these ground antennas were modeled as part of the DSCS space system. The following equation shows that the ground antennas ($k = 8$) are available to all six systems ($j = 1,\ldots,6$) during time period t as long as the total use of the antennas does not exceed the number available:

$$(c_{6,1,8} * y_{6,1,8,t}) + (c_{6,2,8} * y_{6,2,8,t}) +$$
$$(c_{6,3,8} * y_{6,3,8,t}) + (c_{6,4,8} * y_{6,4,8,t}) +$$
$$(c_{6,5,8} * y_{6,5,8,t}) + (c_{6,6,8} * y_{6,6,8,t}) \leq 11 \qquad (4.28)$$

where $b_{6,8,t} = 11$.

The third set of constraints model "system availability." These constraints are formed by first selecting a time period (t) and using space system (j). Then, for each subsystem needed to restore the space system ($c_{i,j,k} > 0$, $k = 1,\ldots,11$), the product of the resource usage parameter, $c_{i,j,k}$, and the decision variable $y_{i,j,k,t}$ is summed over the source space systems (i). Finally, these products are set greater than or equal to the product of the resource usage parameter for the space system's original configuration and the decision variable for the using space system, $x_{j,t}$. Thus:

$$\sum_{i=1}^{6} (c_{i,j,k} * y_{i,j,k,t}) \geq x_{j,t} \qquad \begin{array}{l} t = 1, 2, 3 \\ j = 1,\ldots,6 \\ k = 1,\ldots,11. \end{array} \qquad (4.29)$$

An example of these constraints is the requirement to have a ground antenna (k = 8) allocated to DSCS (j = 6) before DSCS is restored in time period t:

$$\begin{aligned} &(c_{1,6,8} * y_{1,6,8,t}) + (c_{2,6,8} * y_{2,6,8,t}) + \\ &(c_{3,6,8} * y_{3,6,8,t}) + (c_{4,6,8} * y_{4,6,8,t}) + \\ &(c_{5,6,8} * y_{5,6,8,t}) + (c_{6,6,8} * y_{6,6,8,t}) \geq x_{6,t} \end{aligned} \qquad (4.30)$$

This set of constraints shows the kinds of subsystems required to operate each space system. The constraints state that in order to restore a system in the specified time period, the number of subsystems of a particular type allocated to the system must be greater than or equal to the minimal number of subsystems in the original configuration (t = 0). There are 198 equations in this set.

Summary of Goal Programming Formulation. For each conflict phase t, find $\overline{X}_t$ so as to:

lexicographically minimize

$$\overline{A}_t = (a_{0,t}, a_{1,t}, a_{2,t}, a_{3,t}) \qquad (4.31)$$

where

$$a_{s,t} = \sum_{i=1}^{6} [(w_{i,t} * n_{i,t}) + (w_{i,t} * n_{1i,t})] \qquad s = 1,2,3 \quad (4.32)$$

s.t.

$$x_{i,t} + n_{i,t} = 1 \qquad i = 1,\ldots,6 \quad (4.33)$$

$$\sum_{k=1}^{11} y_{i,i,k,t} + n_{1i,t} = g_i \qquad i = 1,\ldots,6 \quad (4.34)$$

$$\sum_{j=1}^{6} (c_{i,j,k} * y_{i,j,k,t}) \leq b_{i,k,t} \qquad \begin{array}{l} i = 1,\ldots,6 \\ k = 1,\ldots,11 \end{array} \quad (4.35)$$

$$\sum_{i=1}^{6} (c_{i,j,k} * y_{i,j,k,t}) \geq x_{j,t} \qquad \begin{array}{l} j = 1,\ldots,6 \\ k = 1,\ldots,11 \end{array} \quad (4.36)$$

$$0 \leq n_{1i,t} \leq g_i \qquad i = 1,\ldots,6 \quad (4.37)$$

$$x_{i,t},\ y_{i,j,k,t},\ n_{i,t} = 0,\ 1 \qquad (4.38)$$

Equation 4.31 is the objective function for time period t. Equation 4.32 is the function to be minimized at each priority s. Equation 4.33 are the restoration goals for the restoration management decision. Equation 4.34 are the configuration goals. Equation 4.35 are the system technical requirement constraints. Equation 4.36 are the system availability constraints. Equation 4.37 indicates the possible values of the deviation variable associated with the configuration goals. Equation 4.38 are the non-negativity constraints.

Appendix D contains the complete listing of equations for the model at t = 0 and explains the format used in writing the variables and parameters for MPOS.

Priorities and Weights

There are three steps in applying AHP to the problem: decomposition of objectives to determine measurable criteria, pairwise comparison of criteria and synthesis. Consistency tests can also be used to check the subjective priorities.

Decomposition of Objectives. Figure 4.1 shows a hierarchy for the restoration problem. The levels are based on the research goal (top level), and the missions and criteria discussed in Chapter II. This hierarchy shows how those criteria can be integrated into solving the restoration problem. Once the missions have been listed as the second level of the hierarchy, the criteria become measures of achieving that objective. The inputs for measuring attribute levels of these criteria would come from the status reports transmitted to the USSPACECOM headquarters by the command and control center for each space system (as discussed in Chapter II).

Pairwise Comparison. Using the hierarchy shown in Figure 4.1, 14 separate matrices of pairwise comparisons

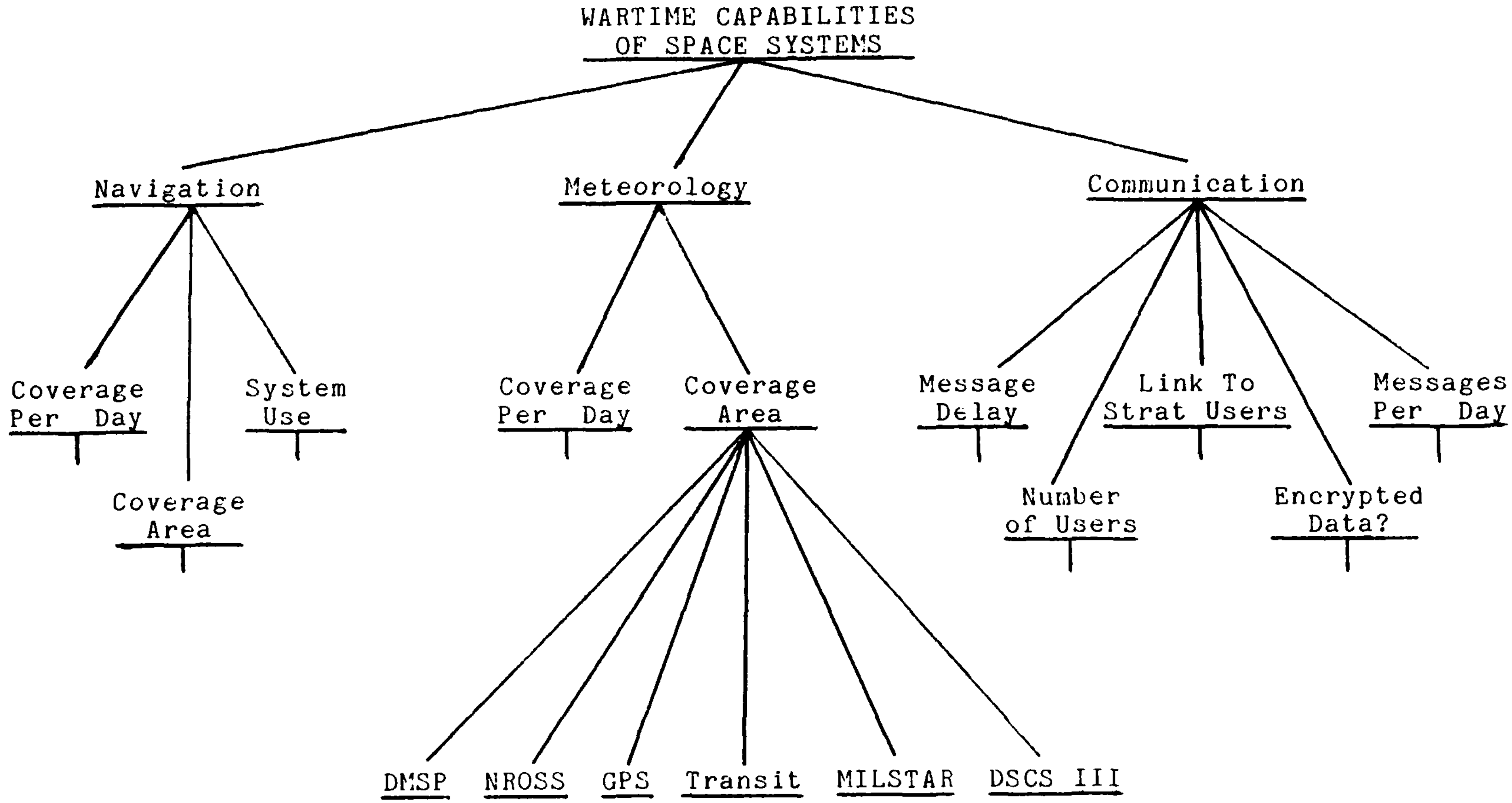

Figure 4.1 AHP Hierarchy

would be made. At the highest level of the hierarchy, the decision maker (CINCUSSPACECOM) is asked to compare the relative contributions of each space mission to achieving the needed wartime capabilities. At the bottom of the hierarchy, the decision maker (or technical expert) is asked to compare the relative contributions of each space system to achieving a specific criterion. Each pairwise comparison of missions or criteria produces one matrix.

Synthesis. The final step in the AHP process is synthesis of the criteria rankings into a column of priorities. First, each column in each matrix is normalized. This is done by dividing each element in a matrix column by the sum of the elements in the column. The result is a normalized matrix (or, in the study, 14 normalized matrices). Next, each row in the normalized matrix is averaged. This is accomplished by summing the elements in each row and dividing the sum by the number of elements in the row. These two steps - normalizing and averaging - generate a vector whose elements are the relative priorities of the rows, that is, the missions, criteria or space systems.

Space System Weights. The weights for each criterion and space system are determined from these priorities. First, the weights for each space system relative to each criterion are determined. To do this the priority vector of space systems under each criterion is multiplied by the priority value of the criterion to produce a vector of weighted priorities. Then the weighted priority vectors are summed across the ten criteria. The resulting vector contains the weights for the six space systems relative to the three missions. This process of multiplying by each element of a given level's priority vector and summing across the level can be repeated to yield a vector of space system weights relative to the goal of optimizing wartime capabilities (30:80).

This chapter provided the formulation of the restoration management decision process using the goal programming approach. Following the formulation, the application of AHP for determining priorities for restoration and weights for space systems was discussed. An example of the model's use is shown in the next chapter.

V. Model Use and Results

Introduction

This chapter demonstrates the application of the problem formulation to an example restoral management problem. The example begins with the selection of a wartime scenario. The priorities for space system restoral are then developed using AHP. Finally, the Goal Programming model is constructed and solved.

Problem Flow

Figure 5.1 shows the process used in solving the example problem.

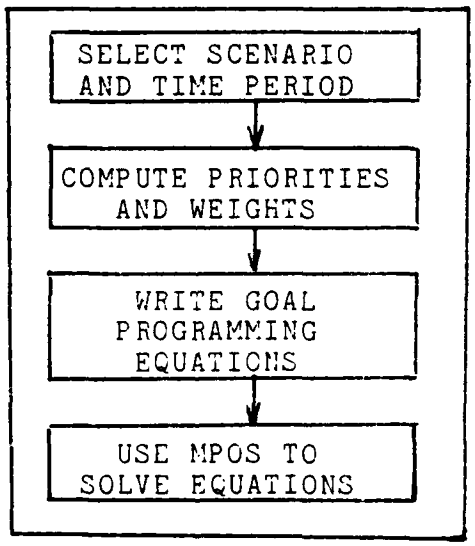

Figure 5.1 Solution Process

Select Scenario and Time Period. The central conflict scenario was selected for the example. This scenario is the most stressing conflict since the restoration management decision must consider the effects of attacks on all space systems. The second time period, the attack phase described in the introduction to Chapter II, was selected to ensure the effects of Soviet attacks would be incorporated into the decision. In addition, the time period represents a very complex decision making environment for CINCUSSPACECOM. Although the last period is more stressing in terms of the numbers and types of remaining subsystems, the restoration decision is considerably less complex.

