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DESIGN OF AN ORBITAL INSPECTION SATELLITE

THESIS

Harold D. Getzelman
Captain, USAF

AFIT/GSO/AA/86D-4

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DESIGN OF AN ORBITAL INSPECTION SATELLITE

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Space Operations

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Harold D. Getzelman, B.S.

Captain, USAF

December 1986

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Acknowledgments

Maj David Aderhold of Space Command proposed this project. I am also thankful for the valuable guidance he provided as my thesis sponsor.

I am deeply indebted to my two thesis advisors LtCol J. W. Widhalm and Capt S. C. Kramer, and to my thesis reader Maj D. W. Reyen for their technical and editorial assistance.

Special thanks is extended to my neighbors Capt Pete and Betsy McGraff for their extensive editorial assistance.

Finally, I wish to thank my wife, Marian, for her significant contributions to my thesis.

Harold D. Getzelman

Table of Contents

List of Figures

List of Tables

Abstract

The need for the inspection of space objects by satellite is identified. The historical and legal context of the inspection satellite is discussed and its implications on the design of the satellite are understood. Systems engineering tools are used to identify the basic design of an orbital inspection satellite. The satellite is partitioned into six major subsystems for analysis. The interactions between subsystems and among competing technologies for each subsystem is investigated. An orbital inspection satellite composed of the best systems and supporting subsystems is described. Finally, recommendations for futher study and the impact of key decisions are described.

DESIGN OF AN ORBITAL INSPECTION SATELLITE

I. Introduction

General Issue

The majority of space objects are observable today only through ground-based sensors. Currently, we use these ground-based sensors for tracking, identification, and some fault diagnosis.

Current ground-based sensors are inadequate to determine the exact status of all space systems. For example, during the first space shuttle mission, ground-based sensors were used to determine if shuttle tiles were missing (33:82). Due to weather problems, the attempt failed. Ground-based optical, radar, and infrared sensors are severely limited by the atmosphere, lighting, and weather as well as the excessive range to the space object. These limitations are covered extensively in Appendix C, Ground-Based Sensors.

North American Aerospace Defense Command (NORAD) uses a collection of optical, radar, and infrared sensors to track and identify space objects. The requirement for inspection of space systems will expand as the number of space objects continues to increase. There are currently over 5000 space objects that must be tracked continually by NORAD (34:129). Ground-based sensors are inadequate to track and identify these space objects (13:306).

The United States has a large segment of its communications and intelligence resources in space. These vital assets can be threatened by hostile satellites. The hostile satellites could electronically disrupt friendly satellites or destroy them through collision or shrapnel devices. Ground-based sensors cannot adequately identify these hostile satellites.

To compensate for the limitations of ground-based sensors, the space shuttle could be considered for inspection of space objects. However, the space shuttle is limited to low earth orbit (350km), which restricts the utility of this method. Further, as only three shuttles remain in the fleet, missions must be dedicated to higher priority needs.

An inspection satellite system could compensate for the limitations of ground-based sensors, providing an accurate diagnosis and adequate identification of space objects. The inspection satellite could resolve mechanical anomalies or characterize damage to friendly satellites. Further, the inspection satellite could identify each satellite and determine its origin and function. Since the inspection satellite could use a more complete set of sensors in space, more information would be available to understand a problem.

Problem Statement

The United States does not have an adequate means to inspect space objects in earth orbit.

Scope

This study will only consider space-based inspection systems and hardware, identifying the requirements of each subsystem. Only current space hardware or that which is in an advanced state of development will be considered for use on the inspection satellite. The research will not consider ground support equipment or the interface with launch vehicles. Nor will the research attempt to design the specific software or hardware required.

Research Question

What type of orbital inspection satellite would be the most effective space inspection system? Is current hardware adequate to implement an inspection satellite or would new hardware be required? What capabilities of the inspection satellite are required, desired, or simply nice to have? What degree of autonomy should be used?

Objectives

The overall objective of this research is to provide a basic functional design for an orbital inspection satellite. Specific supporting objectives are:

1. Define the key characteristics for observation by the inspection satellite.
2. Define the package of sensors and the level of sensitivity required of each sensor for the inspection satellte.

3. Define an appropriate propulsion system and the quantity of propellant necessary for the inspection satellite.

4. Define a guidance and control system that would permit intercept, rendezvous or proximity operations through remote control or autonomous operations.

5. Choose a structure and power system capable of holding all the sensors and powering the spacecraft equipment.

6. Choose a communications package to relay sensor and command data as well as housekeeping information to the earth or store the data for later use.

Background

Since the early 1960s, the United States has adopted an aggressive policy for the use of space. Space has been used for reconnaissance, communications, astronomy, navigation, weather, astro-physics, and man-related activities. During this period, the design of an orbital inspection satellite was first begun. The satellite inspector (SAINT) did not progress beyond paper studies. It was cancelled for technical reasons in 1962, during a period of decreasing tension between the superpowers. Appendix A contains an extensive discussion of the history and the political considerations for the orbital inspection satellite.

In an effort to achieve the best economy, the United States has developed highly reliable satellites. This effort has provided some impressive achievements, with the average lifespan of a communications satellite exceeding seven years. In conjunction with improvements in reliability, an effort was made to increase the complexity of satellites so that one vehicle could do the work of several. Today the United States network is composed of a limited number of highly sophisticated and reliable satellites. In contrast, the Soviet Union depends on a proliferation of low technology and low reliability satellites (the average life span of a Molynia 3 Communications Satellite is 25 months) (20:4).

The move by the United States to higher technology satellites significantly raised the cost of each satellite. The changing economics caused a move toward replenishment and repair of satellites versus abandoning them at the end of their lifetime. The ability to recover and repair satellites was first demonstrated by the space shuttle crew when it repaired Solar Max and later when it recovered Palapa B and Westar 6. The ultimate in high value satellites is the Hubble space telescope, a 1.2 billion dollar investment which can be serviced in space. NASA is developing a reuseable Orbital Maneuvering Vehicle (OMV) to inspect, recover, and deploy payloads to low earth orbit (see Appendix F) (30:35). The OMV project will focus on recovery and repair of satellites, while the orbital inspection satellite will focus on inspection.

In the 1950s the United Stated recognized the need to assign responsibility for certain activities in space. The National Aeronautics and Space Act of 1958 defines the civilian and military responsibilities. It states that activities peculiar to or primarily associated with the the development of weapons systems, military operations, or the defense of the United States (including research and development necessary to make effective provision for the defense of the United States) shall be the responsibility of, and directed by, the Department of Defense (51).

The orbital inspection satellite must operate with in the framework of space law. The design is influenced by the requirement to avoid interference with other peaceful satellites. The origin and the implications of space law are discussed in Appendix B.

The Military Space Doctrine Air Force Manual 1-6 requires that the United States will develop and maintain an integrated attack warning, notification, verification, and contingency reaction capability which can effectively detect and react to threats to United States space systems. (11:3). The orbital inspection satellite is a system designed to detect space-based threats.

As the United States became more reliant on fewer, more sophisticated satellites, these satellites became very enticing targets for a potential adversary. The ability to replace these critical satellites became a serious concern after the successive failures of the Titan 3, Space Shuttle, Delta, and Ariane launch vehicles.

The Soviet Union has the means to destroy United

States' satellites with the only operational Anti-Satellite Weapon (ASAT) in the world. Although the Soviet ASAT has a limited engagement envelope and a poor record of development testing, it still represents a credible threat to Western satellites.

President Reagan announced the promise of a new era in world relations with the development of the Strategic Defense Initiative (SDI). When the SDI is operational, satellites which could destroy intercontinental ballistic warheads will be placed into orbit. These satellites will be the ultimate high value target. An inspection satellite could be used to detect a hostile threat to this space system.

The detection of threats to our space systems will be greatly enhanced by space-based inspection. An orbital inspection satellite could gather intelligence on space objects, the identifying of offensive space weapons.

Overview

This thesis will focus on the space segment of an orbital inspection satellite.

Chapter I presents the problem, providing objectives, background, and an overview.

Chapter II presents the methodology of systems engineering providing justification, models, and decision rules.

Chapter III uses the seven steps of systems engineering: problem definition, value system design, system synthesis, systems analysis, optimization of alternatives, decision making, and planning for future action. Key decisions in the development of the orbital inspection satellite are identified and design considerations are determined for six major subsystems. An orbital inspection satellite composed of the best subsystems is described.

Chapter IV concludes the thesis recommending further study and providing the impact of the key decisions.

A significant amount of information relative to the design of an orbital inspection satellite is contained in the seven appendixes listed below:

A. History of the Satellite Inspector.

B. Legal Aspects of an Inspection Satellite.

C. Ground-Based Sensors.

D. Spacecraft Subsystems.

E. Models: Cost, Baseline Vehicle, Launch Window, Observability, Ratio of Delta-V.

F. Orbital Maneuvering Vehicle.

G. Space-Based Telescopes.

II. Methodology

Systems Engineering

Systems engineering is a methodology used to effectively manage large-scale systems. It has proven very useful to decision-makers who must design or modify a system. However, systems engineering is more than just a method; it encompasses a broad range of tools needed to analyze a problem. Many books on systems engineering include case studies which demonstrate how systems engineering is used to successfully cope with a problem. A natural inclination is to apply the solution for a similar problem to the problem of interest. This approach to problem-solving could be disastrous. It is very important to understand when a particular tool of systems engineering is appropriate for use.

Systems engineering approaches a problem in a logical manner. Several authors have broken this logical progression into different steps. For example, Hill divides the process into these steps (38:61):

1. Analysis and planning.
2. Preliminary design.
3. Detailed design and test.
4. Production design.

Although the division of the methodology is arbitrary, the key point is that a "top down" orientation is used. More specifically, goals and objectives are defined first.

Only after a problem is thoroughly understood can a suitable solution be identified.

Since systems engineering often involves a large number of experts working together on a problem, it becomes necessary to parcel out the work. Some people have assumed that the key to successful systems engineering is learning how to break a problem apart. Although this is important, the building of a system is more important (53:9). Systems engineering focuses on the interaction between elements and the interaction of the system and its environment. This holistic approach recognizes that it is not sufficient to look at the parts separately, but rather treat systems as a whole.

Systems Engineering in this Problem

Systems Engineering was chosen as an appropriate methodology for an orbital inspection satellite. In developing an adequate method to inspect space objects, the result should possess many of the ingredients that Sage says are required for a large-scale system. There will certainly be many interrelationships between elements. The construction and deployment will result in far-reaching and controversial value judgments. The design of a space vehicle will require specialized knowledge in several disciplines.

Weinberg states that the analyst should consider more than the technical aspects of the system. No system exists in a vacuum; therefore, all external as well as internal interactions should be considered. The inspection satellite must operate in the legal environment of space law. It must satisfy the needs of the intelligence, defense, and space administrations because each has a different role that the inspection satellite must meet. The space vehicle must compete with ground-based sensors for funding. Finally, political considerations will affect the design of the satellite.

It is also important to define the boundaries of the problem. Every system is a part of a larger system, and each subsystem may be thought of as a separate system. An orbital inspection satellite is a part of the space inspection system which would use both ground-based and space-based equipment. This study is only concerned with the space segment of the inspection system. Excluded from the study is launcher compatibility, ground control network, and the servicing of the satellite.

Hall's Method

Although there are many variants of systems engineering, the one chosen for this project was proposed by Hall and is described by Sage in "Methodology for Large Scale Systems." Three dimensions are associated with systems engineering: knowledge, time, and logic.

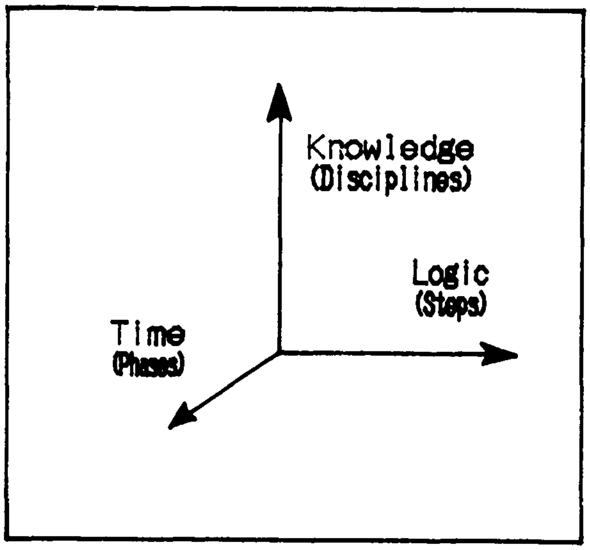


Figure 1. Three-dimensional Framework (38:4)

The knowledge dimension corresponds to the different disciplines used to understand the problem and generate a solution. The knowledge dimension may involve such diverse disciplines as medicine, engineering, law, and social science. The time or course dimension corresponds to the seven phases in the life of a system (38:61):

1. Program planning.
2. Project planning.
3. System development.
4. Production.
5. Installation.
6. Operation.
7. Retirement.

Program planning, the most general phase, is concerned with general programs and policies. Project planning is more specific and focuses on the particular projects that will comprise the total system. System development is the actual design of a system. Production involves transferring the design into reality. Installation is putting a system into use. Operations is the phase concerned with using the system most effectively. Retirement is the phase which removes a system at the end of its useful lifespan.

The logic dimension corresponds to the seven steps in the system engineering process:

1. Problem definition.
2. Value system design.
3. Systems synthesis.
4. Systems analysis.
5. Optimization of alternatives.
6. Decision making.
7. Planning for future action.

In the first step, problem definition, the background, scope, and nature of the problem are identified. Needs, alterables, and constraints are determined and related to the problem. The next step is value system design, where the objectives are defined and measures of effectiveness are constructed. During the third step, systems synthesis, all feasible alternatives are listed. Systems analysis and modeling begins during the fourth step. Analytical models are created which provide information about the consequences of the different alternatives to the decision-maker. These results are used in the fifth step, rank alternatives.

TABLE I

Hall Activity Matrix (38:5)

Phases of the coarse structure (Time ↓) \ Steps of the fine structure (Logic →)	Problem definition	Value system design	System synthesis	Systems analysis	Rank (optimize) alternatives	Decision making	Planning for action
Program planning							
Project planning							
System development							
Production							
Distribution							
Operations							
Retirement							

Alternatives are ranked, and dominated solutions are eliminated. Dominated solutions are those that are inferior to some combination of the other alternatives. The remaining alternatives are investigated during the decision step. Various techniques may be helpful to the decision-maker. The inspection satellite lends itself to the technique of multi-objective analysis. The final step is planning for action. This communicates the entire systems engineering process and provides the recommendations for future action.

The activity matrix brings together the phases of the time dimension and the steps of the logic dimension. The intersection of these two dimensions is an activity. The steps in the activity plane are carried out in an iterative fashion. That is, each step is dependent on a previous step, and subsequent steps may modify the steps that have preceded them.

In the next chapter this methodology will be applied to the design of an orbital inspection satellite. The study was conducted at the first phase, program planning, and proceeds through the seven steps. The study was conducted at two levels, overall systems design and subsystems design, to support the overall design. The study was conducted in an iterative fashion; eventhough, it is presented here in straight-forward sequence.

III. Analysis

Problem Definition

The first step in the logic dimension is problem definition. Chapter one and Appendix A define the problem of the inadequate means to inspect space objects. This study recognizes the synergism between ground and space elements of the space object inspection system. However, the scope of this study will be limited to an orbital inspection satellite.

Three typical scenarios for the use of an orbital inspection satellite follow. In the first scenario, information from an inspector satellite would be useful when the Soviet space shuttle is launched from Tyuratam Launch Complex (43:42). The shuttle spends five days in orbit and returns to the earth. The Soviet press announces a historic first with the use of the Soviet space shuttle: the launch of three scientific payloads for the benefit of all mankind. The United States Space Defense Operations Center (SPADOC) is able to detect only one launch from the Soviet shuttle due to limited ground-based sensor coverage. However, the Naval Surveillance Fence has detected seven uncorrelated space objects now in low earth orbit. Space Command urgently needs to know if these seven space objects pose any threat to space assets or ground forces of the United States.

A second scenario involves a similar case of space intelligence. The Soviets have launched three new satellites to replace two aging satellites in a typical Molynia communications orbit. After the new satellites reach their orbits, the aging satellites are turned off and abandoned. However, three months later the Kettering Group (a British group of private space watchers) states that one of the new satellites has failed, but one of the abandoned satellites is functioning normally (20:26). The director of intelligence urgently needs to know if this report is true, and also how many orbital spares the Soviet Union possesses in satellites previously thought derelict. This will drastically affect his planning document, the Soviet Space Order of Battle.

A third scenario involves the failure of an upper stage to deliver a spacecraft to geosynchronous orbit. NASA has lost a Syncom spacecraft after it was launched from the United States space shuttle. The launch appeared normal until 30 seconds into the transfer burn when all telemetry was lost. SPADOC has located three pieces of space debris in low earth orbit which have tentatively been identified as the Syncom spacecraft. NASA needs to know what went wrong. The same type of upper stage will be used on several other payloads, and these payloads must be postponed until the failure mode can be isolated.

All of these scenarios illustrate a need for an orbital inspection satellite. In some cases improved ground-based sensors could provide the necessary data. In other cases only a space-based system could provide the necessary data.

The first procedure is to identify the needs of the orbital inspection satellite.

Needs

1. Detect a threat from a space object.
2. Gather signature data on the space object.
3. Diagnose a satellite failure.
4. Affordable (life cycle cost).
5. Deter weapons in space.
6. Rapid response to inspect.
7. Flexible capabilities.
8. Determine function or purpose of space object.
9. Assign a space object to a known class.
10. Secure and reliable data return.

The first need comes from the Air Force Manual on Space Doctrine which mandates "a capability which can effectively detect and react to threats to United States space systems" (11:3). Gathering signature data means collecting the raw information which will be used to classify a space object. Number three is related to the third scenario which identified our inability to diagnose a failure of a friendly space system. The fourth need is for a system that can be implemented for a reasonable amount of money. The fifth need is for a system that would deter any aggressive power from putting weapons in space. This would result from the knowledge that there is a high likelihood of it being detected by the inspection system. The sixth need, rapid inspection of a space object, results from a desire to preempt hostile action or isolate a failure quickly with minimal impact on operations. Since space objects are scattered in many different orbits, the inspection system should be flexible in its capabilities. The next need is determining a space object's function, which is derived from all available signature data. The last need is to assign a space object to a known class.

Next, the alterables in the problem were identified. The following is a list of items that could be varied in the design:

<u>Alterables</u>

1. Missions per vehicle.
2. On board computing power.
3. Mode of operations (rendezvous, fly-by, long-range).
4. Level of autonomy.
5. Mode of control.
6. Size.
7. Mass.
8. Serviceability.
9. Basing mode.

10. Subsystems for spacecraft.

   a. Power generation.

   b. Propulsion.

   c. Guidance and control hardware.

   d. Thermal control.

   e. Communications.

   f. Sensors.

The alterables can be varied through the choice of subsystems and design philosophies. Most of the alterables are self-evident. The mode of operation is the method the inspection satellite will use to collect data. The servicing capabilities correspond to three options: replenishment of expendables, refurbish and relaunch, and single use. The inspection satellite can be ground-based and launched when needed or based in space. In all designs there is freedom to choose the size and type of each subsystem.

In a similar manner the constraints on the system were identified.

<u>Constraints</u>

1. Existing launch vehicles.
2. Limited servicing available.
3. Current technology of subsystems.
4. Large dispersion of space objects.
5. Existing space law.
6. Recovery of film (if used).

7. Propellant and power consumed during operations.
8. Communications links during operations.
9. Space environment.
10. Ground support facilities.
11. Return data within three days.
12. Two centimeters resolution in the visible band.

The current United States launch vehicles, which produce varying launch acceleration forces, can place vehicles in orbit which have limited size and mass. Servicing of an inspection satellite can only be done by the space shuttle or at the future space station. The design is limited to the technology that will be available in the next ten years. The space objects that will be inspected are widely dispersed in altitude, inclination, and eccentricity. Current space law will constrain the methods used during inspection. If film is used, it must be recovered. Propellant and power are expended during inspections and must be replenished. The coverage of the ground communications network is limited, and relay through satellites will be required. The space environment will impose harsh operating conditions on the inspection satellite. A ground support facility will be required to control the satellite and analyze the data. Maj Aderhold of Space Command determined that data should be returned within three days to be useful. In addition, the resolution of that data should be two centimeters in the visible bands. The needs, alterables and constraints form the basic guidelines for the develpment of the orbital inspection satellite. These factors will be further refined and measures of effectiveness determined in the next section of value system design.

Value System Design

The next step in systems engineering is to derive the objectives from the needs of the problem. These objectives give the systems analyst more specific guidance on the goals of the project. The overall objective is to provide the decision maker with useful information in timely manner for minimum cost. This objective is divided into several supporting objectives.

Objectives

1. To provide useful information to the decision-maker for minimunm cost in a timely manner.
2. To obtain the highest quality data consistent with needs.
3. To meet objectives for minimum life cycle cost for ten years with 25 equivalent inspections per year.
4. To return inspection data as rapidly as possible.

Measures of Effectiveness. The objectives above must be measured to have any impact on the design of the systems. Three measures of effectiveness were derived from the above objectives. The first measure is the total time to receive data after a decision to inspect is made. The second measure is the cost of inspection over ten years at a rate of

25 equivalent inspections (see Appendix E-1). The third measure is overall quality of the data.

The time to receive inspection data (T_{RD}) is composed of several factors. This overall time is composed of several constituent times: planning (T_P), launch (T_L) (if required), activate equipment (T_A), phasing for launch window (T_W), data acquisition (T_Q), and data return (T_R). The following model is used to evaluate this measure of effectiveness.

Time to Inspection

$$T_{RD} = T_P + T_L + T_A + T_W + T_Q + T_R \qquad (1)$$

The second measure of effectiveness is the lifecycle cost during the ten-year lifetime of the inspection system. The cost is based on 25 equivalent inspections per year or a total of 250 inspections. Total cost of inspection (C_T) is the accumulation of development (C_{DV}), production (C_P), deployment (C_{DP}), operations (C_P), and retirement (C_R). The operations cost is calculated by the number of resupply or replacement missions that must be launched (see Appendix E-1).

Cost Model

$$C_T = C_{DV} + C_P + C_{DP} + C_O + C_R \qquad (2)$$

The third measure of effectiveness is the overall quality of the data returned. The quality is determined by the weighted sum of the individual qualities of each data type. There are varying measures of data quality which depend on the type of data taken. For instance, in the visible band high spatial resolution is required, while a temperature measuring device requires higher spectral resolution and only moderate spatial resolutions. A weight was assigned to each data type to describe its relative importance in the overall design. The analysis of the individual Q_is is dependant on the available sensors and mode of operations. These two effects are discribed in more detail in the subsystems design section and in Appendix D.

<u>Quality of Data</u>

$$C_d = \Sigma W_i Q_i \quad (3)$$

System Synthesis

At the grossest level of detail, there are three basic areas that can be altered to form an orbital inspection satellite. These are basing mode, servicing mode, and modes of operation. The inspection satellite may be ground-based in a mode for quick reaction or space-based. The satellite may be serviced in orbit, refurbished on the ground and relaunched, or used only once. There are also three modes of operation: close rendezvous, fly-by, and long-range observation. These are defined on the next page.

Close Rendezvous

The inspector satellite intercepts and rendezvous with the space object. The vehicle continues station-keeping about the space object while collecting sensor data. After data collection is complete the inspector satellite moves off in preparation for another rendezvous mission.

Fly-By

The inspection satellite is maneuvered to an intercept orbit that will bring it close to the space object. During the close approach, the inspector satellite will collect sensor data.

Long-Range Observation

The inspector satellite is placed in a fixed orbit that will allow observation of many space objects. The inspector will employ long-range sensors to collect data. No attempt will be made to maneuver closer to the space object.

Although the choice of an overall system design preceeds the discussion of subsystems design, the actual process first considered the availability of certain technologies for subsystems required to support the overall design. By understanding subsytems and their particular capabilities and weaknesses, the character of the overall design becomes clearer. In particular, the quality of the sensor data from the different mode of operations could not be assigned until sensor subsystem were investigated. This iterative or circular manner is a tenant of systems engineering. The presentation from gross system design to specific subsystem design is merely for the convience of the reader and should not be interpeted as the method followed.

Systems Design

The systems design section of this report is concerned with the overall design of the orbital inspection satellite which impacts the design of spacecraft subsystems. The three steps: systems analysis, optimization, and decision making are combined in this section. The combination of these three step provides a clear foundation for subsystem analysis and a more fully integrated study.

The three choices for the overall design, basing mode, servicing mode, and mode of operation, generate 18 different systems. The systems are analyzed on the basis of time to return data, cost over ten years, and quality of data. Some solutions are clearly inferior, and some are illogical. For example, the ground-based but serviced in space is a contradiction in terms. The individual measures of effectiveness are weighted to reflect the relative importance of each measure in the overall decision. The best system has the highest overall weighted score.

The ranking of the 18 systems was accomplished by creating a baseline inspection design for each mode of operation (see Appendix E-2). This baseline design reflects the mass of each subsystem (propulsion, sensors, structure, etc.) and the delta-V that would be available. The delta-V available is computed using the mass ratio of the vehicle and a propulsion system with an specific impulse (I_{SP}) of 285 seconds. Each system is tasked to accomplish 25 inspections

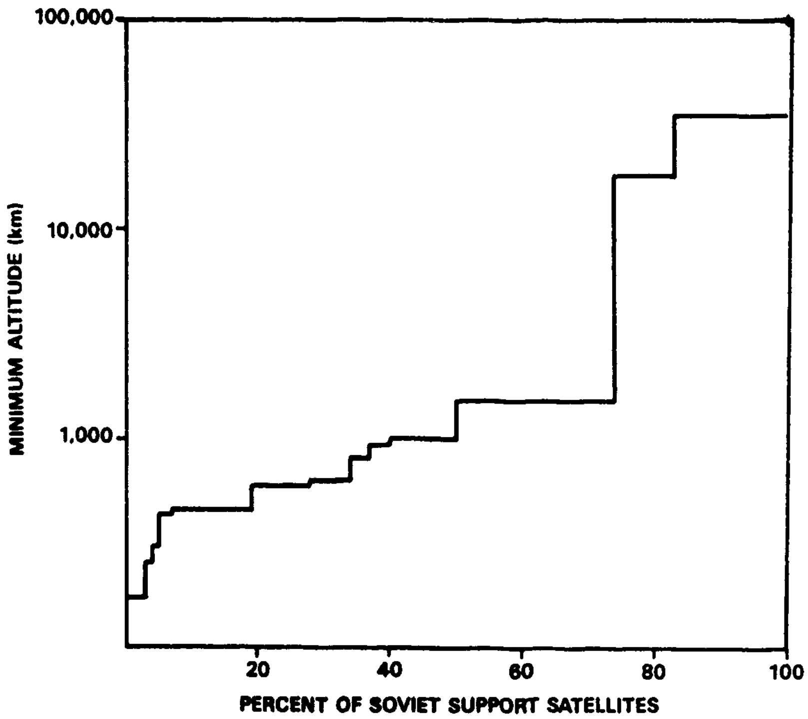


Figure 2. Satellite Minimum Altitude

per year for ten years.

A baseline inspection mission was created to put all systems at the same level. The objective of this equivalent mission is to inspect a vehicle at 1500 km altitude from a 330 km parking orbit. The 330 km parking orbit is a typical altitude that can be achieved by the space shuttle or expendable launch vehicle. The higher altitude of 1500 km is used because 75% of all United States and Soviet Satellites have minimum altitudes less than or equal to 1500 km (20:5).

The delta-V for the equivalent mission was determined using Hohmann transfers between orbits. Finally, a total number of missions per refueling was determined by dividing the total delta-V available by the delta-V for an equivalent mission. Other orbits were considered and Appendix E-5 shows the results of that analysis.

The time required for return of inspection data was determined by the sum of the times used for individual tasks. Times are derived from similar functions that are performed by current space systems. For instance, the minimum time required to launch a space vehicle is 30 days with current technology. The phasing time is a result of waiting for a suitable launch window or good visibility. The phasing time is illustrated in Appendixes E-3 and E-4. This phasing time is a worst case computation. After phasing is complete, data acquisition begins. Rendezvous and interception require the vehicle to fly to the space object for data acquisition. All vehicles are assumed to possess real time data return subsystems; therefore, data return time is zero.

TABLE II

Time to Inspection

Planning	Launch	Activate	Phasing	Data Aq.	Data Return
S-3	S-0	S-1	R-6.7	R-1.5	0
G-0	G-30days	G-6	FB-6.7	FB-1.0	0
			LR-4.8	LR-0.0	0

* All times in hours unless listed otherwise.
* Time for planning a ground launch included in 30 days.
* Abbreviations: S, space basing; G, ground basing; R, rendezvous; FB, fly-by; LR, long-range.