Compute Priorities and Weights. Beginning with the top level of the AHP hierarchy shown in Figure 4.1, the priority vector for each level of the hierarchy was computed using the process of pairwise comparison and synthesis described in Chapter IV. Saaty's AHP program was used for these calculations. The matrix inputs to the program are shown in Appendix E.

The user priorities are the elements of the priority vector for the top level of the hierarchy and result from the first matrix shown in Appendix E. The values are:

1. Priority 1: communications (AHP weight = .7662). Thus:

$$P_{3,2} = 1 \tag{5.1}$$

2. Priority 2: navigation (.1578) and:

$$P_{2,2} = 2 \tag{5.2}$$

3. Priority 3: meteorology (.0758) and:

$$P_{1,2} = 3 \tag{5.3}$$

The priority vector for the ten criteria was computed from the second, third and fourth matrices of Appendix E by repeating the pairwise comparison and synthesis process for the second level of the hierarchy. The values are:

1. NCD - .0105
2. NCA - .0344
3. NSU - .1128
4. MCD - .0126
5. MCA - .0632
6. CMD - .0980
7. CNU - .0960
8. CE - .2596
9. CDT - .0245
10. CSC - .2879

Finally, the priority vectors for the six space systems under each criterion - the third level of the hierarchy - were computed from the remaining ten matrices in Appendix E. The resulting priority vectors are shown in Figure 5.2. These values reflect the relative potential capabilities among comparable space systems when all systems are fully operational (t = 0).

To determine overall space system weights, the ten element priority vector for the criteria under all missions

Space System	NCD	NCA	NSU	MCD	MCA	CMD	CNU	CE	CDT	CSC
DMSP	.04	.04	.04	.54	.41	.08	.06	.30	.06	.04
NROSS	.04	.04	.04	.29	.41	.03	.03	.03	.04	.04
GPS	.54	.54	.58	.04	.04	.03	.03	.03	.04	.04
Transit	.29	.29	.26	.04	.04	.03	.03	.03	.04	.04
MILSTAR	.04	.04	.04	.04	.04	.53	.54	.30	.45	.41
DSCS	.04	.04	.04	.04	.04	.29	.29	.30	.36	.41

Figure 5.2 AHP Priority Vectors for Criteria

was multiplied by the array of space system priority vectors shown in Figure 5.2. However, the weights are to be compared within mission categories only and must sum to one. To do this, the weights of both space systems within each mission were summed. Then the individual weights were divided by this sum to normalize the values. The hierarchy weights and normalized weights were:

1. DMSP - .1448 and .6899;
2. NROSS - .0651 and .3101;
3. GPS - .1235 and .6197;
4. Transit - .0758 and .3803;
5. MILSTAR - .3204 and .5426;
6. DSCS - .2701 and .4574.

Write Goal Programming Equations. Using the AHP priorities and weights and the central conflict data base as inputs, the equations for priority level one of the goal programming model were written. The equations and control statements required by MPOS are shown in Appendix F.

Use MPOS To Solve Equations. The goal programming problem formulated in Chapter IV is a zero-one integer programming problem. Several software packages are available at AFIT for solving linear programming problems. However, MPOS, operating on the Aeronautical System Division's Cyber computer, is the only readily available program capable of solving large zero-one integer programming problems.

The problem's dimensions - the number of variables and constraint equations - were large even for MPOS, so the problem was divided into two parts in a solution process called Sequential Linear Goal Programming. First, the restoration goals for each priority level were run to insure a feasible solution existed. Using the results of the MPOS run for the first priority, the program was run for the second priority level. With the results from the second priority level, the third priority level was run. In each run additional equations were added to indicate the restoration decisions reached in previous runs. Three MPOS runs were used to solve the restoration goals.

Then the minimum configuration goals were run, solving the problem for each of the six restored space systems in order of mission priority and space system weight. Thus, a total of nine MPOS runs were needed. The solution to the ninth MPOS run is the solution to the restoration management problem for time period two of the central conflict scenario since it shows the allocation of available subsystems and minimizes deviation from all goals.

Scenario Results

Tables 5.1 through 5.3 show the architecture for time period two of the central conflict scenario. These tables compare the original minimal requirements for each space system (the $c_{j,j,k}$ values shown in the second column) with the number and source of the subsystems reallocated by the restoration management decision (shown in the fourth column).

Table 5.1 shows that the restoration and configuration goals (and availability of the required subsystems) drove the solution to the minimal configuration for DSCS. Also, the optimal configuration was nearly achieved for MILSTAR. Since the scenario called for loss of MILSTAR's data processing capabilities, reallocation of another system's data processor was needed to restore MILSTAR. The goal programming solution used DMSP's subsystem to meet this requirement ($y_{1,5,3,2}$ = 1).

Similarly, Table 5.2 shows GPS achieved its minimal configuration despite a reduction in the number of ground communications, ground antennas and ground links available. Transit did not achieve its minimal configuration since the number of ground links available within the system

TABLE 5.1

SOLUTION FOR CENTRAL CONFLICT TIME PERIOD 2
Priority 1

MILSTAR	Minimum Subsystem Required	Source of Subsystem	Number
Space Segment			
1. Payload	27	MILSTAR	27
2. Comm	1	MILSTAR	1
3. Data Proc	1	DMSP	1
Ground Segment			
4. Telemetry	1	MILSTAR	1
5. CmdControl	1	MILSTAR	1
6. Comm	1	MILSTAR	1
7. Planning	1	MILSTAR	1
8. Antennas	1	MILSTAR	1
Data Links			
9. Space Link	0	Not Required	0
10. GroundLink	1	MILSTAR	1
11. Cross Link	1	MILSTAR	1
DSCS			
Space Segment			
1. Payload	3	DSCS	3
2. Comm	1	DSCS	1
3. Data Proc	0	Not Required	0
Ground Segment			
4. Telemetry	1	DSCS	1
5. CmdControl	1	DSCS	1
6. Comm	1	DSCS	1
7. Planning	1	DSCS	1
8. Antennas	1	DSCS	1
Data Links			
9. Space Link	1	DSCS	1
10. GroundLink	1	DSCS	1
11. Cross Link	0	Not Required	0

TABLE 5.2

SOLUTION FOR CENTRAL CONFLICT TIME PERIOD 2
Priority 2

GPS	Minimum Subsystem Required	Source of Subsystem	Number
Space Segment			
1. Payload	2	GPS	2
2. Comm	2	GPS	2
3. Data Proc	0	Not Required	0
Ground Segment			
4. Telemetry	1	GPS	1
5. CmdControl	1	GPS	1
6. Comm	3	GPS	3
7. Planning	1	GPS	1
8. Antennas	3	GPS	3
Data Links			
9. Space Link	1	GPS	1
10. GroundLink	1	GPS	1
11. Cross Link	1	GPS	1
Transit			
Space Segment			
1. Payload	1	Transit	1
2. Comm	1	Transit	1
3. Data Proc	1	Transit	0
Ground Segment			
4. Telemetry	1	Transit	1
5. CmdControl	1	Transit	1
6. Comm	1	Transit	1
7. Planning	1	Transit	1
8. Antennas	1	Transit	1
Data Links			
9. Space Link	0	Not Required	0
10. GroundLink	3	DMSP	1
11. Cross Link	0	Not Required	0

TABLE 5.3

SOLUTION FOR CENTRAL CONFLICT TIME PERIOD 2
Priority 3

DMSP	Minimum Subsystem Required	Source of Subsystem	Number
Space Segment			
1. Payload	1	NROSS	1
2. Comm	1	DMSP	1
3. Data Proc	1	DMSP	1
Ground Segment			
4. Telemetry	1	DMSP	1
5. CmdControl	1	DMSP	1
6. Comm	1	DMSP	1
7. Planning	1	DMSP	1
8. Antennas	1	DMSP	1
Data Links			
9. Space Link	1	DMSP	1
10. GroundLink	1	DMSP	1
11. Cross Link	0	Not Required	1
NROSS			
Space Segment			
1. Payload	1	NROSS	1
2. Comm	1	NROSS	1
3. Data Proc	1	NROSS	1
Ground Segment			
4. Telemetry	1	NROSS	1
5. CmdControl	1	NROSS	1
6. Comm	1	NROSS	1
7. Planning	1	NROSS	1
8. Antennas	1	NROSS	1
Data Links			
9. Space Link	1	NROSS	1
10. GroundLink	1	NROSS	1
11. Cross Link	0	Not Required	0

($b_{4,10,2} = 1$) was insufficient ($c_{4,4,10} = 3$). To restore Transit, a DMSP ground link was reallocated ($y_{1,4,10,2} = 1$).

Finally, the loss of both DMSP payloads ($b_{1,1,2} = 0$) prevented the system from achieving its minimal configuration. To achieve its restoration goal, an NROSS payload was reallocated ($y_{2,1,1,2} = 1$). Despite this reallocation, NROSS was able to achieve its minimal configuration since its minimal restoration only required one of the two payloads available during the time period ($c_{2,2,1} = 1$ and $b_{2,1,2} = 2$). Table 5.3 shows the results for the third priority.

Table 5.4 summarizes the restoration management results for the six scenarios. Within each scenario and time period the missions are ordered according to user priorities. Thus, the order of missions within all three time periods of the central conflict is communications, navigation and weather. This is the order computed earlier in this chapter.

One problem occurred while running MPOS for some of the scenarios. The restoration process for some priorities imposed goal programming constraints which exhausted MPOS' resources. To reduce the dimensions of the problem, system availability constraints for systems already restored were removed. Decision variables for subsystems allocated by achieving restoral and configuration goals for higher priorities were set equal to one. The remaining priorities were solved using this modified MPOS input. These changes

TABLE 5.4

SUMMARY OF SCENARIO RESULTS

SCENARIO PERIOD	MISSION PRIORITIES	SYSTEMS RESTORED	COMMENTS
Limited 1	Nav	GPS* Transit	Transit restored using DMSP ground link.
	Comm	MILSTAR* DSCS*	MPOS resource limitation.
	Weather	DMSP* NROSS*	
Major 1	Nav	GPS* Transit	Transit restored using DMSP ground link.
	Weather	DMSP* NROSS*	MPOS resource limitation.
	Comm	MILSTAR* DSCS*	
Major 2	Nav	GPS Transit	GPS restored using DMSP ground communications and Transit ground antennas. Transit restored using DMSP ground link.
	Comm	MILSTAR DSCS*	MILSTAR restored using DMSP data processor. MPOS resource limitation.
	Weather	DMSP NROSS*	DMSP restored using NROSS payload.

Note: * indicates space system was restored using original subsystems.

SCENARIO PERIOD	MISSION PRIORITIES	SYSTEMS RESTORED	COMMENTS
Central 1	Comm	MILSTAR* DSCS*	
	Nav	GPS* Transit*	
	Weather	DMSP* NROSS*	MPOS resource limitation.
Central 2	Comm	MILSTAR DSCS*	MILSTAR restored with DMSP data processor.
	Nav	GPS* Transit	Transit restored using DMSP ground links.
	Weather	DMSP NROSS*	DMSP restored using NROSS payload.
Central 3	Comm	MILSTAR DSCS*	MILSTAR restored with DMSP data processor.
	Nav	GPS* Transit	Transit restored using DMSP ground links.
	Weather	DMSP NROSS*	DMSP restored using NROSS payload. MPOS resource limitation.

did not alter the original goal programming problem since the equations removed were no longer constraints on the solution. The subsystem decision variables inserted into the MPOS input represented the problem constraints since any new solution could not reallocate these subsystems to a lower priority space system. Table 5.4 notes occurrences of this problem.

This chapter demonstrated the procedure for solving the goal programming formulation of the restoration management problem. The solution procedure applied the inputs described in Chapter II and AHP to the problem formulated in Chapter IV. Finally, the goal programming formulation was sequentially solved for each priority level. In the next chapter, the scenario results are analyzed and compared to the results for the weighted priority goal programming methodology discussed in Chapter III.

VI. Analysis of Results

Introduction

This chapter analyzes the reallocation decisions presented in Chapter V. Then the effects of the space system weights in the problem are described. Finally, the restoration results for one scenario and one time period using the lexicographic goal programming approach are compared to the solution obtained using a weighted goal programming approach.