Cost is the sum of development, production, deployment, operations, and retirement. The cost of development is considered equal between all systems and was removed from analysis. The production cost of the space system becomes significant when large numbers of single-use satellites are procured and when operation costs are small, as in the case of long-range inspection systems. The cost of deployment is based on the current figure of $2000 per pound to low earth orbit (31:17). Thus, the baseline vehicle mass and the total number of vehicles launched determine deployment cost. The cost of operations is determined by the amount of expendables that are delivered to the satellite (propellant). After ten refuelings the vehicles would return to earth for refurbishing. After ten missions the reliability of the system would decrease below 90%, which was considered unacceptable (37:127). The cost of retirement is zero for most system since each would re-enter the atmosphere at no expense. The only system that would require expensive retirement cost would be nuclear-based subsystems. The following tables reflect the results of the cost analysis in millions. The cost data should be used to rank alternatives only and not as planning figures for actual costs.

TABLE III

Serviced in Space

Mode	Devel.	Prod.	Deploy.	Ops.	Retire	Total
R	same	240	192	103	0	1432
FB	same	150	96	400	0	645
LR	same	210	33	0	0	243

TABLE IV

Refurbish and Relaunch

Mode	Devel.	Prod.	Deploy.	Ops.	Retire	Total
R	same	240	1700	550	0	2490
FB	same	150	840	350	0	1340
LR	same	210	33	30	0	273

TABLE V

Use Only Once

Mode	Devel.	Prod.	Deploy.	Ops.	Retire	Total
R	same	1650	1700	0	0	3350
FB	same	875	840	0	0	1720
LR	same	210	33	0	0	243

The quality of data is based on the weighted sum of the individual quality of each data type. Each mode of operation would impose constraints on the gathering of sensor data, which is independent of basing mode or servicing. Seven key properties of space objects were identified, and appropriate sensors to measure these properties were found (this is explained in more detail in the subsystem design section). The sensors have limitations in the range and speed of data acquisition. These factors influence the quality of each data type. Each key property is weighted to reflect its importance in the overall system design. The best system has the highest overall quality of data. The following table reflects the quality of sensor data that can be obtained by using the three modes of operations.

TABLE VI

Quality of Data

Characteristic	Weight	Rendezvous	Fly-By	Long-Range
Visible Image	4	4	4	2
Size	2	4	4	2
Material	2	3	3	2
Temperature	3	4	4	2
Communications	4	4	2	2
Emissions	3	4	3	2
Mass	1	1	0	0
Weighted Sum		71	59	36

Ratings		Weights	
Excellent	4	Very High	4
Good	3	High	3
Fair	2	Medium	2
Poor	1	Low	1
Unaccept.	0	None	0

The following table shows the rankings of the 18 alternative designs based on time to return data, life cycle cost, and quality of data. Prior to ranking the overall designs, a preliminary analysis of subsystems was completed.

TABLE VII

Alternative Ranking

BASING	-------SPACE---------------GROUND-------
SERVICING	SERVICE----REFURB & RELAUNCH----USE ONCE
MODE OF OPS	RENDEZVOUS------FLY-BY--------LONG RANGE

SYSTEM[1]	VECTOR[2]	SCORE[3]	
S-S-R	{4,1,4}	30	
S-S-FB	{4,3,4}	34	* Best Solution
S-S-LR	{4,4,1}	27	
S-R&R-R	{4,0,4}	28	
S-R&R-FB	{4,1,4}	30	More Expensive than Service
S-R&R-LR	{4,4,1}	27	
S-UO-R	{4,0,4}	28	
S-UO-FB	{4,1,4}	30	
S-UO-LR	{4,4,1}	27	
G-S-R			
G-S-FB	NONSENSE		
G-S-LR			
G-R&R-R	{0,0,4}	16	
G-R&R-FB	{0,1,4}	18	Unable to meet time objective
G-R&R-LR	{0,4,1}	11	
G-UO-R	{0,0,4}	16	
G-UO-FB	{0,1,4}	18	Unable to meet time objective
G-UO-LR	{0,4,1}	11	

Ratings		Weights	
Excellent	4	Very High	4
Good	3	High	3
Fair	2	Medium	2
Poor	1	Low	1
Unaccept.	0	None	0

[1] Systems are listed by basing, servicing, and modes of operation.
[2] Vector is listed by time, cost, and quality of data.
[3] Scores are based on weights of 3 for time, 2 for cost, and 4 for quality of data.

The ranking of alternatives begins by removing those systems that are not valid (ground-based, serviced in space). Next, space-based refurbished and relaunched systems are identified as dominated by serviced in space because of the expense of relaunching. Ground-based systems are unable to meet the goal of launching in three days, which counts heavily against them. The analysis showed that the long-range mode is least costly but offers the worst data. The rendezvous system offers the best data but at the highest cost. The space-based and serviced in space system using fly-by operations offers the best overall solution, with the rendezvous system being second.

The space-based inspection satellite that can be serviced in space forms the basis for further study. The choice of a rendezvous or fly-by mode will impact three areas: sensors, guidance, and propulsion requirements. The fly-by mode is the most demanding on sensors, while rendezvous is the most demanding on guidance and propulsion. The problem of sensor pointing and tracking appears soluble, while orbital mechanics will always require more fuel for rendezvous than fly-by (see Appendix E-5). Therefore, the study will continue with the basic preference of a system that can perform a fly-by inspection. However, rendezvous mode will continue to be investigated. This will allow the operator to decide the mode which is best for each particular space object. This choice of an overall design allows further refinement of the best subsystem design.

Subsystem Design

The goal of this next level of study is to identify the subsystems that should be used on the orbital inspection satellite. The three steps: systems analysis, optimization, and decision are combined in this section. This section outlines the process used to choose the subsystem design. Appendix D provides more extensive information on subsystems technology.

The design of an orbital inspection satellite is broken down into six major subsystems. These six subsystems were chosen to correspond to the standard disciplines that are used in spacecraft design. Spacecraft structure was not explicitly included in subsystem design since it is common to all designs. However the mass of the structure is included in the mass of the baseline vehicles in Appendix E-2. The six subsystems are propulsion, power, thermal control, guidance and control, communications and sensors. The interaction between these major subsystems were identified through a directed self-interaction matrix.

The interaction matrix shows the relationship between each subsystem in a pairwise fashion. The directed interaction matrix shows cause and effect relations and not merely that a relation exits. Three levels were used to discribe the interaction strong, moderate, and none. To interpret the chart, the subsystem on the left side

Subsystem: Directed Interaction Matrix

Legend

S - Strong
M - Moderate
Ø - None

Interaction ↑

	Propulsion	Power	Thermal Control	Guid. & Control	Communications	Sensors
Propulsion	Ø	Ø	Ø	Ø	Ø	Ø
Power	S	Ø	S	Ø	Ø	Ø
Thermal Control	Ø	M	Ø	M	Ø	Ø
Guid. & Control	Ø	M	Ø	Ø	S	M
Communications	M	M	M	Ø	Ø	Ø
Sensors	M	S	M	M	S	Ø

Figure 3. Subsystems Interaction Matrix

interacts with subsystems on the top of the matrix. For example, thermal control systems use power to heat the spacecraft; therefore, thermal control moderately interacts with the power production system.

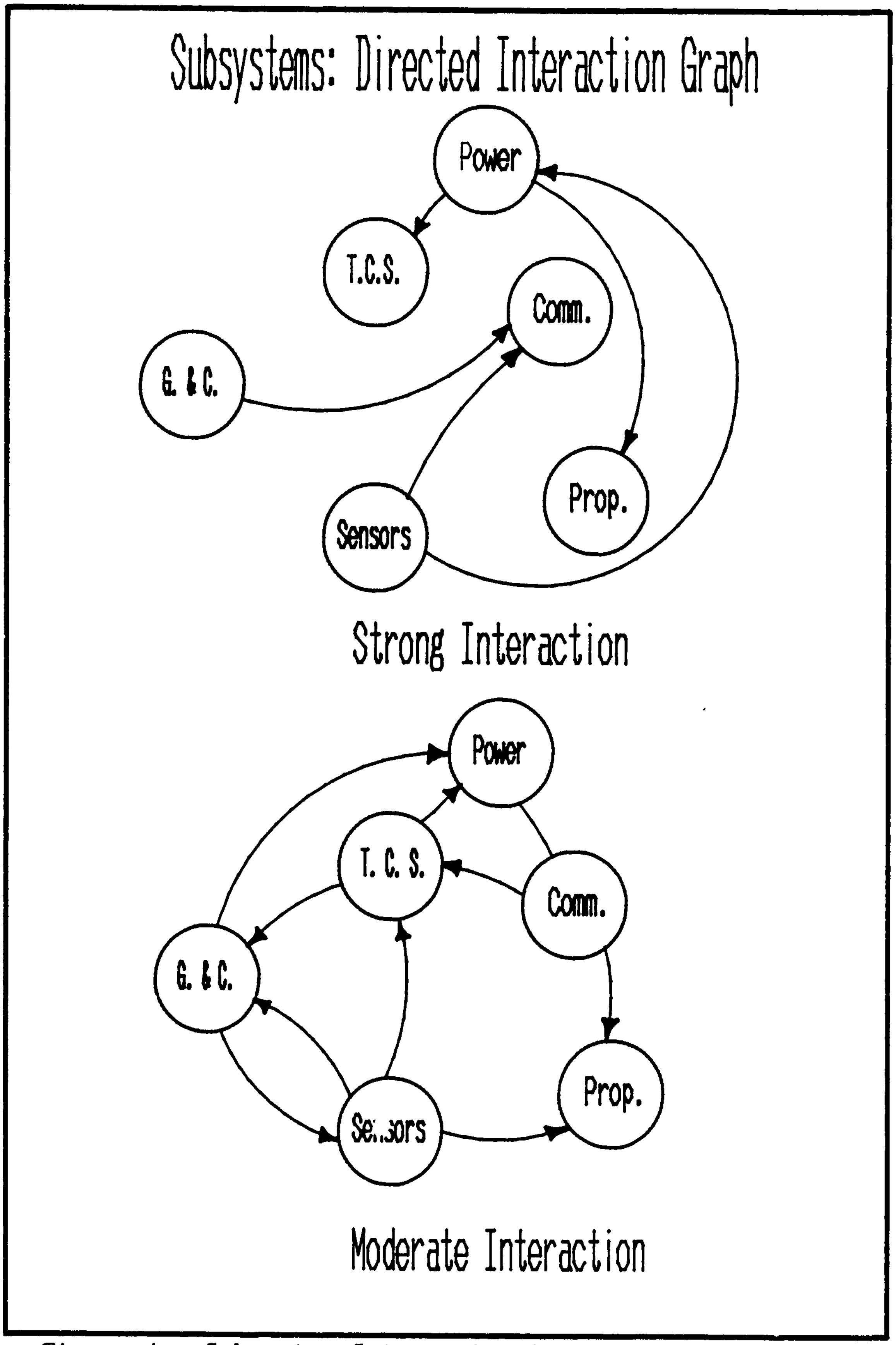


Figure 4. Subsystem Interaction Graphs

Once the matrix has been formed, an interaction graph is formed which is easier to interpret visually.

Since all subsystems are interrelated it is necessary to chose certain subsystems before analyzing the next subsystem. The choice is between competing hardware or functional designs. The six major subsystems are the key elements in the design of the satellite. These subsystems will be evaluated in the order dictated by the directed interaction graphs. The graphs show that sensors affect every other subsystem in the design. Therefore, sensors are analyzed first. As guidance and control is not strongly driven by any other subsystem it is studied second. Communications, which is driven by sensors and guidance and control is studied third. Power is studied fourth. Finally, propulsion and thermal control are analyzed.

Sensors. The selection of the sensor subsystem is done in a three step process. The first step in sensor selection is to identify the key characteristics for sensing a space object. This is contrasted with a philosophy to sense everything possible which would prove very expensive. The second step is to identify sensors which could observe these key characteristics. The third step is to chose the best sensors from those available. The selection was made on three criteria: best able to sense desired characteristic, least power required, and lowest mass. For each characteristic, several attributes which a sensor should exhibit were identified. Minimum power is desirable because for every additional watt of power, additional power generation equipment must be built with additional mass. This additional mass reduces the delta-V available for rendezvous or fly-by. These criteria are directly related to the overall measures of effectiveness of the inspection satellite.

<u>Key Characteristics of a Space Object</u>

1. Visible image.
2. Size.
3. Material.
4. Temperature.
5. Communications.
6. Emissions.
7. Mass.

A high resolution image of the space object would significantly improve the identification of components and space systems. The size of a space object is important for understanding its operating characteristics. Certain operating characteristics, such as the power of solar arrays can be determined from the size. The material used in construction gives an understanding of the function of some components. The temperature profile provides valuable information on the type of power generation and the cooling requirements of sensors. A knowledge of the communications system of the space object enhances the understanding of its function. The space object may emit radar, light, or atomic particles. This data provides an insight into the inner working of the space object. The mass of the vehicle is useful in determining the amount of propellant on board and the composition of the components. When all of these individual characteristics are observed, the true function of a space object may be discerned.

The rating of all sensors were based on a scale of zero to four for each attribute (or property). These attributes were weighted on a scale of zero to four to reflect the relative importance in sensing the key characteristics (see Alternative Rankings for the definition of the scale).

Visible Image. There are several sensors that are suitable for space-based imaging systems. Three competing sensors, film, charged coupled device (CCD), and Vidicon systems are considered. For the visible sensor, the attributes of resolution, power consumption, mass, frame time, return time, and sensitivity are considered. The property of pixel size is used as a surrogate measure for resolution. Each attribute is weighted to reflect its relative importance in the design.

TABLE VIII

Visible Image (22:335; 41:42; 49:274)

Type	Res.	Power	Mass	Frame-Time	Data R.	Sens.	Total
Film	4	3	2	3	0	3	41
CCD	3.5	3.5	3	4	4	3	61
Vidicon	3	2	3	3	4	3	53
Weights	4	2	2	3	4	2	

The CCD camera was chosen as the best imaging system. It offers real time return of data and high resolution for low power and mass. The film offers excellent resolution but the data is not real time. The overall requirements are 23 watts of power and 65 pounds.

Size. In order to determine size, the visual image must be correlated to range information. Two systems were considered: laser-ranging and radar-ranging systems. The attributes considered for the ranging system are power consumption, mass, and range accuracy. Each attribute was weighted to reflect its relative importance in the design.

TABLE IX

Range Instruments (16:248; 30:245)

Sensor	Mass	Power	Accuracy	Total
Laser	4	4	4	40
Radar	2	1	3	19
Weights	3	4	3	

The laser-ranging system was chosen for its low power and mass and high accuracy. The overall requirements are five watts of power and 10 pounds.

Material. Discerning the material used in a space object is a difficult challenge. Without taking a satellite apart or taking an x-ray, there is little hope of determining the composition of the vehicle. However, it is possible to determine the composition of the exterior of the space object through spectrographic analysis of reflected sunlight. The proper instrument for this task is a spectroradiometer (a device which measures the intensity of light over various bands). The use of a magnetic anomaly detector would be helpful in determining the overall content of ferrous metal on the spacecraft. Two typical devices are described below.

TABLE X

Sensors for Material (41:458; 19:734)

Skylab S191 Spectroradiometer	
	403 pounds
	200 watts
DHAX-3 Magnetic Anomaly Detector	
	32 pounds
	30 watts estimated

The S191 instrument is an instrument used for remote earth sensing. It contains additional gear that would not be necessary for the inspection satellite. An estimated 50% savings in mass and power would result from a redesign of the actual space gear. Therefore, the two sensors could be built for an estimated total of 120 watts and 250 pounds.

Temperature. The temperature of the space object could be determined through the use of infrared sensors. The infrared sensors must be sensitive to the frequency of energy emitted by radiation. Wein's displacement law is used to calculate the wavelength at which maximum energy is emitted.

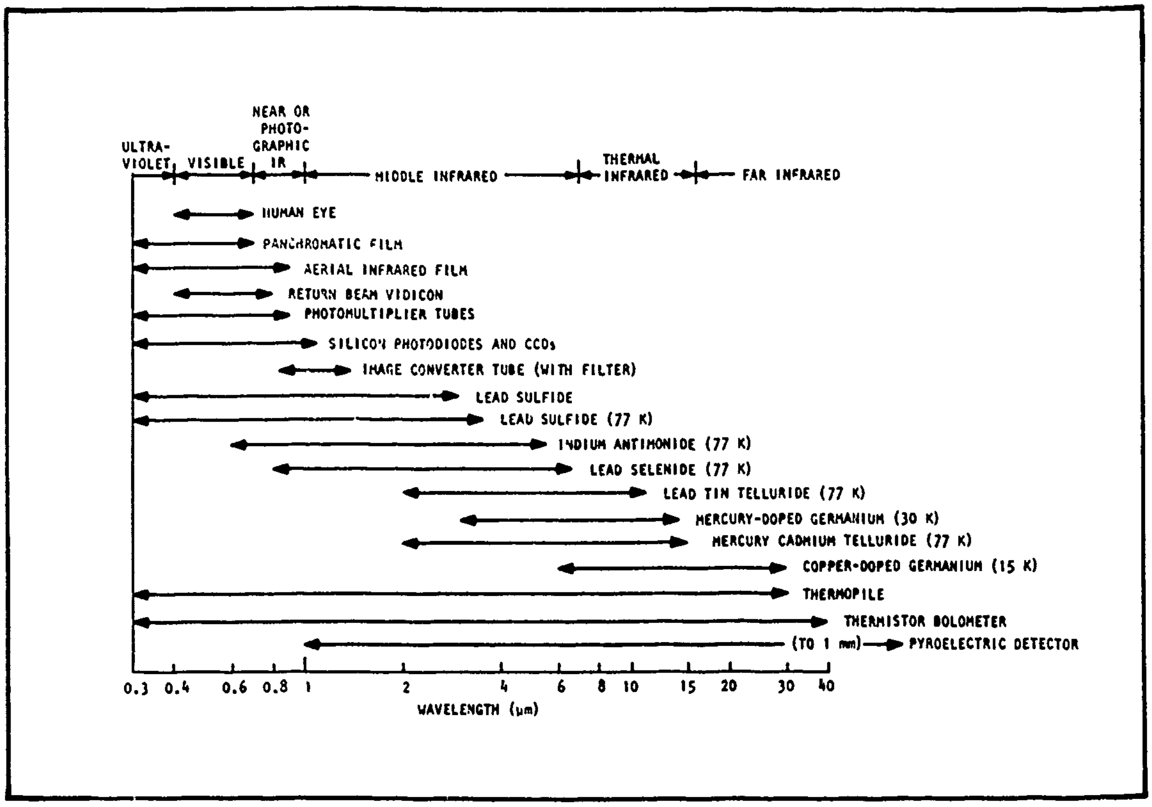


Figure 5. Infrared Sensors (41:403)

$$\lambda_{MAX} = 2897.8 / T \qquad (4)$$

where

T is temperature in degrees Kelvin
λ is in μm

TABLE XI

<u>Typical space objects</u> (5:74)

Spherical Spacecraft	280°K ->	10 μm
Nuclear Power Radiator	700-1000°K ->	3-4 μm
Cold Sensors	77°K ->	38 μm
Very Cold Sensors	10°K ->	289 μm

Infrared sensors must have the following properties: power consumption, mass, spectral resolution, frame time, data return time, and sensitivity. The above figure illustrates some suitable sensor types.

Two systems, a CCD imaging system and a semiconductor Ge(Zn), were chosen for further investigation. The CCD infrared sensor offers low power consumption, rapid frame time, good spectral and spatial resolution, but with limited sensitivity (.4 - 12.5 μm) (23:98). The Ge(Zn) device offers good sensitivity (2 - 40 μm) and rapid frame time, but requires a cyro-cooler to lower the sensor to 5^{0}K. The overall design could be a combination of sensors in the 1-40 μm band or a single sensor with a requirement for active cooling. The estimated requirements are 10 watts of power and 40 pounds.

Communications. A scanning receiver would gather the communications to and from the space object. The scanning receiver should be sensitive to the frequencies used today. Nicholas Johnson lists all the known operating frequencies of Soviet spacecraft in "The Soviet Year in Space 1985". These frequencies are listed below:

TABLE XII

Soviet Satellite Frequencies (MHz) (20:80-82)

20-30
137-248
400
926
1690
2300

Since no description of signal intelligence equipment for space-based operations exists in unclassified literature, ground-based equipment was evaluated as follows.

TABLE XIII

Signal Intelligence Equipment (19:597-601)

SR-1126 VHF/UHF Search Receiver Systems		
Power: 300 watts	Mass: 95 lbs	Freq.: 20 MHz-1.02GHz
SR-1195 VHF/UHF Analysis System		
Power: 220 watts	Mass: 77 lbs	Freq.: 20 MHz-1GHz
RA-1794 EW Receiver		
Power: 40 watts	Mass: 36 lbs	Freq.: 2 MHz-500MHz

In addition to signal reception, signal intelligence functions must also be performed. This function could be performed better by the ground support segment. This would reduce the power and mass placed in space with no impact on operations. The SR-1126 and SR-1195 are units that depend on commercial power or a mobile generator. The RA-1794 EW Receiver is a system used by mobile units where low power consumption is important. This reflects the "true" power consumption that a space-based system might have. The estimated requirements for communication sensors are 40 watts of power and 36 pounds.

Emissions. In addition to the reflected sunlight and the radiated thermal energy, the space object may emit particles and high energy electromagnetic waves. The use of nuclear power or nuclear material may be detected by appropriate sensors. Nuclear processes will create alpha particles, beta particles, x-rays, gamma rays, and neutrons. Of these, alpha and beta particles can be stopped easily by minimal shielding. X-rays, gamma rays, and fast neutrons are difficult to stop without massive shielding. When size and mass requirements are tight (nuclear submarines), alternate layers of lead and polyethylene are used (32:415). For space-based nuclear reactors, the mass of the shielding is significant. David Buden estimates that up to 30% of the total mass for a 100 kW nuclear reactor may be shad[illegible] shielding (protects only the payload).

The sensor system focuses on the detectors for x-rays, gamma rays, and neutrons. Since these emissions pass easily through shielding, they are difficult to detect. Gamma rays are extremely difficult to detect without massive detectors. They are difficult to focus with traditional optics. For instance, the gamma ray observatory being design by TRW will weigh 33,000 lbs and cost $480 million (42:62). Two prospective systems were investigated, one based on a germanium (Ge), the other mercury iodine (HgI_2).

TABLE XIV

X-Ray Detectors

Sensor	Power	Mass
Ge(Li)	150 watts	150 pounds
HgI_2	3 watts	3 pounds

The Ge detector requires active cooling and hence uses more power and mass. The HgI_2 detector requires no cooling and hence requires less power and mass. The germanium based system is ready today; while the mercury iodine system is still under development.

No statistics are available for space-based neutron detectors. Although, "No neutral particle detectors have yet been flown by NASA, this technology is both available and suitable for future missions" (23:203).

The overall requirements are based on the Ge detector and its cooling system. This is estimated to require 150 watts of power and 150 pounds.

Mass. No suitable non-intrusive methods were identified to determine mass. Mass could be determined by accelerating a vehicle with a known force, or by attaching a known mass to the space object. These methods are illegal under space law. Variations in the gravity field caused by a 2000 to 20,000 pound space object could not be measured by any device. One possible system would be an x-ray source and detector to form a CAT scan of the space object. This scheme would involve two spacecraft and a cooperative target. The x-ray system was considered too expensive and complex, and it relied too heavily on target cooperation. Therefore, no method was determined suitable for the inspection satellite.

Sensor Summary. Seven characteristics of a space object were Identified for the inspection satellite to observe. Sensors were identified for six of the seven characteristics. Each sensor exhibited certain attributes which were weighted and scored to select the best sensor. When space-based hardware was available, the sensors were competed directly. When no space-based hardware could be identified ground-based hardware was evaluated and estimates for a space-based version is given. The following table is an estimate of the sensors and their mass and power requirements. The total budget for the sensor subsytem is estimated below.

TABLE XV

Sensor Summary

Characteristic	Sensor	Power[1]	Mass[2]
Visible Image	CCD Camera	23	65
Size (image)	Laser Ranger	5	10
Material	Spectrometer	120	250
Temperature	CCD, Ge(Zn)	10	40
Communications	Elint Receiver	40	36
Emissions	Nuclear Detectors	150	150
Mass	none available	0	0
	Total	348	551

[1] power in watts
[2] mass in pounds

Guidance and Control. Guidance and control was selected in three steps: the choice of an operating method, the level of autonomv, and the determination of power and mass to implement these needs.

The first choice under guidance and control is the operating mode of the orbital inspection satellite. The three different modes of operation are: long-range, fly-by, and rendezvous would require increasing levels of sophistication. The fly-by mode was previously identified as the best mode of operations. A separate but related issue is the level of autonomy for the satellite. The level of autonomy that is appropriate for the orbital inspection satellite is the minimum level that will not adversely affect the mission. This places most of the sophisticated computer power on the ground and not on the spacecraft.

The level of autonomy that meets the primary measures of effectiveness is space-based attitude and location determination, ground-based navigation, and proximity operations. The next step is to identify the proper hardware to meet these functions. The following table illustrates the guidance and control hardware used on the OMV which uses the rendezvous mode and ground control.

TABLE XVI

Guidance and Control (30:245)

GN&C Hardware	Power[1]	Mass[2]
Value Control Electronics	10	10
Inertial Measurement Unit	20	42
GPS receiver	50	51
Star Sensor	7	12
Sun Sensor	1	2
Horizon Sensor	6	4
Sensor Interface	5	7
Total	99	128

[1] power in watts
[2] mass in pounds

Communications. The communications system is the vital link between the ground and the space segment (see Appendix D). The goal for this subsystem is to identify the power and mass requirements. Real time data return is the only method that could meet the objective of three days for data return. Therefore, it is considered the baseline for this subsystem. In order to decrease the demand on the communications subsystems, temporary storage of low priority data is desirable. The following are typical values for communications hardware used on the OMV.

TABLE XVII

Communications Hardware (30:225)

Subsystem	Power	Mass
Communications	89	186
Data Management	151	124

[1]power in watts
[2]mass in pounds

The total estimated for the communications requirements is 240 watts and 310 pounds.

Power. The power subsystem choice for the orbital inspection satellite is based on two criteria. The ability to produce power throughout the period of operation and the highest ratio of power to mass in the predicted range for demand (approximate peak load 700 watts). Although Appendix D contains a more complete discussion, the following table summarizes the three competitive power generation systems.

TABLE XVIII

Power Generation Systems (2:1.7)

	Watts/lbs	
Generation Type	present	1990's
Solar/Battery	3-5	6-8
Advance Nuclear	---	20
RTG	1-2	3-4

Fuel cells and batteries were eliminated because of the limited lifetime of such systems. Solar Dynamic systems (reflecting mirror and power plant) have two disadvantages, the precise pointing requirement and the large mass of the turbo-machinery. This makes solar dynamic systems unattractive for small power demands. Nuclear power will offer improvements over solar/battery systems in the near future, but only when large amounts of power is required. At the power level needed, solar/batteries offer the best power to mass ratio (12:10; 2:1.5).

Propulsion. The propulsion subsystem was chosen on the basis of five criteria which can be related directly to measures of effectiveness: lifecycle cost, transit time, and quality of data. These propulsion attributes are transit time, overall efficiency, controllability, contamination, and level of development. Transit time was determined by the level of thrust available (48:466). Overall efficiency is a ratio of power-in to propulsion-out (48:42). The controllability is the ability to restart and throttle the engine. Contamination is based on the exhaust gases of the engine. State of development is graded 4 for extensive use, 3 for limited use, 2 for advanced development, 1 for prototype, 0 for concept. For each criteria a value from zero to four was assigned. Each attribute was weighted relative to its importance in the overall design. Each propulsion subsystem was given an overall score based on the sum of the values times the weight. The selection is based on the subsystem that had the highest overall score.

TABLE XIX

Propulsion Subsystem

Propulsion Type			Transit Time	Overall Efficiency	Control	Contam.	State of Develop.	Overall Score
Chemical	Solid		Excel	Good	Poor	Poor	Excel	45
Chemical	Liquid	Hot	Excel	Excel	Excel	Poor	Excel	61
Chemical	Liquid	Cold	Good	Good	Excel	Good	Excel	55
Non-Chemical	Electric	Contact	Poor	Fair	Excel	Fair	Good	39
Non-Chemical	Electric	Resist	Poor	Good	Excel	Excel	Excel	48
Non-Chemical	Electric	ARC	Poor	Fair	Excel	Excel	Poor	35
Non-Chemical	Electric	Bomb	Poor	Fair	Excel	Excel	Good	41
Non-Chemical	Nuclear		Good	Good	Good	Poor	Unacc	37
Non-Chemical	Solar		Unacc	Excel	Poor	Excel	Fair	27
Weighting			4	4	4	1	3	—

Ratings: Excellent 4, Good 3, Fair 2, Poor 1, Unacceptable 0

Weighting: Very High 4, High 3, Medium 2, Low 1, None 0

The above table summarizing the results for the propulsion subsystem of the orbital inspection satellite. The best subsystem is liquid-fueled because it exhibits excellent transit time, overall efficiency and a high level of development.