Analysis of Reallocation Decisions

The goal programming solutions for several scenarios consistently used DMSP subsystems for the restoration of other space systems. In five of the six scenarios, a DMSP subsystem was reallocated.

When a higher priority system lost a subsystem, the first space system reallocated was DMSP. This reallocation occurred, for example, in the second time period of the central conflict when a replacement data processor was needed for MILSTAR. DMSP subsystems were also used to restore Transit's ground link and GPS' ground communications. The order of the reallocation was seen in the intermediate results reported by MPOS as the program sought to minimize the objective function.

This order of reallocation was also seen within priorities. For example, both GPS and Transit had the same restoration priority in all scenarios. In the second time period of the major conflict, GPS used a Transit ground antenna for restoration. Also, DMSP was restored in the third time period of the central conflict by using an NROSS payload. In both cases, the system with the higher weight was given first use of the subsystem.

This reallocation of subsystems from space systems is not limited to DMSP but extends to the entire set of lower priority systems. It is a problem because the original subsystems of a system may still be available. As discussed in Chapter III, if they are available they should be used. This problem emphasizes the need for more control over the reallocation process. In Chapter IV the minimal configuration was defined as the minimal number of specific subsystems required to keep a space system operational without reallocation of subsystems from other space systems. The configuration goals are the first step in achieving this control since they direct the solution towards the original system configuration. When the minimal configuration cannot be reached, the configuration goals ensure that to the maximum extent possible the remaining available subsystems from the minimal configuration are used in the space system's new configuration. However, the configuration goals do not determine how the search for replacement subsystems is ordered. Thus, they do not affect the reallocation process. More controls (either rigid constraints or goals) will be needed to direct reallocation and ensure subsystems designated by CINCUSSPACECOM or technical experts are used for restoration.

Space System Weights

Weights are assigned to space systems performing the same mission to specify the penalty for not restoring the systems. To determine the sensitivity of the solution to these weights, the values for MILSTAR ($w_{5,2}$) and DSCS ($w_{6,2}$) were varied increments of .1 during the second time period of the central conflict.

The effect of the weights depended on the complexity of the restoration decisions for a specific time period. When only minor losses occurred, most subsystems were still available. The restoration results were not affected by the variation of the weights since in these time periods all space systems were restored. However, a zero-valued weight effectively removed the system from the problem.

When the restoration decisions for a time period became complex, as in later time periods of the major and central conflicts, subsystem losses increased. Here the weights controlled the order of subsystem reallocation. This process of restoring subsystems to minimize the objective function was seen in the partial solutions reported by MPOS.

Comparison of Preemptive and Weighted Goal Programming

Generalized goal programming can be used with either preemptive (lexicographic) or weighted priorities to formulate the restoration management decision. In Chapter III both approaches were discussed and the lexicographic approach was described as the more natural way to model restoration management. Samples of the solutions reached by both approaches are analyzed below.

The central conflict scenario was used to compare approaches. The results for the lexicographic solution of the second time period were already presented in Tables 5.1 through 5.3.

In a weighted priority formulation all deviation variables are included in one objective function. Weights are attached to the various deviation variables to indicate their relative importance. In the current problem, the AHP weights for the three missions were:

1. Meteorology - .0758
2. Navigation - .1578
3. Communications - .7662

These weights were then multiplied by the normalized space system weights ($w_{i,2}$, $i = 1,\ldots,6$) which indicate the relative preferences for space systems performing the mission:

1. DMSP - .6899
2. NROSS - .3101

3. GPS - .6197

4. Transit - .3803

5. MILSTAR - .5426

6. DSCS - .4574

The products were:

1. DMSP - .0522

2. NROSS -.0235

3. GPS - .0977

4. Transit - .0600

5. MILSTAR - .4160

6. DSCS - .3506

These weights indicate the relative importance of the six space systems in the overall restoration management decision. Using them, the objective function is:

$$\begin{aligned} \text{minimize} \quad & .0522n_{1,2} + .0522n_{11,2} + .0235n_{2,2} + .0235n_{12,2} \\ & + .0977n_{3,2} + .0977n_{13,2} + .0600n_{4,2} + .0600n_{14,2} \\ & + .4160n_{5,2} + .4160n_{15,2} + .3506n_{6,2} + .3506n_{16,2} \qquad (6.1) \end{aligned}$$

subject to equations 4.29 through 4.36.

This objective function represents both the restoration goals and the configuration goals. As formulated here however, the results will not be comparable to the results from the lexicographic priority approach. The range of the $n_{i,t}$ is

$$0 \leq n_{i,t} \leq 1 \qquad i = 1,..,6 \quad (6.2)$$

while the range of the $n_{1i,t}$ is

$$0 \leq n_{1i,t} \leq g_i \qquad i = 1,\ldots,6 \quad (6.3)$$

where

$$g_i = 9,\ i = 1,\ 4$$
$$g_i = 10,\ \text{otherwise} \quad (6.4)$$

When the restoration and configuration goals for system i are not achieved, the value of the objective function can change by

$$(w_{i,t} * n_{i,t}) + (w_{i,t} * n_{1i,t}) \quad (6.5)$$

which has a maximum value of

$$w_{i,t} + 10w_{i,t} = 11w_{i,t} \quad (6.6)$$

Thus the penalty for not achieving the configuration goal can be as much as ten times the penalty for not achieving the restoration goal. Thus, the solution procedure will attempt to configure the systems before restoring them. This is inconsistent with the solution process described in Chapter V for the lexicographic priority approach. To be comparable the results of the two approaches should follow the same solution procedure.

Comparable results can be achieved by solving the weighted priority problem sequentially. The first step uses an objective function based on the restoral goals:

$$\text{minimize} \quad 0522n_{1,2} + .0235n_{2,2} + .0977n_{3,2} + .0600n_{4,2} + .4160n_{5,2} + .3506n_{6,2} \tag{6.7}$$

The second step uses an objective function based on the configuration goals:

$$\text{minimize} \quad .0522n_{11,2} + .0235n_{12,2} + .0977n_{13,2} + .0600n_{14,2} + .4160n_{15,2} + .3506n_{16,2} \tag{6.8}$$

Since the problem is the penalty in the objective function associated with the configuration goals, an alternative approach would have been to divide the weight of the deviation variable for the configuration goal by its maximum value. For example, for GPS (i = 3)

$$(.0977 * n_{13,t}) / 10 = .0098 * n_{13,t} \tag{6.9}$$

At its maximum value, $n_{13,t}$ will then have the value as $n_{3,t}$, the restoration goal deviation variable for GPS. Since the first procedure most resembles the steps in the lexicographic priority approach, it was used here.

A partial solution for the weighted priority problem is shown in Table 6.1. This table represents achievement of the configuration goals only. The computer time required for solving the configuration problem was excessive and MPOS could not generate a solution. When properly formulated, the weighted priority approach made the configuration goals of the six space systems comparable. This was not true in the

TABLE 6.1

RESTORATION MANAGEMENT SOLUTION FOR WEIGHTED PRIORITIES

DMSP	Minimum Subsystem Required	Source of Subsystem	Number
Space Segment			
1. Payload	1	NROSS	1
2. Comm	1	DMSP	1
3. Data Proc	1	DMSP	1
Ground Segment			
4. Telemetry	1	DMSP	1
5. CmdControl	1	DMSP	1
6. Comm	1	DMSP	1
7. Planning	1	DMSP	1
8. Antennas	1	DMSP	1
Data Links			
9. Space Link	1	DMSP	1
10. GroundLink	1	DMSP	1
11. Cross Link	0	Not Required	0
NROSS			
Space Segment			
1. Payload	1	NROSS	1
2. Comm	1	DMSP	1
3. Data Proc	1	DMSP	1
Ground Segment			
4. Telemetry	1	NROSS	1
5. CmdControl	1	NROSS	1
6. Comm	1	NROSS	1
7. Planning	1	NROSS	1
8. Antennas	1	DMSP	1
Data Links			
9. Space Link	1	DMSP	1
10. GroundLink	1	DMSP	1
11. Cross Link	0	Not Required	0

GPS	Minimum Subsystem Required	Source of Subsystem	Number
Space Segment			
1. Payload	2	GPS	2
2. Comm	2	GPS	2
3. Data Proc	0	Not Required	0
Ground Segment			
4. Telemetry	1	DMSP	1
5. CmdControl	1	DMSP	1
6. Comm	3	GPS	3
7. Planning	1	DMSP	1
8. Antennas	3	GPS	3
Data Links			
9. Space Link	1	NROSS	1
10. GroundLink	1	DMSP	1
11. Cross Link	1	GPS	1

Transit			
Space Segment			
1. Payload	1	GPS	1
2. Comm	1	Transit	1
3. Data Proc	1	Transit	1
Ground Segment			
4. Telemetry	1	GPS	1
5. CmdControl	1	GPS	1
6. Comm	1	DMSP	1
7. Planning	1	GPS	1
8. Antennas	1	Transit	1
Data Links			
9. Space Link	0	Not Required	0
10. GroundLink	3	NROSS	1
11. Cross Link	0	Not Required	0

MILSTAR	Minimum Subsystem Required	Source of Subsystem	Number
Space Segment			
1. Payload	27	MILSTAR	27
2. Comm	1	DMSP	1
3. Data Proc	1	DMSP	1
Ground Segment			
4. Telemetry	1	GPS	1
5. CmdControl	1	GPS	1
6. Comm	1	GPS	1
7. Planning	1	Transit	1
8. Antennas	1	GPS	1
Data Links			
9. Space Link	0	Not Required	0
10. GroundLink	1	NROSS	1
11. Cross Link	1	MILSTAR	1

DSCS			
Space Segment			
1. Payload	3	MILSTAR	27
2. Comm	1	DMSP	1
3. Data Proc	0	Not Required	0
Ground Segment			
4. Telemetry	1	Transit	1
5. CmdControl	1	Transit	1
6. Comm	1	Transit	1
7. Planning	1	MILSTAR	1
8. Antennas	1	Transit	1
Data Links			
9. Space Link	1	NROSS	1
10. GroundLink	1	NROSS	1
11. Cross Link	0	Not Required	0

lexicographic priority approach. With six comparable systems in the problem, its dimensions expanded and may have caused a computer capacity problem similar to that noted in Chapter V. However, even with expanded capacity and time there is no guarantee of identical solutions for the approaches.

Another difference in approaches was the amount of operator time required for the lexicographic approach. Even after becoming experienced in the sequential approach described in Chapter V, solving the problem for one time period of a scenario took an hour. Most of this time was used to interpret MPOS results and prepare inputs for the next priority. Running the weighted priority problem to a complete solution would require more computer time than the lexicographic approach but very little operator interaction. Once the system weights for the goals were determined, operator intervention ended. This intervention could be eliminated by automating the Sequential Linear Goal Programming process.

Finally, the number of decision variables and constraint equations in the lexicographic approach was consistently near the maximum allowed. Also, the number of constraints increased as lower priority goals were achieved. Thus while the feasible region for each new priority became smaller, the size of the problem statement increased. As noted in Chapter V, operator guidance was needed at the lower priorities of some scenarios in order to remain within

MPOS' limits while solving the problem. With the weighted priority approach, all constraints were included in the one problem input. If the problem was run to a solution for all goals, the computer solution would require more time and iterations to reach an optimal solution than in the lexicographic priority approach.

This problem can limit the size of a restoration problem and restrict the use of configuration controls discussed earlier in this chapter. Thus, while they are not problems in the goal programming formulation, they still represent potential limitations on use of the lexicographic priority approach.

This chapter analyzed the results of restoration management decisions made in six scenarios. The results suggest more controls will be needed to direct reallocation and ensure subsystems designated by CINCUSSPACECOM or technical experts are used for restoration. The restoration management decisions made in time period two of the central conflict using lexicographic and weighted priorities were also compared. The lexicographic approach restored more systems and required less computer time to reach a solution. However, less operator interaction was required for the weighted priority approach. In the next chapter, study conclusions and recommendations for future research are presented.