Thermal Control. The thermal control system choice was between active and passive designs. The choice was based on the least mass and power required to achieve the needed temperature control (see Appendix D). The need for sensors that do not require active cooling has been discussed. These needs were considered under the sensor subsystem section. No attitude control techniques are used to give the satellite unlimited maneuvering. The primary need for thermal control is the fuel which must be heated to prevent freezing. The second problem area is the heat that must be rejected from the batteries. The total for heaters, thermal blankets, and external coatings on the OMV is an estimated 38 watts and 104 pounds (30:143).

Subsystem Summary. Once the system design was fixed, futher refinement of the subsystems began. However, the overall system design was based on preliminary analyses of subsystems. The first procedure was to identify how the six major subsystems worked together. Through the use of directed interaction graphs, the effects of one subsystem on another could be visualized. This prompted the study to preceed in a particular sequence. The analysis first looked at subsystems which had strong influence on other subsystems and next subsystems which had moderate influence on other subsystems. Subsystems were chosen by either picking the best hardware or the best functional approach.

Sensors were the subsystem with the strongest influence on other subsystems. The sensor analysis began by identifying seven key characteristics that should be sensed by an inspection satellite. Sensor types or actual hardware were identified for six of the seven characteristics. No practical method could be used to determine mass. Table XV summarizes the results of the sensor subsystem analysis.

Guidance and control was analyzed second, selecting the hardware to support the particular mode of operations. The second issue was the level of autonomy that the satellite possesses. Limited autonomy on the satellite was chosen since it did not impact the operational mission.

The communications subsystem would receive commands and send sensor data to the ground. Real time systems were determined to be better suited for the mission. Typical values for the mass and power consumption of the communication subsystem are given in Table XVII.

The power system selected was a combination of solar power and battery storage. This combination offered the highest power to mass ratio of any power systems in the predicted demand range.

A liquid fueled inspection satellite proved the best choice, meeting all criteria for a propulsion system. Liquid fueled system offered high thrust with high efficiency.

Thermal control analysis identified the advantages of a passive means of thermal control. An estimate of the mass and power requirements for thermal control is given.

All subsystems analyses reinforced assumptions made on the baseline vehicles and on the choice of an overall design.

IV. Conclusions and Recommendations

Conclusions

The requirement for orbital inspection will increase as the United States puts more emphasis on space systems. The inspection satellite would achieve three major goals: detection of threatening space objects, object identification, and spacecraft fault diagnosis. Ground-based systems could be improved but have inherent limitations. They cannot provide all the information that a space-based system could provide. The orbital inspection system could provide useful information to the decision maker in a timely manner.

Systems engineering was chosen as an appropriate methodology to design an orbital inspection satellite. Systems Engineering was able to impart a greater understanding of the orbital inspection system and its complex interactions. The analysis was conducted at the first phase, program planning. The study was conducted through the seven steps of the logic dimension.

The legal and historical context of the orbital inspection satellite was described. These two factors have heavy impact on the design and operation of [illegible]lite. Space based inspection is legal when it does not inte[illegible] with the normal operations of the space object. The range at which the mere presence of a inspection satellite constitutes interference is debatable. The legal framework and protocols for inspection could be better defined through negotiation.

The preliminary design of an orbital inspection satellite began in the early 1960's. The project was cancelled when treaties decreased the perceived threat from space. The satellite inspector (SAINT) was also cancelled because it combined the function of inspection and satellite destruction. This design philosophy, although very cost effective, was politically unsupportable. Today as we rely more on space-based systems, the need for a satellite inspector is apparent. In addition to threat detection the new economics in space, provides incentives for inspection and repair of very costly space-based systems.

In the first step of problem definition, the exact nature of the problem was identified and scoped. Needs, alterables, and constraints were identified and related. The second step was the value system design, the primary objective: to provide useful information to the decision maker in timely manner, was complied from several supporting objectives which were identified and related to the needs, alterables, and constraints of the problem definition step. During the third step, system synthesis, eighteen different orbital inspection designs were described. They resulted from the three basic design choices: basing mode, servicing mode, and mode of operations.

Systems analysis was conducted through the use of several models. A baseline inspection mission was created to compete all systems at the same level. A baseline vehicle was created for each of the modes of operations. These models provided inputs to the effectiveness of each design. The space-based inspection satellite that can be serviced in space is the best system design. The fly-by mode of operations is the best method of operations. However, if very high quality data is required regardless of cost, the rendezvous mode is preferred.

After a basic design was chosen (space-based, serviced in space, fly-by mode), the subsystems design began. Subsystems were partitioned into six areas: propulsion, power, thermal control, guidance and control, communications, and sensors. Sensors were shown to be the driving force among the subsystems. Sensor components identified conform with six of the seven key characteristics (visible image, size, material, temperature, communications, emissions, and mass). A typical list of guidance and control equipment was listed along with associated mass and power requirements. The mass and power for the communications subsystems were determined. Solar/battery power was chosen as the best power subsystem for the inspection satellite. A liquid propulsion subsystem exhibits superior performance over other choices. A thermal control subsystem using passive control along with limited heaters for the propellant tanks was identified. There is technology currently available to support the development of and orbital inspection satellite. The orbital maneuvering vehicle will provide many of the subsystems and much of the technology required for the orbital inspection satellite (see Appendix F).

Recommendations

The system and subsystem design sections identify the type and components that would be used for an orbital inspection satellite. The best satellite inspector uses space-basing and can be serviced in space. It will use the fly-by mode of operations. The decision was based on three measures of effectiveness: time for data return, cost during the life of the program, and quality of the data. The measures of effectiveness were calculated using low fidelity models which capture the essential features of the problem. However, higher fidelity models should be created to enhance the accuracy of the results. These higher fidelity models will be important during future project planning and systems development phases. There are two key models which should be refined: the missions per vehicle model, and the dynamics of data collection model. The missions per vehicle model should consider better management of limited propellant to inspect a larger number of space objects between refueling. A more refined model of the dynamics of data collection would exhibit the interaction between fly-by trajectory and range, range rate, and angular tracking data. These two models would greatly impact the mode of operations.

Current space-qualified hardware should be investigated for use with the orbital inspection satellite. Two current space programs provide the possibility for use as inspection platform: the orbital transfer vehicle, and space-based telescopes. See Appendixes F and G for a brief analysis of these systems. These systems have been deployed in space or are under development and could greatly reduce the cost of the program. However, these systems would require modifications to be suitable for use as an inspection satellite.

The orbital maneuvering system provides an adequate host for the sensor subsystem. An enhanced version of the OTV could meet the essential needs of an orbital inspection satellite. The baseline OTV will require enhanced power generation, and guidance and control subsystems to support a space-based inspection satellite. The development of the inspection satellite should build heavily on the research and development that has been done on the OTV.

The sensor subsystem is identified as the driving element in the design of the orbital inspection satellite. This area should be the focus of attention in subsequent studies. The goal should be to design a sensor system which captures the key characteristic of a space object for minimum power and mass. The tradeoffs between sensor types, power, and mass should be futher refined.

The choice of systems and subsystems design was based on the high value of a rapid rate of return, and high quality data. It is unlikely that the time requirement could be relaxed enough to make ground-basing a viable option. If the quality of data or if the completeness of data requirements were relaxed, the long range observation would provide a very cost effective mode of operations.

The program will cost a large amount of money to implement regardless of the design chosen. The next monies should be spent on the refinement of the sensor subsystems, because other subsystems show sufficient maturity to support the orbital inspection satellite. Even though there is a large effort to develop sensors for remote earth sensing and astrophysical research, the sensor design will produce requirements that are somewhat unique. Therefore, continued study and development of sensors is paramount. The sensor subsystem will prove the key factor in determining the time to deploy and the total expense of the orbital inspection satellite.

Two additional models would prove useful in the design of the satellite. One would quantify the power requirements during orbit storage and data collection. This model would describe the interplay between peak demand and steady state demand to quantify the ratio of batteries to solar collectors. The other model would refine the interplay between shielding nuclear material and the ability to detect nuclear material with sensors.

This study made no analysis of space objects that deliberctely camoflage or maneuver to frustrate the inspection satellite. It is doubtful that a space object could maneuver in time to avoid the fly-by mode of operations. The total time from propulsion burn to intercept is just 52 minutes. This would not allow sufficient time to detect a change in the inspection satellite's orbit and to maneuver the vehicle to be inspected out of position. Further, random maneuvers involve large expenditures of propellant.

The requirements for the inspection satellite have been established in this study. A methodology was proposed to alnalyze the system and its objectives. The impact of legal and political influences were described. A spaced-based orbital inspection satellite which can be serviced in space is the best design. No subsystem in the design of the orbital inspection satellite was identified as deficient. Sensor design is the critical subsystem and will significantly impact the design of all other subsystems. The development should proceed to the project planning phase with emphasis on the development of the sensor subsystem.

Appendix A

History of the Satellite Inspector

The concept of a satellite inspector is an old idea. The military has been interested in procuring a vehicle to inspect other satellites since the late 1950s. The initial Soviet launch of Sputnik produced concern that the Soviets would dominate the space area and upset the strategic balance (15:37). Senate Majority Leader Lyndon Johnson said that whoever controlled the "high ground" of space would control the earth (54:70) This fear was fostered by Nikita Khrushchev during a reception to honor cosmonaut Titov on 9 August 1961 when he said, "You (United States) do not have 50 and 100 mega-ton bombs. We have stronger than 100 mega-tons. We place Gagarin and Titov in space, and we can replace them with other loads that can be directed to any place on the earth" (45:75;41).

This method of deploying nuclear weapons in space became known as the Orbital Bombardment System. A nuclear weapon that could re-enter the atmosphere on radio command would be placed in a low orbit. A variation on this theme, the Fractional Orbital Bombardment System (FOBs), would involve placing a weapon into an orbit. The payload would then reenter the atmosphere on the first orbit. This system would avoid the current radar detection net. Most military planners believed that orbital bombs or FOBs offered very few advantages over Intercontinental Ballistic Missiles (ICBM) and had several disadvantages. Nevertheless, a crash program was started to develop an Anti-Satellite weapon (ASAT). Some ICBM boosters were pressed into service with nuclear-tipped warheads. These Thor Boosters and the Army's air defense Nike Zeus were deployed to Johnson Island in the Pacific Ocean.

The United States could not indiscriminately destroy every space object that flew over Johnson Island. There had to be some method to distinguish the nuclear bombs from the scientific and manned payloads. On 23 May 1960 Deputy Secretary of Defense James Douglas said, "We have embarked on studies to inspect satellites at close range in the interest of our own satellite operations" (45:47). This research program for a satellite inspector became known as SAINT. The program got new emphasis in November 1960 when an unidentified space object was detected by the North American Air Defense Command (NORAD). The existing ground-based sensors were unable to identify the object, and a program was begun to build better ground-based and space-based sensors for space object identification. As the United States attempted to improve its ground surveillance, it also started using reconnaissance satellites.

The United States began to rely heavily on reconnaissance satellites for Soviet intelligence after Francis

Gary Powers was shot down in a U-2 spy plane over the Soviet Union. At the 1960 Paris Summit, during a lecture on the U-2 incident, President deGaulle questioned Khrushchev about a Soviet reconnaissance satellite that just flew over Paris. Khrushchev broke in to say he was talking about airplanes and not satellites. He said any nation in the world who wanted to photograph Soviet areas by satellite was free to do so. After the Soviet ambassador to the United Nations dropped the customary objection to American espionage satellites, the future of intelligence satellites seemed assured.

SAINT had two missions: the primary mission was satellite inspection, and the secondary mission was to destroy the target satellite (35:8-4). It was logical to destroy the target if the inspection proved it was hostile. During Congressional hearings the Air Force stressed the need for inspection at close range before destruction. The Navy proposed an ASAT system using Polaris missiles with nuclear warheads to destroy objects in space that fly over submarine patrol areas (45:73). Like President Eisenhower, President Kennedy preferred a political agreement to arms in space. President Kennedy's administration approached Soviet Foreign Minister Gromyko and Ambassador Dobrynin with a proposal to prohibit stationing weapons of mass destruction in space on 17 October 1962 (45:87). As a consequence, on 3 December 1962 the Air Force announced it was cancelling

SAINT, but would continue to support research in this area and participate in NASA's project Gemini. The program cancellation seemed to be due to technical and economic reasons as well as political reasons (45:80). On 17 October 1963, United Nations resolution 1884 was adopted which prohibited weapons of mass destruction in space.

The Air Force's interest in space inspection continued with the Manned Orbiting Laboratory, which was an enhanced Titan booster launched into a highly inclined orbit from Vandenberg AFB. The laboratory had a large telescope for Earth observation and the capability for satellite inspection. The Air Force also had a Blue Gemini program to fly the basic Gemini vehicle with Air Force personnel. Both programs were cancelled when less expensive Big Bird reconnaissance satellites became available.

The development of the inspection satellite was initially fostered by the threat of orbital bombs during the 1950s; however, treaties resolved this concern. As the political perception of a threat from space objects changed, the motivation for an orbital inspection satellite fluctuated. Today, the United States is dependent on a few highly sophisticated satellites. Once again the need for an orbital inspection satellite is evident.

Appendix B

Legal Aspects of an Inspection Satellite

Background. The actions of any nation in space will be judged by two key measures: the existing treaties and agreements and international law. The legal framework found on the earth has been extended into space. There are five Space Law Treaties in force today, as well as several other bilateral agreements and arms control agreements that restrict the use of space. The five Space Law Treaties were created under the auspices of the United Nations Committee on the Peaceful Uses of Outer Space. These five treaties are:

1. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, January 1967.

2. Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space, April 1968.

3. Convention on International Liability for Damage Caused by Space Objects, March 1972.

4. Convention on Registration of Objects Launched into Outer Space, January 1975.

5. Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, December 1979 (6:407).

Other notable agreements include the Nuclear Test Ban Treaty in October 1963 and several agreements on the multinational Communications Satellite Corporation (COMSAT).

These documents, along with and international law form the framework for actions in space. The inspection satellite will be examined in this framework.

__Use of Space__. The primary goal of all the treaties has been to promote the peaceful use of space and to provide equal access to all nations. The distinction between peaceful and hostile actions can become obscure. While most observers can identify offensive nuclear weapons as clearly illegal, reconnaissance, communication, and weather satellites are not provocative by nature and appear to be legal. However, all these systems have military capabilities during wartime (55:365). In his book World Peace through Space Law, Jerome Morenoff points out the foolishness of outlawing all systems that have any warfare capabilities (29:220). United States Ambassador to the United Nations Gore said, "There is, in any event, no workable dividing line between military and non-military uses of space" (45:70). Therefore, the United States has always pressed for agreements that stress the peaceful use of space rather than the Soviet position of non-military use of space.