VII. Conclusions and Recommendations

Introduction

The testing and analysis presented in Chapters V and VI provided insight into the problem of how to maximize the wartime capabilities of space systems. This insight is applied to the research questions posed in Chapter I. Next, the utility of AHP and Goal Programming is discussed, followed by recommendations for future research and implementation of a restoration management system.

Conclusions

Information Required by the Decision Maker. To make meaningful restoration decisions, CINCUSSPACECOM must know the conflict level and objectives of the other US military commanders, and the subsystems available for reconfiguration. This minimal information should be supplemented by technical information of space system capabilities, technical constraints on system operation, and preferences for subsystem reconfiguration.

The Effect of User Priorities. User priorities determine the wartime capabilities restored during a conflict. The needs of the battlefield commanders are the criteria for selecting space systems for restoration. In this study, the needs of one battlefield commander were modeled.

Depth of Modeling Subsystems. Subsystems need to be studied to determine the true technical constraints on their reallocation. The current model assumed generic subsystems which were easily reallocated. In reality, these subsystems may not be entirely compatible, even though they serve the same function in different systems.

Appropriate Scenarios. The model user must select appropriate scenarios for evaluating restoration management systems. The six scenarios developed during this study were considered representative of scenarios USSPACECOM might encounter, but only one of the six truly exercised the model. Nevertheless, one of the benefits of a restoration management system is the ability to handle many varied scenarios in the model.

Performance. The performance of a restoral management system should be evaluated by the capabilities it restores. The restoration management model developed in this study showed there are many ways to restore six space systems providing capabilities in three missions. These alternate solutions are all reasonable because they meet the restoration goals imposed. The capabilities provided by these solutions may vary because the subsystems are not technically compatible or efficient. The variation among solutions can be linked to desired capabilities through the user's priorities however, allowing the battlefield commander to decide what capabilities he needs. Which space systems are restored and how they are restored flow from this decision.

Utility of AHP and Goal Programming

The Analytic Hierarchy Process and Goal Programming were very useful tools for modeling restoration management. AHP was immediately applicable for determining user priorities and system weights. The process was simple to learn and apply. Ranging of the system weights indicated problem solutions for small sets of space systems were insensitive to wide variation in values. Thus the consistency of the decision maker's subjective judgments was not a significant factor affecting the restoration management subsystem reallocation. However, the resulting system weights provided immediate guidance for system restoral in complex decision periods. So in a large operational restoration management system, strict requirements for consistency may be imposed on the decision maker.

The advantage of goal programming was its ability to find optimal solutions for multiple objective problems. Although the following suggestions for future research will offer alternate approaches to the restoration management problem, neither of the approaches offered will provide an optimal solution. Furthermore, the need for better control during the reallocation of subsystems is a criticism of the constraints rather than goal programming. Strict prioritization of the space systems may provide this control.

Future Research

Information Needed by the Decision Maker. The next possible step towards an operational restoration management system would be refinement of the configuration requirements used during restoration. Analysis of the initial results in this study led to the definition of configuration goals based on the assumptions of efficiency and compatibility. These assumptions need to be tested.

Either the current direction or an alternative approach to restoration management must consider the need for sensitivity analysis. CINCUSSPACECOM will need to know how wartime losses during later phases of a conflict might affect current capabilities and restoration management decisions. Given two or more configurations that provide the same wartime capabilities, the configuration least sensitive to potential wartime losses would be preferable. This information would be added to the information shown in the influence diagram.

The Effect of User Priorities. This study examined the restoration management problem from the viewpoint of CINCUSSPACECOM. Thus, given a set of capabilities, how should the space systems be reconfigured? Future research should look at the problem of inconsistent and possibly conflicting requirements for capabilities. Thus, the research question could be: How should CINCUSSPACECOM balance the needs of tactical and strategic commanders who may have conflicting requirements for space system capabilities?

Depth of Modeling Subsystems. As suggested in the conclusions, the ability of subsystems from different space systems to work together will have a dramatic impact upon their reconfiguration and performance of the restoration management system. Subsystem modeling must be improved to ensure the reallocation decisions reached in the model are implementable in reality.

Appropriate Scenarios. Should further research seek other directions, one approach might be simulation using programs such as the Simulation Language for Alternative Modeling (SLAM). While simulation cannot be used to optimize the restoration management solution, the methodology may be useful in determining problem parameters related to the wartime losses in specific scenarios. Increasing the detail of the scenarios would help research in measuring the performance of the restoration management system. The scenarios in the current study may not have stressed the model sufficiently to accurately measure its performance. Thus detailed scenarios would aid the evaluation of future models.

Performance. Two problems in the study were not resolved and need additional research. The first problem involved modeling the NROSS system and its use of parts of DMSP's ground segment. A satisfactory method could not be found for linking restoration of the two systems during reallocation of DMSP's ground segment. For example, if DMSP's ground communications were reallocated to MILSTAR, could the subsystem simultaneously support DMSP? One approach to the problem might be to examine how the model responds to shared use of the Air Force Satellite Control Facility resources. Their use may offer some insight into the NROSS problem.

A second problem not resolved in this study was the use of continuous decision variables for modeling the allocation of subsystems. The zero-one formulation used in this study led to the use of each allocated subsystem by only one space system. Clearly, the allocation of subsystems such as the AFSCF ground antennas to only one space system for an entire time period is not efficient use of the resource. A continuous or general integer solution for the $y_{i,j,k,t}$ decision variables would extend the use of the model by allowing these subsystems to support several space systems during a time period. This approach may also solve the problem of shared subsystems described above.

Another step in the direction taken in this study would be the exploration of nonexact methods, such as approximation methods and heuristics, for solving large scale problems. The dimensions of the restoration management problem are the number of missions, space systems and subsystems considered. The dimensions of the current problem were large enough to tax the abilities of the zero-one integer program used, particularly with the weighted goal programming technique. An operational restoration management system would expand the dimensions of the problem. As these dimensions increased, the limitations of zero-one integer programming techniques would become more significant. Nonexact methods, particularly a combination of artificial intelligence and heuristics, may be the only way to solve the operational problem.

Recommendations

USSPACECOM should implement a restoration management system for force enhancement space systems. The need to integrate space systems into military planning led to the creation of USSPACECOM. A restoration management system will provide a useful decision aid for ensuring the full value of space systems is realized.

USSPACECOM should support additional research in this area. The list additional research requirements presented here is probably not exhaustive. Nonetheless, these requirements suggest the scope of the problem that must be solved before an operational restoration management system is produced.

This study has offered a framework for a restoration management process for space systems. Work with the model suggests much more development is required to accurately model the decision process, the restoration preferences controlling configuration and the modeling of the subsystems themselves. Nevertheless, the initial results presented here suggest additional research in this area will yield a meaningful tool for USSPACECOM.

AD-A172 492 A DECISION AID FOR RESTORATION OF FORCE ENHANCEMENT SPACE SYSTEMS(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING 2/2

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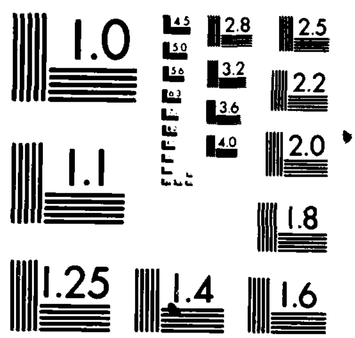
1.0
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1.25
1.4
1.6
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2.8
3.2
3.6
4.0

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Appendix A: Glossary and Definition of Terms

AFSC	Air Force Systems Command
AFSCF	Air Force Satellite Control Facility
AHP	Analytic Hierarchy Process
ASAT	Anti-satellite weapon
C2	Command and Control
CDT	Communications Delay Time
CE	Communications Encrypted
CINCSAC	Commander-in-Chief, Strategic Air Command
CINCUSSPACECOM	Commander-in-Chief, US Space Command
CMD	Communications Messages per Day
CNU	Communications Number of Users
CSC	Connectivity for Strategic Users
CSOC	Consolidated Space Operations Center
DMSP	Defense Meteorological Satellite Program
DOSC	Satellite Control Division, SPACECOM
DSCS	Defense Satellite Communications System
GPS	Global Positioning System
MCA	Meteorological Coverage Area
MCD	Meteorological Coverage per Day
MILSTAR	Military Strategic and Tactical Relay
MPOS	Multipurpose Optimization System
NCA	Navigation Coverage Area
NCD	Navigation Coverage per Day
NSU	Number of System Users
SAC	Strategic Air Command
SPACECOM	Air Force Space Command
SPADOC	Space Defense Operations Center
USSPACECOM	US Space Command

Definition of Terms

Space Control	Force Application
O Space Superiority oo ASAT	O Space Weapons Against Earth Forces oo Strategic Defense Initiative
Force Enhancement	**Space Support**
O Support for Earth Forces oo Global Positioning System oo MILSTAR	O Launch and Control of Space Systems oo Space Shuttle oo Consolidated Space Operations Center

Figure A.1 Space Missions

Space Missions

"Military Space Doctrine", AFM 1-6, lists four space missions: force enhancement, space support, space control and force application. Figure A.1 defines these terms and provides examples of American satellites in these categories (2:90, 7:9).

American Satellite

An American satellite is an unmanned earth-orbiting spacecraft under the control of the US military. The satellite supports ground forces by providing weather, navigation or early warning data; communications links; or intelligence. Military space systems are those space systems owned and operated (or leased) by the Department of Defense to perform a space mission.

Space System

A space system is an integrated collection of orbiting spacecraft, ground-based command and control organizations and equipment, and communication equipment linking the two. The spacecraft is considered the space segment while the command and control organizations are considered the ground segment.

Restoral Management

The act of restoring or helping to restore the mission capability of a disabled or destroyed space system component or segment. The responsibility accommodates all DOD space systems as well as other space assets such as civil, intelligence, shuttle, commercial, and foreign cooperative programs (3:1).

Point in Space Attack

A Point in Space attack is an attack against several satellites using nuclear weapons to destroy the electronic components of the satellite. The attack is not directed against one specific satellite in contrast to the ASAT which is aimed at one target.

Space System Architecture

A space system architecture is a collection of the subsystems required to operate the system or achieve a mission capability. When the subsystems requirements for a space system can be satisfied by several different collections of subsystems (where the subsystems belong to the original space system or to other systems), each collection is an alternative architecture for that space system.

Appendix B: Data Sheets For SPADOC Data Base

DMSP (12,25)

A. Space Segment

1. Number of satellites in constellation: 2.
2. Number of satellites required for full operation: 2.
3. Number of satellites required for partial operation: 1.
4. On-board data processing capability: yes.
5. Sensor type (payload): Meteorological data.
6. Orbital parameters:
   a. period: 101 minutes
   b. inclination: 98 degrees
   c. altitude: 450 nautical miles
   d. eccentricity: circular
7. Major subsystems:
   a. attitude
   b. power
   c. thermal
   d. communications
   e. data processing
   f. sensors

B. Ground Segment

1. Location of ground antennas:
   a. Fairchild AFB
   b. Loring AFB

c. Offutt AFB

d. AFSCF network

2. Ground data processing capability: yes.

3. Link to Space Defense Operations Center: yes.

4. Major subsystems:

a. telemetry

b. command and control

c. communications

d. planning

e. antennas

C. Data Links

1. Encryption on links: yes.

2. Type link:

a. space based

b. ground based

NROSS

A. Space Segment

1. Number of satellites in constellation: 2.

2. Number of satellites required for full operation: 2.

3. Number of satellites required for partial operation: 1.

4. On-board data processing capability: yes.

5. Sensor type (payload): Meteorological data

6. Orbital parameters:

    a. period: 101 minutes

    b. inclination: 98 degrees

    c. altitude: 450 nautical miles

    d. eccentricity: circular

7. Major subsystems:

    a. attitude

    b. power

    c. thermal

    d. communications

    e. data processing

B. Ground Segment

1. Location of ground antennas:

    a. Fairchild AFB

    b. Loring AFB

    c. Offutt AFB

    d. AFSCF network

2. Ground data processing capability: yes.

3. Link to Space Defense Operations Center: yes.

4. Major subsystems:

    a. telemetry

    b. command and control

    c. communications

    d. planning

    e. antennas

C. Data Links

1. Encryption on links: yes.

2. Type link:

    a. space based

    b. ground based

D. Other attributes: this system will be operated by the operators of DMSP under guidance from the US Navy (33). As currently planned, NROSS will use a space segment based on DMSP but with fewer meteorological sensors.

NAVSTAR GPS (14,25,26)

A. Space Segment

1. Number of satellites in constellation: 21.

2. Number of satellites required for full operation: 18.

3. Number of satellites required for partial operation: 15.

4. On-board data processing capability: yes.

5. Sensor type (payload): Navigation

6. Orbital parameters:

    a. period: 720 minutes

    b. inclination: 55 degrees

    c. altitude: 10900 nautical miles

    d. eccentricity: circular

7. Major subsystems:

    a. communications

    b. timing

    c. power

B. Ground Segment

1. Location of ground antennas:

    a. Kwajelein: ground antenna and monitor station

    b. Diego Garcia: ground antenna, monitor station

    c. Ascension Island: ground antenna, monitor station

    d. CSOC: monitor station

    e. Hawaii: monitor station

2. Ground data processing capability: yes.

3. Major subsystems:

a. Satellite monitoring

b. telemetry

c. satellite tracking

d. command and control

e. data transmission

f. planning

g. satellite ranging

h. antennas

C. Data Links

1. Encryption on links: yes.

2. Type link:

a. space based

b. ground based

c. satellite crosslink

Transit (31)

A. Space Segment

1. Number of satellites in constellation: 3.

2. Number of satellites required for full operation: 4.

3. Number of satellites required for partial operation: UNK

4. On-board data processing capability: yes.

5. Sensor type (payload): Low dynamic navigation

6. Orbital parameters:

   a. period: 96 minutes

   b. inclination: 51 degrees

   c. altitude: 500 nautical miles

   d. eccentricity: circular

7. Major subsystems:

   a. timing

   b. power

   c. attitude control

   d. data processor

   e. telemetry

   f. communications

B. Ground Segment

1. Location of ground antennas:

   a. Hawaii

   b. White Sands

   c. Massachusetts

   d. Point Arguello

e. Woomera, Australia

2. Ground data processing capability: yes.

C. Data Links

1. Encryption on links: yes.

2. Type link: ground based.

D. Where data could not be obtained, UNK is inserted.

MILSTAR (25,32)

A. Space Segment

1. Number of satellites in constellation: 8.

2. Number of satellites required for full operation: 7.

3. Number of satellites required for partial opera tion: UNK.

4. On-board data processing capability: yes.

5. Sensor type (payload): Communications

6. Orbital parameters:

   a. period: 720 minutes

   b. inclination: 0 / 80 degrees

   c. altitude: 22300 / 22000 x 350 nautical miles

   d. eccentricity: circular / elliptical

7. Major subsystems:

   a. satellite crosslink

   b. 50 EHF/4 UHF communications channels

   c. attitude

   d. navigation

   e. power

   f. maneuver

B. Ground Segment (TT&C: CSOC/AFSCF; C^2 CSOC/E-4/mobile)

1. Location of ground antennas: CSOC

2. Ground data processing capability: UNK

3. Link to Space Defense Operations Center: UNK

4. Major subsystems:

   a. Mobile C^2

b. Telemetry

c. Communications

d. Planning

e. Antennas

C. Data Links

1. Encryption on links: UNK

2. Type link:

a. ground based

b. satellite crosslink

D. Where data could not be obtained, UNK is inserted.

DSCS (13,25)

A. Space Segment

1. Number of satellites in constellation: 3.
2. Number of satellites required for full operation: 3.
3. Number of satellites required for partial operation: 2.
4. On-board data processing capability: yes.
5. Sensor type (payload): Communications
6. Orbital parameters:
   a. period: 1440 minutes
   b. inclination: 0 degrees
   c. altitude: 23300 statute miles
   d. eccentricity: circular
7. Major subsystems:
   a. multiple beam antennas
   b. six communications channels
   c. fixed earth coverage antennas
   d. narrow coverage beam antenna
   e. earth coverage horn antennas
   f. AFSATCOM transponders
   g. attitude
   h. power

B. Ground Segment (TT&C - AFSCF; C^2 - DCA)

1. Location of ground antennas: seven AFSCF sites
2. Ground data processing capability: UNK
3. Link to Space Defense Operations Center: UNK

C. Data Links

1. Encryption on links: UNK

2. Type link:

    a. space based

    b. ground based

D. Where data could not be obtained, UNK is inserted.

Appendix C: Subsystem Availability Tables for Scenarios

TABLE C.1

LIMITED CONFLICT - TIME PERIOD 1

	DMSP	GPS	MILSTAR
Space Segment			
1. Payload	2	21	378
2. Comm	6	42	7
3. Data Proc	4	0	7
Ground Segment			
4. Telemetry	2	2	2
5. CmdControl	2	2	3
6. Comm	2	6	3
7. Planning	2	1	1
8. Antennas	2	6	1
Data Links			
9. Space Link	1*	7	0
10. GroundLink	3	6	1
11. Cross Link	0	1	1

	NROSS	Transit	DSCS
Space Segment			
1. Payload	2	3	18
2. Comm	6	3	3
3. Data Proc	4	3	0
Ground Segment			
4. Telemetry	0	1	7
5. CmdControl	0	1	1
6. Comm	0	1	1
7. Planning	0	1	1
8. Antennas	0	3	11
Data Links			
9. Space Link	2	0	7
10. GroundLink	3	1*	2
11. Cross Link	0	0	0

Note: * indicates value that has changed during current time period.

TABLE C.2

MAJOR CONFLICT - TIME PERIOD 1

	DMSP	GPS	MILSTAR
Space Segment			
1. Payload	2	21	378
2. Comm	6	42	7
3. Data Proc	4	0	7
Ground Segment			
4. Telemetry	2	2	2
5. CmdControl	2	2	3
6. Comm	2	6	2*
7. Planning	2	1	1
8. Antennas	2	6	1
Data Links			
9. Space Link	1*	7	0
10. GroundLink	3	6	1
11. Cross Link	0	1	1

	NROSS	Transit	DSCS
Space Segment			
1. Payload	2	3	18
2. Comm	6	3	3
3. Data Proc	4	3	0
Ground Segment			
4. Telemetry	0	1	3*
5. CmdControl	0	1	1
6. Comm	0	1	1
7. Planning	0	1	1
8. Antennas	0	3	9*
Data Links			
9. Space Link	2	0	7
10. GroundLink	3	1*	2
11. Cross Link	0	0	0

TABLE C.3

MAJOR CONFLICT - TIME PERIOD 2

	DMSP	GPS	MILSTAR
Space Segment			
1. Payload	0*	21	378
2. Comm	6	42	7
3. Data Proc	4	0	0*
Ground Segment			
4. Telemetry	2	2	2
5. CmdControl	2	2	3
6. Comm	2	2*	2*
7. Planning	2	1	1
8. Antennas	2	2*	1
Data Links			
9. Space Link	1	7	0
10. GroundLink	3	2*	1
11. Cross Link	0	1	1

	NROSS	Transit	DSCS
Space Segment			
1. Payload	2	3	18
2. Comm	6	3	3
3. Data Proc	4	3	0
Ground Segment			
4. Telemetry	0	1	7
5. CmdControl	0	1	1
6. Comm	0	1	1
7. Planning	0	1	1
8. Antennas	0	2*	11
Data Links			
9. Space Link	2	0	7
10. GroundLink	3	1	2
11. Cross Link	0	0	0

TABLE C.4

CENTRAL CONFLICT - TIME PERIOD 1

DMSP		GPS		MILSTAR	
Space Segment		**Space Segment**		**Space Segment**	
1. Payload	2	1. Payload	21	1. Payload	378
2. Comm	6	2. Comm	42	2. Comm	7
3. Data Proc	4	3. Data Proc	0	3. Data Proc	7
Ground Segment		**Ground Segment**		**Ground Segment**	
4. Telemetry	2	4. Telemetry	2	4. Telemetry	2
5. CmdControl	2	5. CmdControl	2	5. CmdControl	3*
6. Comm	2	6. Comm	6	6. Comm	2
7. Planning	2	7. Planning	1	7. Planning	1
8. Antennas	2	8. Antennas	6	8. Antennas	1
Data Links		**Data Links**		**Data Links**	
9. Space Link	2	9. Space Link	7	9. Space Link	0
10. GroundLink	3	10. GroundLink	6	10. GroundLink	1
11. Cross Link	0	11. Cross Link	1	11. Cross Link	1

NROSS		Transit		DSCS	
Space Segment		**Space Segment**		**Space Segment**	
1. Payload	2	1. Payload	3	1. Payload	18
2. Comm	6	2. Comm	3	2. Comm	3
3. Data Proc	4	3. Data Proc	3	3. Data Proc	0
Ground Segment		**Ground Segment**		**Ground Segment**	
4. Telemetry	0	4. Telemetry	1	4. Telemetry	7
5. CmdControl	0	5. CmdControl	1	5. CmdControl	1
6. Comm	0	6. Comm	1	6. Comm	1
7. Planning	0	7. Planning	1	7. Planning	1
8. Antennas	0	8. Antennas	3	8. Antennas	11
Data Links		**Data Links**		**Data Links**	
9. Space Link	2	9. Space Link	0	9. Space Link	7
10. GroundLink	3	10. GroundLink	3	10. GroundLink	2
11. Cross Link	0	11. Cross Link	0	11. Cross Link	0

TABLE C.5

CENTRAL CONFLICT - TIME PERIOD 2

DMSP

	Space Segment	
1.	Payload	0*
2.	Comm	6
3.	Data Proc	4
	Ground Segment	
4.	Telemetry	2
5.	CmdControl	2
6.	Comm	2
7.	Planning	2
8.	Antennas	2
	Data Links	
9.	Space Link	2
10.	GroundLink	3
11.	Cross Link	0

GPS

	Space Segment	
1.	Payload	21
2.	Comm	42
3.	Data Proc	0
	Ground Segment	
4.	Telemetry	2
5.	CmdControl	2
6.	Comm	4*
7.	Planning	1
8.	Antennas	4*
	Data Links	
9.	Space Link	7
10.	GroundLink	4*
11.	Cross Link	1

MILSTAR

	Space Segment	
1.	Payload	378
2.	Comm	7
3.	Data Proc	0*
	Ground Segment	
4.	Telemetry	2
5.	CmdControl	3
6.	Comm	1*
7.	Planning	1
8.	Antennas	1
	Data Links	
9.	Space Link	0
10.	GroundLink	1
11.	Cross Link	1

NROSS

	Space Segment	
1.	Payload	2
2.	Comm	6
3.	Data Proc	4
	Ground Segment	
4.	Telemetry	0
5.	CmdControl	0
6.	Comm	0
7.	Planning	0
8.	Antennas	0
	Data Links	
9.	Space Link	2
10.	GroundLink	3
11.	Cross Link	0

Transit

	Space Segment	
1.	Payload	3
2.	Comm	3
3.	Data Proc	3
	Ground Segment	
4.	Telemetry	1
5.	CmdControl	1
6.	Comm	1
7.	Planning	1
8.	Antennas	2*
	Data Links	
9.	Space Link	0
10.	GroundLink	1*
11.	Cross Link	0

DSCS

	Space Segment	
1.	Payload	18
2.	Comm	3
3.	Data Proc	0
	Ground Segment	
4.	Telemetry	7
5.	CmdControl	1
6.	Comm	1
7.	Planning	1
8.	Antennas	11
	Data Links	
9.	Space Link	7
10.	GroundLink	2
11.	Cross Link	0

TABLE C.6

CENTRAL CONFLICT - TIME PERIOD 3

DMSP

	Space Segment	
1.	Payload	0
2.	Comm	6
3.	Data Proc	4
	Ground Segment	
4.	Telemetry	2
5.	CmdControl	2
6.	Comm	2
7.	Planning	2
8.	Antennas	2
	Data Links	
9.	Space Link	1*
10.	GroundLink	3
11.	Cross Link	0

GPS

	Space Segment	
1.	Payload	21
2.	Comm	42
3.	Data Proc	0
	Ground Segment	
4.	Telemetry	2
5.	CmdControl	2
6.	Comm	3*
7.	Planning	1
8.	Antennas	3*
	Data Links	
9.	Space Link	7
10.	GroundLink	3*
11.	Cross Link	1

MILSTAR

	Space Segment	
1.	Payload	378
2.	Comm	7
3.	Data Proc	7
	Ground Segment	
4.	Telemetry	2
5.	CmdControl	3
6.	Comm	3
7.	Planning	1
8.	Antennas	1
	Data Links	
9.	Space Link	0
10.	GroundLink	1
11.	Cross Link	1

NROSS

	Space Segment	
1.	Payload	2
2.	Comm	6
3.	Data Proc	4
	Ground Segment	
4.	Telemetry	0
5.	CmdControl	0
6.	Comm	0
7.	Planning	0
8.	Antennas	0
	Data Links	
9.	Space Link	2
10.	GroundLink	1*
11.	Cross Link	0

Transit

	Space Segment	
1.	Payload	3
2.	Comm	3
3.	Data Proc	3
	Ground Segment	
4.	Telemetry	1
5.	CmdControl	1
6.	Comm	1
7.	Planning	1
8.	Antennas	2
	Data Links	
9.	Space Link	0
10.	GroundLink	0*
11.	Cross Link	0

DSCS

	Space Segment	
1.	Payload	18
2.	Comm	3
3.	Data Proc	0
	Ground Segment	
4.	Telemetry	7
5.	CmdControl	1
6.	Comm	1
7.	Planning	1
8.	Antennas	11
	Data Links	
9.	Space Link	7
10.	GroundLink	2
11.	Cross Link	0

Appendix D: Initial Constraint Equations

This appendix contains the complete listing of constraint equations for the model at $t = 0$ and explains the format used in writing the variables and parameters. These equations were written according to the format used in the Multi-Purpose Optimization System (MPOS). Because of limitations in the length of variable names, a shortened version of the above terminology was used.