The United Nations resolutions and subsequent treaties have adopted this peaceful use of space, which permits defensive military activities. Furthermore, since both the United States and the Soviet Union have relied on space systems for intelligence and surveillance since the mid-sixties, these satellites have defacto legality. In fact, when the Soviets had built an operational reconnaissance satellite, they dropped their objection to "espionage satellites" (45:71). These intelligence satellites are defended by the United States as being required to insure compliance with arms control treaties. This right to use satellites for treaty verification was codified in the ABM treaty "as a commitment of the parties not to interfere with each other's national technical means (NTM) of verification." However,this obligation only extends to those NTM systems utilized in a "manner consistent with general recognized principles of international law" (10:10). Intelligence satellites are also justified on the basis of self-defense (29:235). By using satellites, a nation can detect another nation's preparation for war.

Key Provisions. The 1967 Outer Space Treaty outlines several key points for the inspection satellite. The treaty states that space is the common property of mankind (*res communis*). This is a similar concept to "freedom of the seas". A space object is the property of the registered nation (launching or owning nation) (50:art 2). However, the space near the object remains free from claims of sovereignty. Some Soviet writers have proposed an exclusion zone to protect the sensitive instruments on satellites. V. D. Bordunov proposes a zone of security to surround a space object (3:89). Any other space vehicle that enters this zone must conform to previous stipulations. If the space object is threatened, it may take measures to protect itself from this threat. In his book, The Military Uses of Space, William Durch states that if a satellite is subject to interference, then a nation has the right to destroy the interference under article 51 of the United Nations Charter (15:177). This is not reflected in article 9 of the Outer Space Treaty, which permits consultation if a nation believes that their satellites may be interfered with by another nation's satellites.

B. G. Dakakov echoes Bordunov's concern for space vehicles that could be used to inspect, damage, or trap space objects (specifically, the U.S. Space Shuttle). He further states "a short duration stationing in the vicinity of the satellite, which as a rule is equipped with sensitive gear, may cause interference or substantially affect satellite performance" (14:100). This is contrasted to Article 10 of the 1967 Outer Space Treaty, which provides for the signature parties to be afforded an opportunity to observe the flight of space objects launched by those states. The nature of such an opportunity for observation and the conditions under which it could be afforded shall be determined by agreement between the states concerned.

There are activities that a satellite inspector could not legally perform. One would be the recovery of a derelict satellite for further investigation. The laws of space specifically reject the concept of salvage. A nation retains ownership of a vehicle from the time of launch until after re-entry. In fact, the vehicle will be returned at the expense of the launching nation (26:88). Another illegal activity would be docking, especially if that docking would affect the orbital parameters of the satellite. If the process of inspection would cause potentially harmful interference with activities of other parties of the 1967 Outer Space Treaty, then consultation is required (50:ART9).

Summary. There is no legal prohibition against a system to inspect satellites. However, the satellite inspector must not interfere with the normal operations of the space object. Also, it must not affect the flight trajectory of the space object. Although the Soviets have claimed an exclusion zone about their space vehicles, none currently exists in legal documents. Their objection seems primarily against the unique capabilities of the United States Space Shuttle for inspection and recovery. When the Soviet Space Shuttle becomes operational, the Soviets may drop this objection.

The United States can assert a right to inspect space objects under the principle of self-defense. The Cuban missile crisis demonstrated the need for observation to protect the national interest. A similar need was cited by the Eisenhower Administration following the U-2 incident. There is also a need for inspection satellites to verify existing treaties, since it is difficult to detect weapons of mass destruction from ground-based sensors.

Certain Soviet payloads have caused damage to the environment. The radar ocean surveillance satellite is a nuclear-power spacecraft. Two of these spacecraft have accidentally returned to earth (36:457). A need to inspect this type of spacecraft could be asserted if it posed a hazard to the environment or space. There are numerous treaties which permit the observation of space objects and the inspection of space installations on celestial bodies. These inspections must be done on a reciprocal basis in an agreement reached between nations. The inspecting nation must give ample notice to avoid interference with normal operations.

The United States can assert their right to inspect space objects within the limits of current space agreements. This assertion should be based primarily on the right of self-defense. Furthermore, the United States can negotiate with the Soviets to establish a protocol for inspections that are covered by existing treaties (17:35). This inspection would be similar to current photographing of ships and aircraft operating on the high seas or in international airspace.

Appendix C

Ground-Based Sensors

The United States has assembled a large number of ground-based sensors for space surveillance. These sensors operate in three bands of the electromagnetic spectrum: microwave, infrared, and visible. These sensors are limited to particular bands due to the transmission qualities of the atmosphere. The molecules and atoms that compose the atmosphere selectively absorb and attenuate many of the frequencies of the electro-magnetic spectrum. The areas of the spectrum that are not absorbed are called windows. Windows exist in the visible band, portions of the infrared band, and the microwave band. Through these windows, energy can be passively received by detectors or actively utilized by transmitter-receiver systems. Sensors and active systems do not exist throughout the spectrum due to design and manufacturing limitations. Other areas of the spectrum are not covered by equipment of suitable power or efficiency. Thus, the atmosphere and sensor availability restrict the operational utility of ground-based sensors.

The ground-based sensor used by the United States in the microwave band is the radar. Several types of radar are used. The Ballistic Missile Early Warning System (BMEWS) radar is used to track intercontinental ballistic missiles

(ICBM's). There are phased array radars at Beale, Eglin, Otis, and Robins Air Force Bases used to detect Submarine Launched Ballistic Missiles (SLBM's). The Perimeter Acquisition Radar Attack Characterization System (PAR'') at Cavalier AFS, North Dakota, was designed as an anti-ballistic missile radar. In addition to their primary role, all of these radars contribute time to space surveillance.

There are radars dedicated to space surveillance located at Shimya, Alaska; San Miguel, Philippines; and Prinçlik, Turkey. Other radars used for surveillance are Millstone and Haystack, the research radars at Westford, Massachusetts. The missile ranging radars at the Western and Eastern Missile Test Ranges are frequently used for space tracking (1:12-12). This impressive set of radars provide tracking data on nearly all space objects and a limited identification capability.

Optical sensors are used for both tracking and identification. The two primary optical ground-based sensors in use are the Baker-Nunn Camera and the Ground-Based Electro-Optical Deep-Space Surveillance System (GEODSS). The Baker-Nunn Camera is a large telescope that uses photographic film. The camera can track the reflected sunlight from a basketball-sized satellite at geosychronous altitude. The system can also image objects in low earth orbit. However, because of the inherent limitations of film, the Baker-Nunn Camera is being replaced by GEODSS. GEODSS is a large telescope which uses a CCD to gather dim reflected sunlight. GEODSS has the ability to collect space object identification (SOI) signature data. There are five planned sites for GEODSS: White Sands, New Mexico; Taega, South Korea; Maui, Hawaii; Diego Garcia Island in the Indian Ocean; and Southern Portugal.

A ground-based sensor similar to the GEODSS is the Maui Optical Tracking and Identification Facility (MOTIF). This sensor operates in the visible and near infrared portions of the spectrum. The sensor uses solid state detectors to image objects in low earth orbit. The system employs several computers to detect objects that move against the star background. The system was used to search for the disabled Westar 6 and Palapa B-2 satellites after their payload assist motor (PAM) failed (34:130).

Limitation of Ground Sensors. All ground-based sensors are limited by three factors: transmission through the atmosphere, range to the space object, and relative motion between the ground site and the space object. These limitations affect the resolution and the signature available for analysis.

Resolution is determined for two areas, spatial and spectral. Spatial resolution is the more common term which measures how much fine detail can be seen (that is how far apart two objects must be before they appear as two distinct objects). Spectral resolution is the ability to separate two closely spaced colors or frequencies.

Spatial resolution is influenced by two design considerations. The first is the diffraction limit. As light passes through a small opening, the wave nature of light causes a diffraction pattern (Airy disk) to be imaged instead of a single point of light. These small disks are produced by all the point sources and must be spaced far enough apart to be seen as individual points. An accepted criteria for spatial resolution is the Rayleigh criteria, which is defined as (25:140):

$$\theta_0 \approx 1.22 \ \lambda / D \tag{5}$$

The formula shows that spatial resolution (θ_0) is dependent on the limiting aperture (D) and the wavelength of light (λ). The shorter the wavelength and the larger the aperture, the smaller the angular separation between point sources. This explains why imaging sensors are normally found in the visual instead of the microwave portion of the spectrum.

The second limitation is the individual size of the detector elements. For point sources to be separated, they must fall on two separate detector elements. Together with the focal length of the optics, the angular separation can be determined from the formula on the next page.

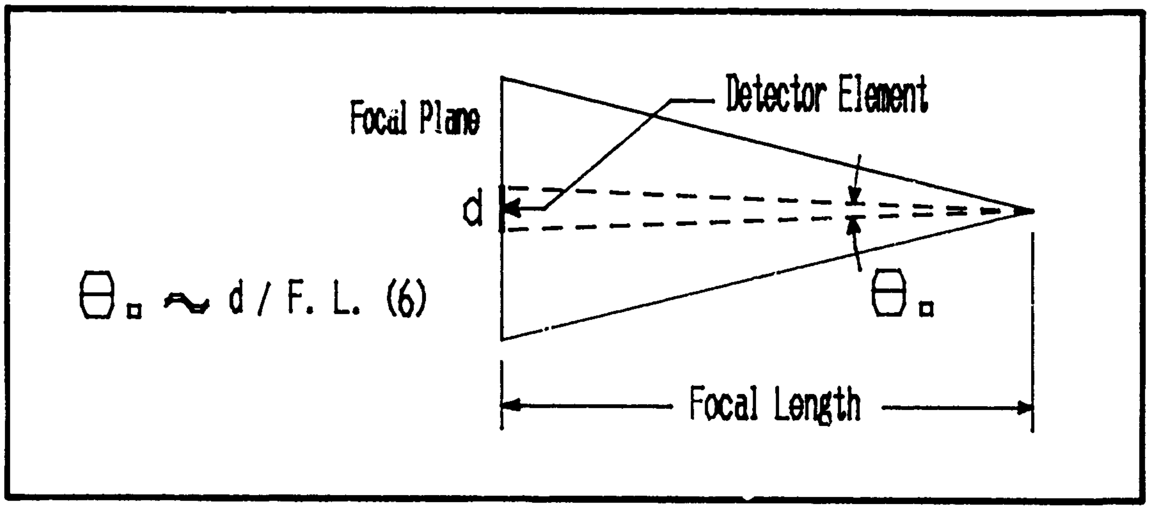


Figure 6. Spatial Resolution

There are practical limitations to the size of the detector elements:

Film 1 - 100 µm

CCD elements 5 - 30 µm

There are important tradeoffs between sensitivity and resolution. The relative motion between the ground and the satellite requires that a high speed film or detector be used. As a result, larger detector elements are needed to capture the quantity of light required during the brief exposure time. A more typical size for high speed detectors is 10 µm (25:II-A-7).

The optics of the detection system must conform to very precise tolerances to accurately focus the electromagnetic energy. This limit is normally about one quarter of the wavelength of the light. For very short wavelengths, this can be difficult to achieve.

Finally, the turbulence in the atmosphere limits the maximum resolution of ground-based sensors to $\theta_o \approx 1.212 \times 10^{-6}$ radians. This limit (seeing limit) restricts the resolution from ground-based sensors. Some typical values of spatial resolution for ground-based sensors are displayed below:

TABLE XX

Baker-Nunn Camera
20 in. Focal Length
5 µm Medium Speed Film

Range	Baker-Nunn	Ideal
100 km	.98 m	.13 m
250 km	2.46 m	.30 m
500 km	4.92 m	.61 m
1000 km	9.80 m	1.20 m
5000 km	49.20 m	6.60 m
15,000 km	147.00 m	18.00 m
36,000 km	354.00 m	43.00 m

From the table above, it can be seen that ground-based sensors have very little application for imaging beyond low earth orbit. The resolution is inadequate for fine detail.

Another limitation of ground-based sensors is the weather and lighting conditions. For most optical sensors, the object must be illuminated with sunlight while the sensor is shaded from the sun. This limits the amount of time the sensors can be used for tracking or space object identification. These limits are discussed more fully in "A Fortran Program for Deep Space Sensor Analysis" by Glenn Hasegawa. However, these limitations would not apply for a space-based inspection system.

Appendix D

Spacecraft Subsystems

The review of spacecraft subsystems concentrated on the six major functional areas necessary to construct an inspection satellite. These areas are propulsion, power supply, thermal control, guidance and control, sensor systems, and communications (see foldout p. 108). Spacecraft subsystems reviewed were either ready for flight or in an advanced state of development. The propulsion review was restricted to systems that can be used in near earth orbit, from low earth orbit (LEO) to geosynchronous orbit (GEO). The power systems investigated were solar voltaic, battery, fuel cell, and nuclear. For the thermal control system, passive and active methods of control were studied. The guidance and control review focused on attitude determination, position location, navigation, interception, rendezvous, and proximity operations. Also, in the guidance and control section, teleoperator (remote control) and autonomous methods of operation were investigated. The sensor section will investigate space-qualified hardware that can be used to effectively characterize a spacecraft anomaly or identify a space object. The review will only identify the general capabilities offered by different choices and not exact measures of the performance.

The goal of the spacecraft subsystems review is twofold: first, to identify which spacecraft subsystems are space-qualified or have reached an advanced state of development, and second, to explore the general capabilities of each subsytem choice and their relative value in the application to an inspection satellite.

Propulsion. Propulsion systems for spacecraft are normally partitioned into two functional types: primary and secondary propulsion. Primary propulsion is used for large orbital changes, while secondary propulsion is used to fine tune orbital maneuvers or compensate for small perturbation effects. The secondary propulsion system would be used during rendezvous and proximity operations where precise control is required. The orbital inspection satellite is unique in its requirement for large orbital changes to accomplish an intercept. This would place a high demand on the primary propulsion system.

The choice for propulsion design is divided into two areas: chemical and non-chemical types. The chemical types are solid, liquid, and hybrid. Solid propellant rockets are the type used in firework displays. The liquid types are hot gas (combustion) or cold gas (high pressure gas ejected through a jet nozzle). The hybrid is a combination of liquid and solid in a single rocket engine. Non-chemical engines include electrical propulsion, nuclear propulsion, solar sail, and several other future technologies (for example, fusion power).