First, the index t was deleted since MPOS solved the equations for each time period individually. Next commas were deleted. Thus the four digit suffix on each decision variable represents the space system index j and the subsystem index k' where:

$$k = [\ (k' - 1) \text{ modulo } 11\ ] + 1 \qquad \text{(D.1)}$$

and

$$i = \text{integer}\ [\ (k' - 1)\ /\ 11\ ] + 1 \qquad \text{(D.2)}$$

A zero digit separates the values of j and k'. For example, decision variable $x_{1,3}$ was represented as X1 and decision variable $y_{6,5,1,3}$ was represented as Y5056. Finally, decision variables with zero coefficients were deleted to reduce the number of variables to a value within the predetermined limits of MPOS.

TABLE D.1

SYSTEM TECHNICAL REQUIREMENTS

```
1Y1001 +  1Y2001 .LE.  0
1Y1002 +  1Y2002 +  1Y5002 +  1Y6002 .LE.  6
1Y1003 +  1Y2003 +  1Y5003 +  1Y6003 .LE.  4
1Y1004 +  1Y2004 +  1Y3004 +  1Y4004 +  1Y5004 +  1Y6004 .LE.  2
1Y1005 +  1Y2005 +  1Y3005 +  1Y4005 +  1Y5005 +  1Y6005 .LE.  2
1Y1006 +  1Y2006 +  1Y3006 +  1Y4006 +  1Y5006 +  1Y6006 .LE.  2
1Y1007 +  1Y2007 +  1Y3007 +  1Y4007 +  1Y5007 +  1Y6007 .LE.  2
1Y1008 +  1Y2008 .LE.  2
1Y1009 +  1Y2009 +  1Y3009 +  1Y4009 +  1Y5009 +  1Y6009 .LE.  2
1Y1010 +  1Y2010 +  1Y3010 +  1Y4010 +  1Y5010 +  1Y6010 .LE.  3
1Y1012 +  1Y2012 .LE.  2
1Y1013 +  1Y2013 +  1Y5013 +  1Y6013 .LE.  6
1Y1014 +  1Y2014 +  1Y5014 +  1Y6014 .LE.  4
1Y1020 +  1Y2020 +  1Y3020 +  1Y4020 +  1Y5020 +  1Y6020 .LE.  2
1Y1021 +  1Y2021 +  1Y3021 +  1Y4021 +  1Y5021 +  1Y6021 .LE.  3
2Y3023 +  1Y4023 .LE. 21
2Y3024 .LE. 42
1Y1026 +  1Y2026 +  1Y3026 +  1Y4026 +  1Y5026 +  1Y6026 .LE.  2
1Y1027 +  1Y2027 +  1Y3027 +  1Y4027 +  1Y5027 +  1Y6027 .LE.  2
1Y1028 +  1Y2028 +  3Y3028 +  1Y5028 +  1Y6028 .LE.  4
1Y1029 +  1Y2029 +  1Y3029 +  1Y4029 +  1Y5029 +  1Y6029 .LE.  1
1Y1030 +  1Y2030 +  3Y3030 +  1Y5030 +  1Y6030 .LE.  4
1Y1031 +  1Y2031 +  1Y3031 +  1Y4031 +  1Y5031 +  1Y6031 .LE.  7
1Y1032 +  1Y2032 +  1Y3032 +  1Y4032 +  1Y5032 +  1Y6032 .LE.  4
1Y3033 .LE.  1
1Y4034 .LE.  3
1Y1035 +  1Y2035 +  1Y3035 +  1Y4035 +  1Y5035 +  1Y6035 .LE.  3
1Y1036 +  1Y2036 +  1Y3036 +  1Y4036 +  1Y5036 +  1Y6036 .LE.  3
1Y1037 +  1Y2037 +  1Y3037 +  1Y4037 +  1Y5037 +  1Y6037 .LE.  1
1Y1038 +  1Y2038 +  1Y3038 +  1Y4038 +  1Y5038 +  1Y6038 .LE.  1
1Y1039 +  1Y2039 +  1Y3039 +  1Y4039 +  1Y5039 +  1Y6039 .LE.  1
1Y1040 +  1Y2040 +  1Y3040 +  1Y4040 +  1Y5040 +  1Y6040 .LE.  1
1Y1041 +  1Y2041 +  1Y3041 +  1Y4041 +  1Y5041 +  1Y6041 .LE.  2
3Y4043 .LE.  1
7Y5045 + 27Y6045 .LE.378
1Y1046 +  1Y2046 +  1Y5046 +  1Y6046 .LE.  7
1Y1047 +  1Y2047 +  1Y5047 +  1Y6047 .LE.  0
1Y1048 +  1Y2048 +  1Y3048 +  1Y4048 +  1Y5048 +  1Y6048 .LE.  2
1Y1049 +  1Y2049 +  1Y3049 +  1Y4049 +  1Y5049 +  1Y6049 .LE.  3
1Y1050 +  1Y2050 +  1Y3050 +  1Y4050 +  1Y5050 +  1Y6050 .LE.  1
1Y1051 +  1Y2051 +  1Y3051 +  1Y4051 +  1Y5051 +  1Y6051 .LE.  1
1Y1052 +  1Y2052 +  1Y3052 +  1Y4052 +  1Y5052 +  1Y6052 .LE.  1
1Y1054 +  1Y2054 +  1Y3054 +  1Y4054 +  1Y5054 +  1Y6054 .LE.  1
1Y3055 +  1Y5055 .LE.  1
3Y5056 +  3Y6056 .LE. 18
1Y1057 +  1Y2057 +  1Y3057 +  1Y4057 +  1Y5057 +  1Y6057 .LE.  3
1Y1059 +  1Y2059 +  3Y3059 +  1Y4059 +  1Y5059 +  1Y6059 .LE.  7
```

```
1Y1060 +  1Y2060 +  1Y3060 +  1Y4060 +  1Y5060 +  1Y6060 .LE.  1
1Y1061 +  1Y2061 +  1Y3061 +  1Y4061 +  1Y5061 +  1Y6061 .LE.  1
1Y1062 +  1Y2062 +  1Y3062 +  1Y4062 +  1Y5062 +  1Y6062 .LE.  1
1Y1063 +  1Y2063 +  3Y3063 +  1Y4063 +  1Y5063 +  1Y6063 .LE. 11
1Y1064 +  1Y2064 +  3Y3064 +  1Y4064 +  1Y5064 +  1Y6064 .LE.  7
1Y1065 +  1Y2065 +  1Y3065 +  1Y4065 +  1Y5065 +  1Y6065 .LE.  2
```

TABLE D.2

SYSTEM AVAILABILITY CONSTRAINTS

```
+ 1Y1001 + 1Y1012 -X1.GE.0
+ 1Y1002 + 1Y1013 + 1Y1035 + 1Y1046 + 1Y1057 -X1.GE.0
+ 1Y1003 + 1Y1014 + 1Y1036 + 1Y1047 -X1.GE.0
+ 1Y1004 + 1Y1026 + 1Y1037 + 1Y1048 + 1Y1059 -X1.GE.0
+ 1Y1005 + 1Y1027 + 1Y1038 + 1Y1049 + 1Y1060 -X1.GE.0
+ 1Y1006 + 1Y1028 + 1Y1039 + 1Y1050 + 1Y1061 -X1.GE.0
+ 1Y1007 + 1Y1029 + 1Y1040 + 1Y1051 + 1Y1062 -X1.GE.0
+ 1Y1008 + 1Y1030 + 1Y1041 + 1Y1052 + 1Y1063 -X1.GE.0
+ 1Y1009 + 1Y1020 + 1Y1031 + 1Y1064 -X1.GE.0
+ 1Y1010 + 1Y1021 + 1Y1032 + 1Y1054 + 1Y1065 -X1.GE.0

+ 1Y2001 + 1Y2012 -X2.GE.0
+ 1Y2002 + 1Y2013 + 1Y2035 + 1Y2046 + 1Y2057 -X2.GE.0
+ 1Y2003 + 1Y2014 + 1Y2036 + 1Y2047 -X2.GE.0
+ 1Y2004 + 1Y2015 + 1Y2026 + 1Y2037 + 1Y2048 + 1Y2059 -X2.GE.0
+ 1Y2005 + 1Y2016 + 1Y2027 + 1Y2038 + 1Y2049 + 1Y2060 -X2.GE.0
+ 1Y2006 + 1Y2017 + 1Y2028 + 1Y2039 + 1Y2050 + 1Y2061 -X2.GE.0
+ 1Y2007 + 1Y2018 + 1Y2029 + 1Y2040 + 1Y2051 + 1Y2062 -X2.GE.0
+ 1Y2008 + 1Y2019 + 1Y2030 + 1Y2041 + 1Y2052 + 1Y2063 -X2.GE.0
+ 1Y2009 + 1Y2020 + 1Y2031 + 1Y2064 -X2.GE.0
+ 1Y2010 + 1Y2021 + 1Y2032 + 1Y2054 + 1Y2065 -X2.GE.0

+ 2Y3023 -X3.GE.0
+ 2Y3024 + 1Y3035 + 1Y3057 -X3.GE.0
+ 1Y3004 + 1Y3026 + 1Y3037 + 1Y3048 + 3Y3059 -X3.GE.0
+ 1Y3005 + 1Y3027 + 1Y3038 + 1Y3049 + 1Y3060 -X3.GE.0
+ 1Y3006 + 3Y3028 + 1Y3039 + 1Y3050 + 1Y3061 -X3.GE.0
+ 1Y3007 + 1Y3029 + 1Y3040 + 1Y3051 + 1Y3062 -X3.GE.0
+ 3Y3030 + 1Y3041 + 1Y3052 + 3Y3063 -X3.GE.0
+ 1Y3009 + 1Y3020 + 1Y3031 + 3Y3064 -X3.GE.0
+ 1Y3010 + 1Y3021 + 1Y3032 + 1Y3054 + 1Y3065 -X3.GE.0
+ 1Y3033 + 1Y3055 -X3.GE.0

+ 1Y4023 + 1Y4034 -X4.GE.0
+ 1Y4035 + 1Y4057 -X4.GE.0
+ 1Y4036 -X4.GE.0
+ 1Y4004 + 1Y4026 + 1Y4037 + 1Y4048 + 1Y4059 -X4.GE.0
+ 1Y4005 + 1Y4027 + 1Y4038 + 1Y4049 + 1Y4060 -X4.GE.0
+ 1Y4006 + 1Y4039 + 1Y4050 + 1Y4061 -X4.GE.0
+ 1Y4007 + 1Y4029 + 1Y4040 + 1Y4051 + 1Y4062 -X4.GE.0
+ 1Y4041 + 1Y4052 + 1Y4063 -X4.GE.0
+ 1Y4010 + 1Y4021 + 1Y4032 + 3Y4043 + 1Y4054 + 1Y4065 -X4.GE.0

+27Y5045 + 3Y5056 -X5.GE.0
+ 1Y5002 + 1Y5013 + 1Y5035 + 1Y5046 + 1Y5057 -X5.GE.0
+ 1Y5003 + 1Y5014 + 1Y5036 + 1Y5047 -X5.GE.0
+ 1Y5004 + 1Y5026 + 1Y5037 + 1Y5048 + 1Y5059 -X5.GE.0
```

```
+ 1Y5005 + 1Y5027 + 1Y5038 + 1Y5049 + 1Y5060 -X5.GE.0
+ 1Y5006 + 1Y5028 + 1Y5039 + 1Y5050 + 1Y5061 -X5.GE.0
+ 1Y5007 + 1Y5029 + 1Y5040 + 1Y5051 + 1Y5062 -X5.GE.0
+ 1Y5030 + 1Y5041 + 1Y5052 + 1Y5063 -X5.GE.0
+ 1Y5010 + 1Y5021 + 1Y5032 + 1Y5054 + 1Y5065 -X5.GE.0
+ 1Y5055 -X5.GE.0

+27Y6045 + 3Y6056 -X6.GE.0
+ 1Y6002 + 1Y6013 + 1Y6035 + 1Y6046 + 1Y6057 -X6.GE.0
+ 1Y6004 + 1Y6026 + 1Y6037 + 1Y6048 + 1Y6059 -X6.GE.0
+ 1Y6005 + 1Y6027 + 1Y6038 + 1Y6049 + 1Y6060 -X6.GE.0
+ 1Y6006 + 1Y6028 + 1Y6039 + 1Y6050 + 1Y6061 -X6.GE.0
+ 1Y6007 + 1Y6029 + 1Y6040 + 1Y6051 + 1Y6062 -X6.GE.0
+ 1Y6030 + 1Y6041 + 1Y6052 + 1Y6063 -X6.GE.0
+ 1Y6009 + 1Y6020 + 1Y6031 + 1Y6064 -X6.GE.0
+ 1Y6010 + 1Y6021 + 1Y6032 + 1Y6054 + 1Y6065 -X6.GE.0
```