The requirements of a propulsion system for the inspection satellite are moderate transit time, high efficiency (thrust/mass ratio), controllability, and low contamination. Moderate transit time to a space object should range from a few hours to a few days. Higher efficiency would allow more missions between refueling, and a wider range of orbits could be reached. Controllability would allow for multiple burns and fine control during proximity operations. The propulsion debris and gasses should not contaminate the space object or the space-based sensors.

The various propulsion systems offer a wide range of transit times. Electrical propulsion is inherently a low thrust system, which would cause long transit times (48:71). Chemical propulsion offers a high thrust level and hence, short transit times. The nuclear systems offer a range of thrust levels. However, no hardware has been tested in space, and little research has been conducted since the Nuclear Engine for Rocket Vehicle Application (NERVA) program (47:518) was cancelled in the late 1970s. The solar sail is a very low thrust system causing excessive transit times that would be unsuitable for this application. The other futuristic propulsion systems would not be available in the near future. The best type of propulsion technology for a short transit time is a chemical or nuclear type.

Propulsion types offer a wide range of efficiency. This study is concerned with the overall efficiency (thrust per pound mass of propellant and power plant) and not just specific impulse (a measure of thrust per pound mass of propellant). Therefore, the energy production system is counted as part of the electrical propulsion system. The chemical propulsion system offers a good overall efficiency. The chemical propulsion system produces thrust by direct conversion of the chemical energy stored in the propellant. The electrical propulsion system has a very high specific impulse. However, overall efficiency is average because of the need for a heavy power plant. Nuclear-powered engines offer outstanding efficiency due to the vast amount of energy stored in the fuel. However, these systems are usually quite massive and are difficult to scale down.

A nuclear electrical propulsion system has been proposed for use as an orbital transfer vehicle (OTV). This would use a nuclear reactor to produce electrical power which would drive an electric thruster (5:70). The advantage of this system is the combining of the functions of power generation and propulsion. However, the reduction in mass is offset by the long transit times associated with a massive system system driven by a low thrust system. This nuclear electric propulsion could deliver a 12,000 kg payload from LEO to GEO in 100 days (5:71). Future concepts offer the promise of vast improvements in overall efficiency but will not be available for a decade. The best choice based on propulsion efficiency, is chemical systems followed by electrical systems.

The propulsion system must be controllable to repeatedly achieve the requirements of intercept, rendezvous, and proximity operations. The solid chemical type offers very little control. The solid motor cannot be actively throttled and normally cannot be restarted. The liquid type offers good throttling and control. The ion thruster offers good control; however, its thrust is limited during proximity operations. The nuclear type has fair control, but fine thrust control during proximity operations is doubtful. The solar sail offers minimal controllability. The design which offers good controllability is the chemical type using liquid fuel or ion type.

A propulsion system which does not contaminate the space object is very important during proximity maneuvering. The nuclear systems in general pose severe contamination risks. Nuclear propulsion systems would expose the sensors to a high level of radiation which would obscure the radiation that the sensors are designed to detect. There are several concepts for radiation-free nuclear propulsion, but they have not been tested in the laboratory. The hot gas chemical system uses very corrosive chemicals which could damage satellites and sensors. The cold jet uses an inert gas which would pose minimal contamination hazard (30:52).

The electric engines expel ions at high velocity under electromotive forces. Some electric propulsive designs can use inert gas ions which would reduce the likelihood of contamination. The solar sail is non-contaminating, since it only uses high speed photons from the sun. The solar sail, cold jet, or electric propulsion using an inert propellant offer the lowest contamination potential.

The propulsion systems that meet the minimum requirements for the inspection satellite are chemical or electrical types. The chemical types appear limited to cold gas or liquid designs. The electrical types are limited to inert gas thrusters for contamination purposes. Because the mission can be divided in two separate phases, transit and proximity, the inspection satellite might use two different propulsion systems. This is the method pursued by the orbit maneuvering vehicle (OMV) using a hydrazine main thruster and cold jet for proximity operations (30:52).

Power. Space power systems have reached an advanced stage of development, and many systems are space-qualified. The following have all undergone space testing: solar voltaic, fuel cells, batteries, radio-isotope thermoelectric generator (RTG), and nuclear generators. The solar cell is the most common power system used today because of its low cost per kilowatt of power. The efficiency of the solar cells will reach 24% (energy output versus solar energy incident) by the end of the decade (40:1.33). The solar cell is not the final solution since all low earth satellites fly in the shadow of the earth. The solar cell is normally used with a battery storage system to provide power during occultation (earth eclipse).

Stephen Schiffer describes a battery which uses nickel-hydrogen cells (39:1.293). This battery design overcomes some previous shortcomings of batteries, such as limited recharging cycles and deep discharge (batteries could not be completely discharged and then recharged).

Fuel cells produce electricity from chemical reactions, usually an oxygen and hydrogen mixture. This system was used on Apollo missions and is currently used on the shuttle. It has a lifespan of a few weeks, when a reasonable supply of fuel is exhausted. The fuel cell can serve as an energy storage device by using electricity to produce oxygen and hydrogen. However, the fuel cell has not received extensive testing for extended storage and subsequent use.

The radioisotope thermal generator RTG system has been used by most deep space probes. It produces electricity from the heat of radioactive decay using thermocouples (a bimetallic junction that converts heat energy directly into electrical energy). Normal radioactive isotopes produce adequate power for three to seven years.

The nuclear reactor was only tested once in space by the United States. It demonstrated good capabilities to convert the vast amount of energy released during fission.

The nuclear systems appear to be the clear choice when a large amount of power is required (2:1.7).

The inspection satellite's need for power would vary during the mission. During orbital storage, only power for thermal control is required. The vehicle would require moderate power levels for communications and sensor equipment while inspecting space objects.

<u>Thermal Control</u>. The harsh environment of space requires that spacecraft be designed to operate in a wide range of temperatures. The sunlight side of a satellite will reach very high temperatures, while the dark side will reach very low temperatures. Satellites experience a rapid drop in temperature when they fly into the shadow of the earth. Certain spacecraft subsystems must be maintained within specified temperature ranges to function normally. For example, some infrared sensors must be cooled to 5^{0}K to reduce temperature-induced noise. The propulsion system may require heating to prevent the fuel from freezing. The electronics and power system may produce excess heat which must be dissipated. The function of a thermal control system is to regulate the temperature so that all systems remain within allowable limits.

There are two general classifications of thermal control systems: those that require the expenditure of energy (active) and those that require no expenditure of energy (passive). Passive systems are normally desired because they do not increase power requirements.

Passive systems use three basic principles: conduction, absorption, and radiation. Heat is conducted from the hot portion of the satellite to the cold portion, which equalizes the temperatures. One way this is accomplished is by spinning the satellite so that no side is constantly in the sunlight. This method evens out the temperature. By choosing the proper coating for a satellite, the desired temperature can be achieved. Absorption regulates the energy that is collected from the sun. Radiation releases heat to space by emitting electromagnetic energy. Nuclear reactors produce an abundance of heat that is radiated into space by large high-temperature panels.

If passive systems are unable to achieve suitable temperatures, active systems must be used. Active systems may employ heaters, refrigeration, louvers, or attitude control. Heaters convert energy into heat to keep certain components warm. Refrigeration may be used to cool sensors to very low temperatures. Louvered doors may be used to control the amount of surface area which radiates heat into space. Normally, louvers regulate the temperature of components on the interior of the spacecraft. Attitude control positions the spacecraft so that the portions which require heating are in the sunlight and those that require cooling are in darkness. All active systems require a control mechanism and energy for thermal control.

Thermal control is a key factor in any spacecraft design. With proper design, the mass and power used for thermal control will be minimal. The design of thermal control may place limits on the operations of the spacecraft, such as how long certain components can be activated or how long an attitude can be maintained.

__Guidance and Control__. The ability to control the spacecraft is critical to a successful inspection mission. The key areas of guidance and control (G&C) are position and attitude determination, navigation, and proximity maneuvering. These areas could be controlled by onboard systems or by ground control. The difference between the two design philosophies is the amount of complex equipment that must be placed in the inspection satellite and the amount of autonomy afforded the satellite. The area of G&C relies heavily on computers and navigation sensors.

The ability to determine attitude is demonstrated every day. All communication and earth-sensing satellites rely on sensors to accurately point antennas and remote sensors. These sensors take many forms; horizon sensors, star sensors, and sun sensors are typical (21:140). Without these sensors, attitude information could be determined from satellite receivers and ground transmitters. This technology is highly developed, and typical accuracy for a horizon sensor is as 5 to 10 arc-sec (arc-sec is 1/3600 of a degree), as quoted by M. A. Chory (7:30).

The problem of position location is more difficult than attitude determination. All methods employ more sophisticated sensors and computer power. There are several systems under advanced design or actual space use. The most common ones are the space sextant, multimission attitude determination and navigation system (MADAN), global positioning system receiver (GPS), and various combinations of star, sun, and horizon sensors. The best system for accuracy, according to the AIAA review of the navigation schemes, was the GPS system with 40 foot spherical error probable (9:369). Both attitude information and position information are required for the next aspect of G&C, navigation.

Navigation is a computer intensive job that takes current information about location and attitude and determines the propulsion commands necessary to move to another location. Under the heading of navigation are two key areas: intercept and rendezvous. Harry Erwin, in his article on Laser Docking Systems, defines rendezvous as "the maneuvering of the interceptor into the same orbit and phase as the target. Rendezvous requires that the interceptor match the target's position and velocity as opposed to interception, in the military sense, which merely requires that the positions be identical" (16:240). In order to accomplish the task of navigation, a computer is used to generate propulsion commands. The computer algorithm of choice is a variation of the Kalman filter (27:358; 28:9). This algorithm lends itself to rapid computation of simple orbital dynamics. Howard Hueberger discusses a GPS receiver and navigation computer that has performed well on Landsat 5 (18:147). Another operational system that has demonstrated rendezvous is the space shuttle. This system relies on ground tracking for its early rendezvous computation, and star sensors, radar ranging, and optical sightings during late rendezvous (8:108).

Once the inspection satellite has completed rendezvous, proximity operations begin. The maneuvering of a satellite around an object that is orbiting the earth is not a simple task. Stern has illustrated that in most computer simulations,the satellite collides with the space object (46:812). A collision by the inspection satellite could not be tolerated due to the high value of the inspection satellite and the space object. Vaughan and Bergman discuss the proximity operations of the space shuttle. They divide the proximity operation into four phases: position offset, fly-around, closure, and docking (52:518). The inspection satellite would primarily be concerned with the first two phases. During these proximity operations the inspection satellite would be stationed off at a controlled range and focus its sensors on the space object.

Sensors. Sensors are devices that extend the ability of humans to perceive nature. The human eye can only see a limited range of the electromagnetic spectrum, known as visible light. Sensors can expand the knowledge that was previously hidden from the natural senses. The orbital inspection satellite will use a collection of sensors to remotely "observe" a space object. The goal of the sensor review was to identify sensors that can measure all the key parameters of a space object. The sensor package should offer abilities that cannot be duplicated by ground-based sensors.

Sensing is conducted by two basic methods: active and passive. Active sensing uses a transmitter to direct energy at a target and a receiver to detect the reflected energy (for example: radar). Passive sensing involves only the receiving element (for example: the human eye detects the reflected light from objects). Space sensors have reached a high level of development for use on earth resources and astrophysical satellites. Many of these sensors will find application in the inspection satellite.

Sensors have different classes of outputs. Counters, which signal when radiation exceeds a certain threshold setting, are the least complex. Radiometric sensors measure the intensity of radiation. Imaging sensors form a picture of an object. The inspection satellite will use a combination of sensor classes.

Sensors have evolved and become more sophisticated. The current trend is to create sensors that are multi-functional with multiple detectors (23:7). These designs make more efficient use of power and mass on the spacecraft. Other advanced sensors are the "smart sensors". Roger Breckenridge defines smart sensors as those that combine sensing and signal processing into a single device (4:40). This provides greater efficiency because only the essential information is passed to the communication device.

Sensors may be designed to operate in a small area of the spectrum (narrow band) or a large area of the spectrum (wide band). When a particular frequency is desired, a narrow band instrument may be used. However, a wide band sensor may also be used with appropriate filters to limit the energy reaching the detector. Wide band instruments can do the work of several detectors with the correct selection of filters. Sensors also have degrees of spatial and spectral resolution.

A typical example of space-qualified hardware is the video camera used on the Voyager mission. It is a passive, wideband, imaging sensor. Each image frame contains 800 x 800 pixels or twice the definition of a high resolution IBM computer monitor (49:274). The narrow angle optics and camera head weigh 13.0 kg. The video signal is relayed to the ground for computer enhancement. The imaging system is designed to withstand the rigors of space flight and has continued to function for nine years.

Many sensors exist that observe the entire electromagnetic spectrum and detect atomic particles. Sensors are normally designed to observe a particular band of the spectrum or a particular particle. It is important to understand how the sensor functions and what is being observed. Each sensor has unique requirements for power, cooling, and data transfer. A survey was made of all sensor types, particularly those that would be useful on the inspection satellite.

Communication. Communication needs were divided into separate areas: uplink (information sent to the satellite) and downlink (information sent from the satellite). Uplink is normally command information which tells the satellite what to do. Downlink is normally sensor data, housekeeping data, and acknowledgment of command functions. There are varied methods for achieving this transfer of information.

Various frequencies of the radio spectrum are used for communication with the satellite. These bands include UHF, SHF, and EHF. There are communication systems under development which use laser light in the visible spectrum. A limiting factor in all satellite communications is the ground receiving network.

After the Apollo space program ended, the extensive NASA space tracking network was dismantled. As the economic and political expense grew, NASA looked for a more cost effective method of satellite tracking. This effort resulted in the four satellite constellation of Tracking and Data

Rely Satellites (TDRS) (one currently in service). These relay stations in geosychronous orbits will allow continuous communications with spacecraft that presently experience periods of blackout (no ground site within line of sight of the spacecraft).

Sensor systems can produce an enormous amount of information for the communication system to downlink. The use of a high resolution video camera is a good example of a communication need. An 800 x 800 pixel CCD array will produce 640,000 pieces of information. When this signal is digitized at eight bits per pixel (allows 256 levels of intensity), 5×10^6 bits of information result. This vast amount of data must be transferred for every frame of information. If a data compression scheme is used, the 8 bits per pixel can be reduced to an average 3.24 bits per pixel (22:336). Therefore, the design of any communication system will be affected by the quantity of data to be transferred.