Appendix E: AHP Input Matrices

Wartime Capability	N	M	C
Navigation (N)	1	3	1/7
Meteorological (M)	1/3	1	1/7
Communications (C)	7	7	1

Matrix 1.

Navigation	NCD	NCA	NSU
NCD	1	1/5	1/7
NCA	5	1	1/5
NSU	7	5	1

Matrix 2.

Meteorology	MCD	MCA
MCD	1	1/5
MCA	5	1

Matrix 3.

Communications	CMD	CNU	CE	CDT	CSC
CMD	1	1	1/3	7	1/5
CNU	1	1	1/3	5	1/3
CE	3	3	1	9	1
CDT	1/7	1/5	1/9	1	1/7
CSC	5	3	1	7	1

Matrix 4.

MCD	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	5	9	9	9	9
NROSS	1/5	1	9	9	9	9
GPS	1/9	1/9	1	1	1	1
Transit	1/9	1/9	1	1	1	1
MILSTAR	1/9	1/9	1	1	1	1
DSCS	1/9	1/9	1	1	1	1

Matrix 5.

MCA	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	1	9	9	9	9
NROSS	1	1	9	9	9	9
GPS	1/9	1/9	1	1	1	1
Transit	1/9	1/9	1	1	1	1
MILSTAR	1/9	1/9	1	1	1	1
DSCS	1/9	1/9	1	1	1	1

Matrix 6.

NCD	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	1	1/9	1/9	1	1
NROSS	1	1	1/9	1/9	1	1
GPS	9	9	1	5	9	9
Transit	9	9	1/5	1	9	9
MILSTAR	1	1	1/9	1/9	1	1
DSCS	1	1	1/9	1/9	1	1

Matrix 7.

NCA	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	1	1/9	1/9	1	1
NROSS	1	1	1/9	1/9	1	1
GPS	9	9	1	5	9	9
Transit	9	9	1/5	1	9	9
MILSTAR	1	1	1/9	1/9	1	1
DSCS	1	1	1/9	1/9	1	1

Matrix 8.

NSU	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	1	1/9	1/9	1	1
NROSS	1	1	1/9	1/9	1	1
GPS	9	9	1	7	9	9
Transit	9	9	1/7	1	9	9
MILSTAR	1	1	1/9	1/9	1	1
DSCS	1	1	1/9	1/9	1	1

Matrix 9.

CMD	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	3	3	3	1/7	1/7
NROSS	1/3	1	1	1	1/9	1/9
GPS	1/3	1	1	1	1/9	1/9
Transit	1/3	1	1	1	1/9	1/9
MILSTAR	7	9	9	9	1	5
DSCS	7	9	9	9	1/5	1

Matrix 10.

CNU	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	2	2	2	1/8	1/8
NROSS	1/2	1	1	1	1/9	1/9
GPS	1/2	1	1	1	1/9	1/9
Transit	1/2	1	1	1	1/9	1/9
MILSTAR	8	9	9	9	1	5
DSCS	8	9	9	9	1/5	1

Matrix 11.

CE	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	9	9	9	1	1
NROSS	1/9	1	1	1	1/9	1/9
GPS	1/9	1	1	1	1/9	1/9
Transit	1/9	1	1	1	1/9	1/9
MILSTAR	1	9	9	9	1	1
DSCS	1	9	9	9	1	1

Matrix 12.

CDT	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	2	2	2	1/8	1/8
NROSS	1/2	1	1	1	1/9	1/9
GPS	1/2	1	1	1	1/9	1/9
Transit	1/2	1	1	1	1/9	1/9
MILSTAR	8	9	9	9	1	2
DSCS	8	9	9	9	1/2	1

Matrix 13.

CSC	DMSP	NROSS	GPS	Transit	MILSTAR	DSCS
DMSP	1	1	1	1	1/9	1/9
NROSS	1	1	1	1	1/9	1/9
GPS	1	1	1	1	1/9	1/9
Transit	1	1	1	1	1/9	1/9
MILSTAR	9	9	9	9	1	1
DSCS	9	9	9	9	1	1

Matrix 14.

Appendix F: MPOS Input File

```
*
TITLE
RESTORATION MANAGEMENT PROBLEM
* SCENARIO: CNTRL2    TIME PERIOD: 2
* PRIORITY LEVEL: 1
*
DSZ1IP
*
VARIABLES
Y1001 Y1012
Y1002 Y1013       Y1035 Y1046 Y1057
Y1003 Y1014       Y1036 Y1047
Y1004       Y1026 Y1037 Y1048 Y1059
Y1005       Y1027 Y1038 Y1049 Y1060
Y1006       Y1028 Y1039 Y1050 Y1061
Y1007       Y1029 Y1040 Y1051 Y1062
Y1008       Y1030 Y1041 Y1052 Y1063
Y1009 Y1020 Y1031             Y1064
Y1010 Y1021 Y1032       Y1054 Y1065
*
Y2001 Y2012
Y2002 Y2013       Y2035 Y2046 Y2057
Y2003 Y2014       Y2036 Y2047
Y2004 Y2015 Y2026 Y2037 Y2048 Y2059
Y2005 Y2016 Y2027 Y2038 Y2049 Y2060
Y2006 Y2017 Y2028 Y2039 Y2050 Y2061
Y2007 Y2018 Y2029 Y2040 Y2051 Y2062
Y2008 Y2019 Y2030 Y2041 Y2052 Y2063
Y2009 Y2020 Y2031             Y2064
Y2010 Y2021 Y2032       Y2054 Y2065
*
            Y3023
            Y3024 Y3035       Y3057
                  Y3036
Y3004       Y3026 Y3037 Y3048 Y3059
Y3005       Y3027 Y3038 Y3049 Y3060
Y3006       Y3028 Y3039 Y3050 Y3061
Y3007       Y3029 Y3040 Y3051 Y3062
            Y3030 Y3041 Y3052 Y3063
Y3009 Y3020 Y3031             Y3064
Y3010 Y3021 Y3032       Y3054 Y3065
            Y3033       Y3055
*
            Y4023 Y4034
                  Y4035       Y4057
                  Y4036
Y4004       Y4026 Y4037 Y4048 Y4059
Y4005       Y4027 Y4038 Y4049 Y4060
Y4006             Y4039 Y4050 Y4061
```

```
Y4007          Y4029 Y4040 Y4051 Y4062
                     Y4041 Y4052 Y4063
Y4009 Y4020 Y4031                Y4064
Y4010 Y4021 Y4032 Y4043 Y4054 Y4065
*
                           Y5045 Y5056
Y5002 Y5013       Y5035 Y5046 Y5057
Y5003 Y5014       Y5036 Y5047
Y5004       Y5026 Y5037 Y5048 Y5059
Y5005       Y5027 Y5038 Y5049 Y5060
Y5006       Y5028 Y5039 Y5050 Y5061
Y5007       Y5029 Y5040 Y5051 Y5062
            Y5030 Y5041 Y5052 Y5063
Y5009 Y5020 Y5031             Y5064
Y5010 Y5021 Y5032       Y5054 Y5065
                        Y5055
*
                        Y6045 Y6056
Y6002 Y6013       Y6035 Y6046 Y6057
Y6003 Y6014       Y6036 Y6047
Y6004       Y6026 Y6037 Y6048 Y6059
Y6005       Y6027 Y6038 Y6049 Y6060
Y6006       Y6028 Y6039 Y6050 Y6061
Y6007       Y6029 Y6040 Y6051 Y6062
            Y6030 Y6041 Y6052 Y6063
Y6009 Y6020 Y6031             Y6064
Y6010 Y6021 Y6032       Y6054 Y6065
N5 N6 N15 N16 X5 X6
*
MINIMIZE
 .1N5+  .1N15+  .9N6+  .9N16
*
CONSTRAINTS
X5 + N5 = 1
X6 + N6 = 1
Y5045+Y5046+Y5047+Y5048+Y5049+Y5050+Y5051+Y5052+Y5054+Y5055+N15=10
Y6056+Y6057+Y6059+Y6060+Y6061+Y6062+Y6063+Y6064+Y6065+N16=9
 +  1Y1001 +  1Y2001.LE.  0
 +  1Y1002 +  1Y2002 +  1Y5002 +  1Y6002.LE.  6
 +  1Y1003 +  1Y2003 +  1Y5003 +  1Y6003.LE.  4
 +  1Y1004 +  1Y2004 +  1Y3004 +  1Y4004 +  1Y5004 +  1Y6004.LE.  2
 +  1Y1005 +  1Y2005 +  1Y3005 +  1Y4005 +  1Y5005 +  1Y6005.LE.  2
 +  1Y1006 +  1Y2006 +  1Y3006 +  1Y4006 +  1Y5006 +  1Y6006.LE.  2
 +  1Y1007 +  1Y2007 +  1Y3007 +  1Y4007 +  1Y5007 +  1Y6007.LE.  2
 +  1Y1008 +  1Y2008.LE.  2
 +  1Y1009 +  1Y2009 +  1Y3009 +  1Y4009 +  1Y5009 +  1Y6009.LE.  2
 +  1Y1010 +  1Y2010 +  1Y3010 +  1Y4010 +  1Y5010 +  1Y6010.LE.  3
 +  1Y1012 +  1Y2012.LE.  2
 +  1Y1013 +  1Y2013 +  1Y5013 +  1Y6013.LE.  6
 +  1Y1014 +  1Y2014 +  1Y5014 +  1Y6014.LE.  4
 +  1Y1020 +  1Y2020 +  1Y3020 +  1Y4020 +  1Y5020 +  1Y6020.LE.  2
 +  1Y1021 +  1Y2021 +  1Y3021 +  1Y4021 +  1Y5021 +  1Y6021.LE.  3
```

```
+  2Y3023 +  1Y4023.LE. 21
+  2Y3024.LE. 42
+  1Y1026 +  1Y2026 +  1Y3026 +  1Y4026 +  1Y5026 +  1Y6026.LE.  2
+  1Y1027 +  1Y2027 +  1Y3027 +  1Y4027 +  1Y5027 +  1Y6027.LE.  2
+  1Y1028 +  1Y2028 +  3Y3028 +  1Y5028 +  1Y6028.LE.  4
+  1Y1029 +  1Y2029 +  1Y3029 +  1Y4029 +  1Y5029 +  1Y6029.LE.  1
+  1Y1030 +  1Y2030 +  3Y3030 +  1Y5030 +  1Y6030.LE.  4
+  1Y1031 +  1Y2031 +  1Y3031 +  1Y4031 +  1Y5031 +  1Y6031.LE.  7
+  1Y1032 +  1Y2032 +  1Y3032 +  1Y4032 +  1Y5032 +  1Y6032.LE.  4
+  1Y3033.LE.  1
+  1Y4034.LE.  3
+  1Y1035 +  1Y2035 +  1Y3035 +  1Y4035 +  1Y5035 +  1Y6035.LE.  3
+  1Y1036 +  1Y2036 +  1Y3036 +  1Y4036 +  1Y5036 +  1Y6036.LE.  3
+  1Y1037 +  1Y2037 +  1Y3037 +  1Y4037 +  1Y5037 +  1Y6037.LE.  1
+  1Y1038 +  1Y2038 +  1Y3038 +  1Y4038 +  1Y5038 +  1Y6038.LE.  1
+  1Y1039 +  1Y2039 +  1Y3039 +  1Y4039 +  1Y5039 +  1Y6039.LE.  1
+  1Y1040 +  1Y2040 +  1Y3040 +  1Y4040 +  1Y5040 +  1Y6040.LE.  1
+  1Y1041 +  1Y2041 +  1Y3041 +  1Y4041 +  1Y5041 +  1Y6041.LE.  2
+  3Y4043.LE.  1
+ 27Y5045 + 27Y6045.LE.378
+  1Y1046 +  1Y2046 +  1Y5046 +  1Y6046.LE.  7
+  1Y1047 +  1Y2047 +  1Y5047 +  1Y6047.LE.  0
+  1Y1048 +  1Y2048 +  1Y3048 +  1Y4048 +  1Y5048 +  1Y6048.LE.  2
+  1Y1049 +  1Y2049 +  1Y3049 +  1Y4049 +  1Y5049 +  1Y6049.LE.  3
+  1Y1050 +  1Y2050 +  1Y3050 +  1Y4050 +  1Y5050 +  1Y6050.LE.  1
+  1Y1051 +  1Y2051 +  1Y3051 +  1Y4051 +  1Y5051 +  1Y6051.LE.  1
+  1Y1052 +  1Y2052 +  1Y3052 +  1Y4052 +  1Y5052 +  1Y6052.LE.  1
+  1Y1054 +  1Y2054 +  1Y3054 +  1Y4054 +  1Y5054 +  1Y6054.LE.  1
+  1Y3055 +  1Y5055.LE.  1
+  3Y5056 +  3Y6056.LE. 18
+  1Y1057 +  1Y2057 +  1Y3057 +  1Y4057 +  1Y5057 +  1Y6057.LE.  3
+  1Y1059 +  1Y2059 +  3Y3059 +  1Y4059 +  1Y5059 +  1Y6059.LE.  7
+  1Y1060 +  1Y2060 +  1Y3060 +  1Y4060 +  1Y5060 +  1Y6060.LE.  1
+  1Y1061 +  1Y2061 +  1Y3061 +  1Y4061 +  1Y5061 +  1Y6061.LE.  1
+  1Y1062 +  1Y2062 +  1Y3062 +  1Y4062 +  1Y5062 +  1Y6062.LE.  1
+  1Y1063 +  1Y2063 +  3Y3063 +  1Y4063 +  1Y5063 +  1Y6063.LE. 11
+  1Y1064 +  1Y2064 +  3Y3064 +  1Y4064 +  1Y5064 +  1Y6064.LE.  7
+  1Y1065 +  1Y2065 +  1Y3065 +  1Y4065 +  1Y5065 +  1Y6065.LE.  2
+ 1Y1001 + 1Y1012 -X1.GE.0
+ 1Y1002 + 1Y1013 + 1Y1035 + 1Y1046 + 1Y1057 -X1.GE.0
+ 1Y1003 + 1Y1014 + 1Y1036 + 1Y1047 -X1.GE.0
+ 1Y1004 + 1Y1026 + 1Y1037 + 1Y1048 + 1Y1059 -X1.GE.0
+ 1Y1005 + 1Y1027 + 1Y1038 + 1Y1049 + 1Y1060 -X1.GE.0
+ 1Y1006 + 1Y1028 + 1Y1039 + 1Y1050 + 1Y1061 -X1.GE.0
+ 1Y1007 + 1Y1029 + 1Y1040 + 1Y1051 + 1Y1062 -X1.GE.0
+ 1Y1008 + 1Y1030 + 1Y1041 + 1Y1052 + 1Y1063 -X1.GE.0
+ 1Y1009 + 1Y1020 + 1Y1031 + 1Y1064 -X1.GE.0
+ 1Y1010 + 1Y1021 + 1Y1032 + 1Y1054 + 1Y1065 -X1.GE.0
+ 1Y2001 + 1Y2012 -X2.GE.0
+ 1Y2002 + 1Y2013 + 1Y2035 + 1Y2046 + 1Y2057 -X2.GE.0
+ 1Y2003 + 1Y2014 + 1Y2036 + 1Y2047 -X2.GE.0
+ 1Y2004 + 1Y2015 + 1Y2026 + 1Y2037 + 1Y2048 + 1Y2059 -X2.GE.0
```

```
+ 1Y2005 + 1Y2016 + 1Y2027 + 1Y2038 + 1Y2049 + 1Y2060 -X2.GE.0
+ 1Y2006 + 1Y2017 + 1Y2028 + 1Y2039 + 1Y2050 + 1Y2061 -X2.GE.0
+ 1Y2007 + 1Y2018 + 1Y2029 + 1Y2040 + 1Y2051 + 1Y2062 -X2.GE.0
+ 1Y2008 + 1Y2019 + 1Y2030 + 1Y2041 + 1Y2052 + 1Y2063 -X2.GE.0
+ 1Y2009 + 1Y2020 + 1Y2031 + 1Y2064 -X2.GE.0
+ 1Y2010 + 1Y2021 + 1Y2032 + 1Y2054 + 1Y2065 -X2.GE.0
+ 2Y3023 -X3.GE.0
+ 2Y3024 + 1Y3035 + 1Y3057 -X3.GE.0
+ 1Y3004 + 1Y3026 + 1Y3037 + 1Y3048 + 3Y3059 -X3.GE.0
+ 1Y3005 + 1Y3027 + 1Y3038 + 1Y3049 + 1Y3060 -X3.GE.0
+ 1Y3006 + 3Y3028 + 1Y3039 + 1Y3050 + 1Y3061 -X3.GE.0
+ 1Y3007 + 1Y3029 + 1Y3040 + 1Y3051 + 1Y3062 -X3.GE.0
+ 3Y3030 + 1Y3041 + 1Y3052 + 3Y3063 -X3.GE.0
+ 1Y3009 + 1Y3020 + 1Y3031 + 3Y3064 -X3.GE.0
+ 1Y3010 + 1Y3021 + 1Y3032 + 1Y3054 + 1Y3065 -X3.GE.0
+ 1Y3033 + 1Y3055 -X3.GE.0
+ 1Y4023 + 1Y4034 -X4.GE.0
+ 1Y4035 + 1Y4057 -X4.GE.0
+ 1Y4036 -X4.GE.0
+ 1Y4004 + 1Y4026 + 1Y4037 + 1Y4048 + 1Y4059 -X4.GE.0
+ 1Y4005 + 1Y4027 + 1Y4038 + 1Y4049 + 1Y4060 -X4.GE.0
+ 1Y4006 + 1Y4039 + 1Y4050 + 1Y4061 -X4.GE.0
+ 1Y4007 + 1Y4029 + 1Y4040 + 1Y4051 + 1Y4062 -X4.GE.0
+ 1Y4041 + 1Y4052 + 1Y4063 -X4.GE.0
+ 1Y4010 + 1Y4021 + 1Y4032 + 3Y4043 + 1Y4054 + 1Y4065 -X4.GE.0
+27Y5045 + 3Y5056 -X5.GE.0
+ 1Y5002 + 1Y5013 + 1Y5035 + 1Y5046 + 1Y5057 -X5.GE.0
+ 1Y5003 + 1Y5014 + 1Y5036 + 1Y5047 -X5.GE.0
+ 1Y5004 + 1Y5026 + 1Y5037 + 1Y5048 + 1Y5059 -X5.GE.0
+ 1Y5005 + 1Y5027 + 1Y5038 + 1Y5049 + 1Y5060 -X5.GE.0
+ 1Y5006 + 1Y5028 + 1Y5039 + 1Y5050 + 1Y5061 -X5.GE.0
+ 1Y5007 + 1Y5029 + 1Y5040 + 1Y5051 + 1Y5062 -X5.GE.0
+ 1Y5030 + 1Y5041 + 1Y5052 + 1Y5063 -X5.GE.0
+ 1Y5010 + 1Y5021 + 1Y5032 + 1Y5054 + 1Y5065 -X5.GE.0
+ 1Y5055 -X5.GE.0
+27Y6045 + 3Y6056 -X6.GE.0
+ 1Y6002 + 1Y6013 + 1Y6035 + 1Y6046 + 1Y6057 -X6.GE.0
+ 1Y6004 + 1Y6026 + 1Y6037 + 1Y6048 + 1Y6059 -X6.GE.0
+ 1Y6005 + 1Y6027 + 1Y6038 + 1Y6049 + 1Y6060 -X6.GE.0
+ 1Y6006 + 1Y6028 + 1Y6039 + 1Y6050 + 1Y6061 -X6.GE.0
+ 1Y6007 + 1Y6029 + 1Y6040 + 1Y6051 + 1Y6062 -X6.GE.0
+ 1Y6030 + 1Y6041 + 1Y6052 + 1Y6063 -X6.GE.0
+ 1Y6009 + 1Y6020 + 1Y6031 + 1Y6064 -X6.GE.0
+ 1Y6010 + 1Y6021 + 1Y6032 + 1Y6054 + 1Y6065 -X6.GE.0
RSCALE 100
BNDALL 1
BOUNDS
N11 TO N16 .LE. 10
ENDOBJ 923
LIMIT 4000
COLUMN 80
STOP
```

VITA

Calvin George Hedgeman was born on 29 September 1948 in New York City, New York. He graduated from high school in Long Island City, New York in 1966 and attended New Mexico Institute of Mining and Technology from which he received the degree of Bachelor of Science in Mathematics in June 1970. Upon graduation, he entered the USAF. He received his commission through Officer's Training School in October, 1976, completing training as a Space Systems Operations officer the same year. He then served with the 1000 Satellite Operations Group, Offutt AFB, NE and the 16 Surveillance Squadron, Shemya AFB, AK. Prior to entering the School of Engineering, Air Force Institute of Technology in October 1972, he was a Space Systems Requirements Officer at HQ SAC, Offutt AFB, NE.

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Box 11 - A Decision Aid for Restoration of Force Enhancement Space Systems

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Associate Professor of Operational Sciences

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The goal of this research ~~is to~~ provides the Commander-in-Chief, United States Space Command, ~~with~~ a prototype model ~~he can use~~ to make restoration management decisions for space systems. The model includes a data base of system attributes and provisions for varying mission priorities.

The study is limited to military space systems performing the communications, navigation and meteorological missions. This restriction simplifies the project without limiting the model's usefulness as a feasibility study. Other space systems and missions can be easily added to the data base as required.

The Analytic Hierarchy Process is used to assess CINCUSSPACECOM's mission priorities and technical preferences among space systems performing the same mission but providing different capabilities. Goal programming is used to develop a mathematical formulation of CINCUSSPACECOM's desire to restore preferred space systems and to specify a preferred configuration for each space system restored. Finally, resource changes resulting from wartime scenarios are used to validate the model.

The study concludes with a recommendation that USSPACECOM implement a restoration management system to realize the full value of force enhancement space systems during a conflict.

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