Different operational schemes may be used on the orbital inspection satellite, with varied demands on the communication system. The least demanding would be a programmed mode of operation where only commands would be sent to the vehicle. The highest demanding would be with a remote control mode of operation with a high degree of feedback to the operator. Feedback would take the form of video pictures, range, range rate, and attitude information.

The data gathered by the inspection satellite must be returned for analysis. This information could be stored on the spacecraft (store and dump) or transmitted to a collection point on earth or in orbit (real time). Both methods have been employed with good results. The common media for storage are high density magnetic tape (HDT), computer memory, laser disk, and film. Film must be retrieved, and a suitable method has been demonstrated on low altitude photo-reconnaissance satellites. All methods seek to achieve reliable storage of the largest amount of data with minimal mass and power expended. The key benefits from storage of information are a decreased dependence on continuous communication with the ground and a decreased peak load on the communication system.

Summary. The inspection satellite will require six separate functional areas: propulsion, power, thermal control, guidance and control, sensors, and communications. These areas were investigated to find any factors that would make the inspection satellite unreasonable. All areas exhibited sufficient development to produce an inspection satellite.

Propulsion systems exist which are suitable. The best system will incorporate a mixture of short transit time, high efficiency, good controllability, and low contamination. Power supply can be accomplished by several different methods. The best system will deliver sufficient power for all subsystems with the smallest expenditure of mass. Thermal control is often overloked but has a key role in the life of a satellite. Passive and active systems are currently used on space vehicles. Guidance and control can be accomplished through the use of existing guidance sensors and computers. The important consideration is the amount of complexity required for the appropriate level of autonomy. Communication technologies offer a large selection of frequencies and techniques. The communication subsystem will transmit, store, and receive data. Space sensors are abundant and have a high level of development in several areas. The proper sensor will observe a desired characteristic with minimal power and mass expended.

The orbital inspection satellite is required to fill the shortcomings of ground-based sensors. However, the development of a satellite will involve several key technologies. During the subsystem review, no key areas were identified as deficient. All functional areas demonstrated that either space hardware had been tested or was in an advanced state of development. From the standpoint of subsystems the development of an orbital inspection satellite is a viable project.

Appendix E

Models

This appendix contains several models of the orbital inspection satellite. These models were created to facilitate the comparison of 18 alternative overall designs. These models are the cost model, the baseline vehicle model, the launch window model, and the observability model. In addition, a graph of the ratio of fly-by delta-V to rendezvous delta-V is provided.

Cost Model The goal of the cost model was to rank the alternative designs on the basis of cost. There was no attempt made to determine the precise cost of an orbital inspection satellite at this early phase of development. The lifecycle cost was determined by considering five separate cost areas: development, production, deployment, operations, and retirement.

The cost of development was determined to be similar for all designs, since all inspection satellites will use comparable technology. Therefore development cost was removed from the analysis. The production cost was based on NASA's estimated purchase price of 150 million for two OMVs and support equipment (24:354). A sliding scale was used to reflect large quantity purchase. The deployment cost was based on launch cost of $2000 per pound times the number of vehicles times the mass of each vehicle (31:42).

Each design was required to perform 25 equivalent missions per year for 10 years. These numbers were chosen based on a Soviet launch rate of 98 per year, and the authors subjective judgement that 25 percent of these launches would warrant inspection and to allow for other inspections for fault diagnosis.

The equivalent mission was a Hohmann transfer from a 330 km parking orbit to a 1500 km inspection orbit. The delta-V required and the delta-V available are given in Baseline Vehicle model. A total mission before refueling was determined by divided the delta-V available by the delta-V required.

All systems were tasked to complete 250 equivalent missions during the life of the program. The primary operational cost was the transfer of propellant to the inspection satellite. The rendezvous and fly-by modes were allowed ten refuelings before they were recovered for maintenance. The long-range satellite was given a four year life time after which a replacement would be launched. The designs which recovered and relaunched were charged 10 million dollars to retrieve the satellite.

The total cost for each overall design was computed and the results and analysis are displayed in chapter III.

Baseline Vehicle. A baseline vehicle for each mode of operations was created to allow comparisons. These vehicles reflect the mass allotted to propulsion, propellant, sensors, and other subsystems. The rendezvous mode has the highest percentage of propellant, while the long-range mode has the highest percentage of sensors.

Each propulsion subsystem is evaluated by equation (7) to determine the delta-V available. Each system is given an I_{SP} of 285 seconds which is typical of a chemical propulsion system (this appeared promising during initial research). The number of equivalent missions before refueling is determined by dividing the delta-V available by the delta-V for an equivalent mission. Finally the capabilities of four space boosters is provided for information.

<u>**Launch Window**</u>. The launch window model is used in the determination of the time to return data. The phasing problem is the particular case of an inspection satellite in a 330 km parking orbit and transferring to intercept or rendezvous with a target at 1500 km.

The calculation was determined from the worst case analysis launch (ie. just missed a launch window). The transfer orbit take 52 minutes to intercept the target. This time is used to determine the proper phase angle between the target and inspection satellite. By knowing the relative angular motion between inspection satellite and target, the maximum time between launch window is determined.

<u>Observability</u>. The observability model is also used in the determination of the time to return data. The long-range inspection satellite is placed in a 330 km orbit. In order to observe a target at 1500 km orbit the inspection satellite must have a clear line of sight above the atmosphere (100 km). A worst case calculation is performed to determine how long between observation times.

<u>Ratios of Delta-V</u>. The ratio of delta-V required to perform an inspection is displayed. The results showed that for zero inclination between the inspection satellite's orbit and the target's orbit, fly-by mode used about 60% of the fuel that a rendezvous would use. As the the inclination increased the delta-V required for a rendezvous grew rapidly while the fly-by stayed constant. This graph illustrates that for anything other than small inclinations, rendezvous mode of operations is very high user of propellant.

TABLE XXI

BASELINE VEHICLES

RENDEZVOUS

1,500	propulsion
10,000	propellant
1,000	sensors
3,500	power, comm, etc
16,000	total

Delta-V_{AV} = 2.74 km/sec[1]
Equivalent Missions ~ 4.5[2]

FLY-BY

1,000	propulsion
6,500	propellant
1,000	sensors
3,500	power, comm, etc
12,000	total

Delta-V_{AV} = 2.18 km/sec
Equivalent Missions ~ 7.2

LONG RANGE

500	tracking
1,500	sensors
3,500	power, comm, etc
5,500	total

Delta-V_{AV} = not a factor
Equivalent Missions -> not limited

[1] $\text{Delta-V}_{AV} = I_{SP} * g_c * \ln(MR)$ (7)

[2] Equivalent missions ~ $\text{Delta-V}_{AV} / \text{Delta-V}_{EQ}$

$\text{Delta-V}_{EQ\text{-}FB}$ ~ .303 km/sec
$\text{Delta-V}_{EQ\text{-}R}$ ~ .604 km/sec

Possible Launch Vehicles (44:172,174)

Shuttle	65,000	-> 200 km
Titan 34D	27,600	-> 185 km
Altas G	5,200	-> GEO transfer
Delta	2,800	-> GEO transfer

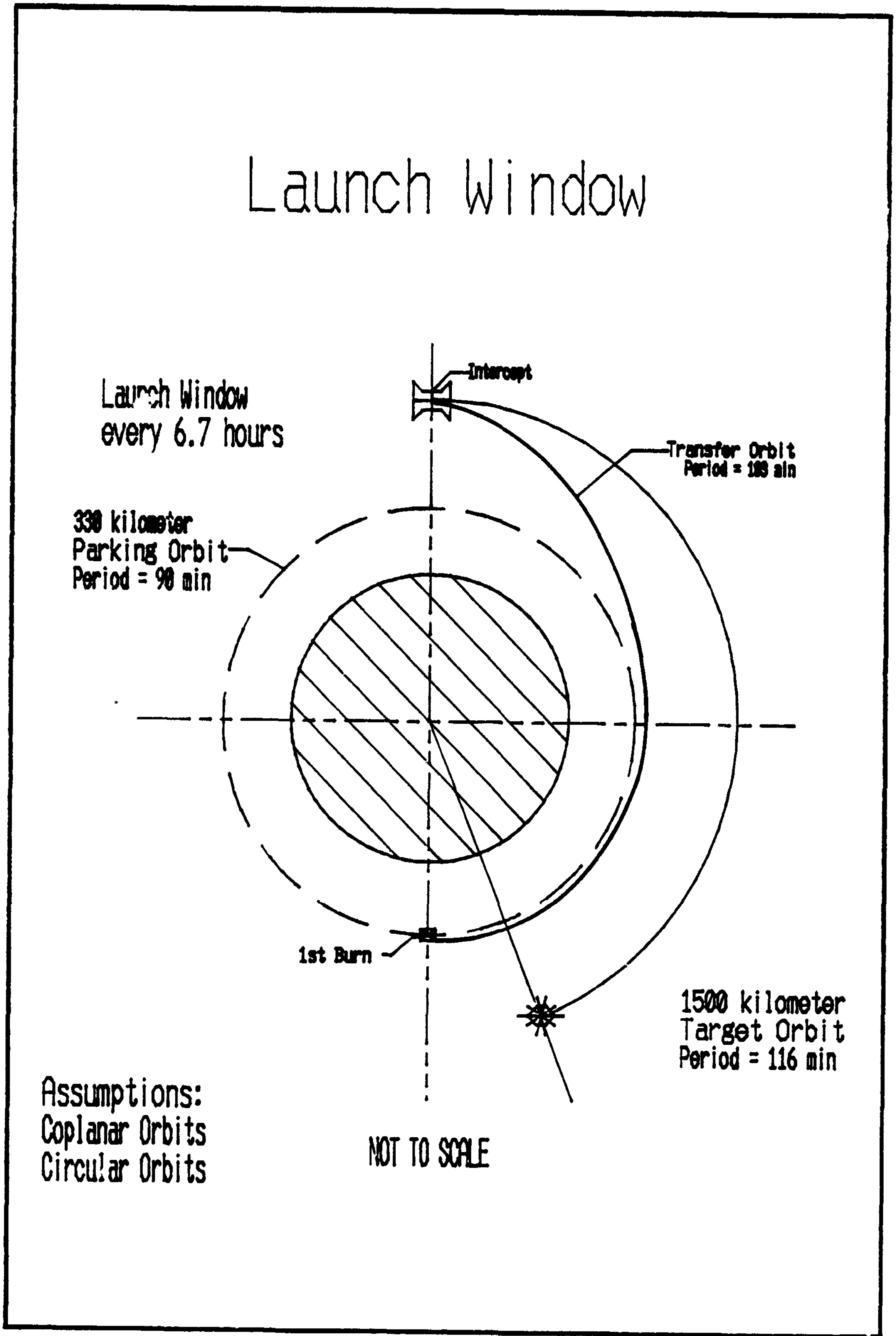


Figure 7. Launch Window

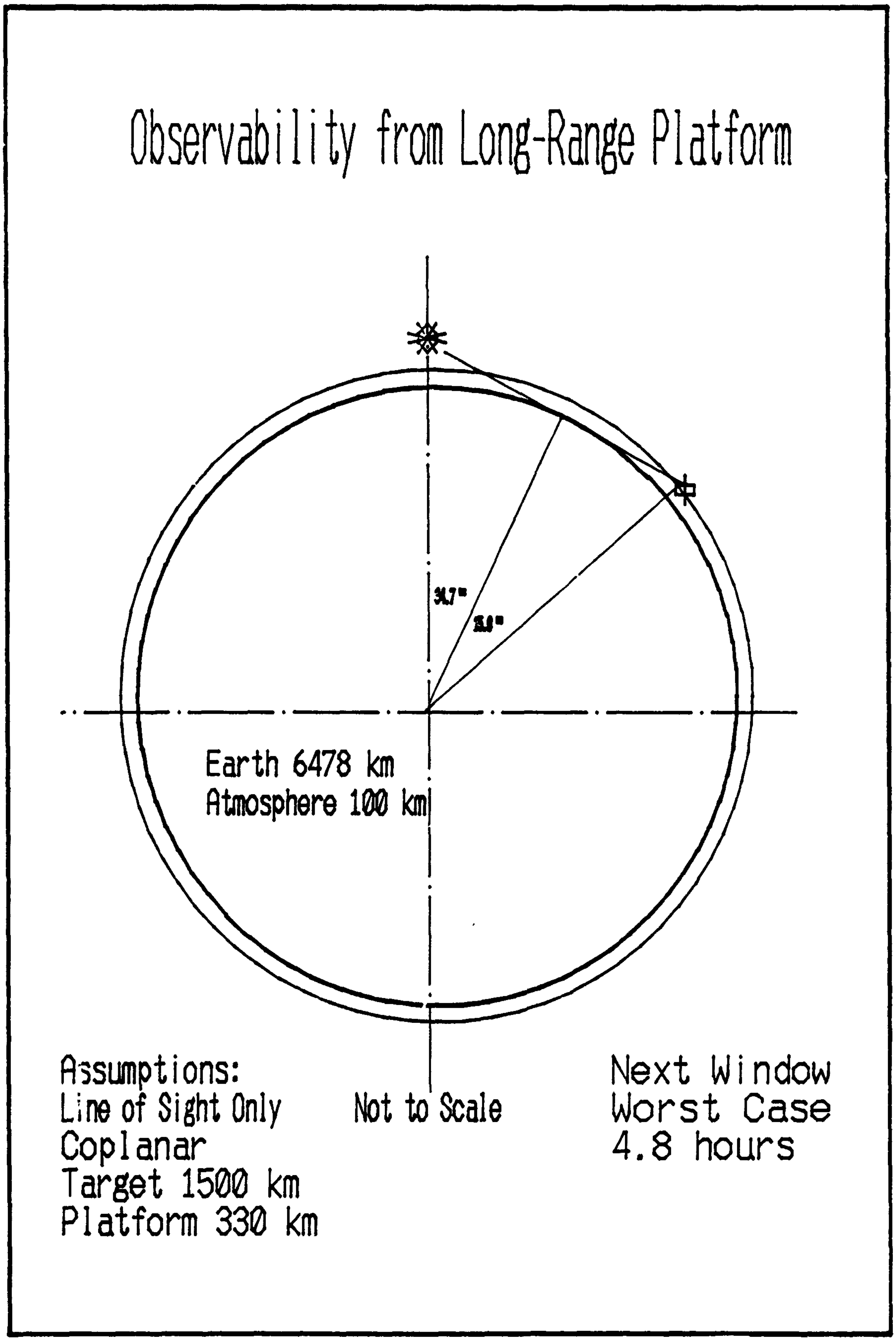


Figure 8. Observability from Long-Range Platform

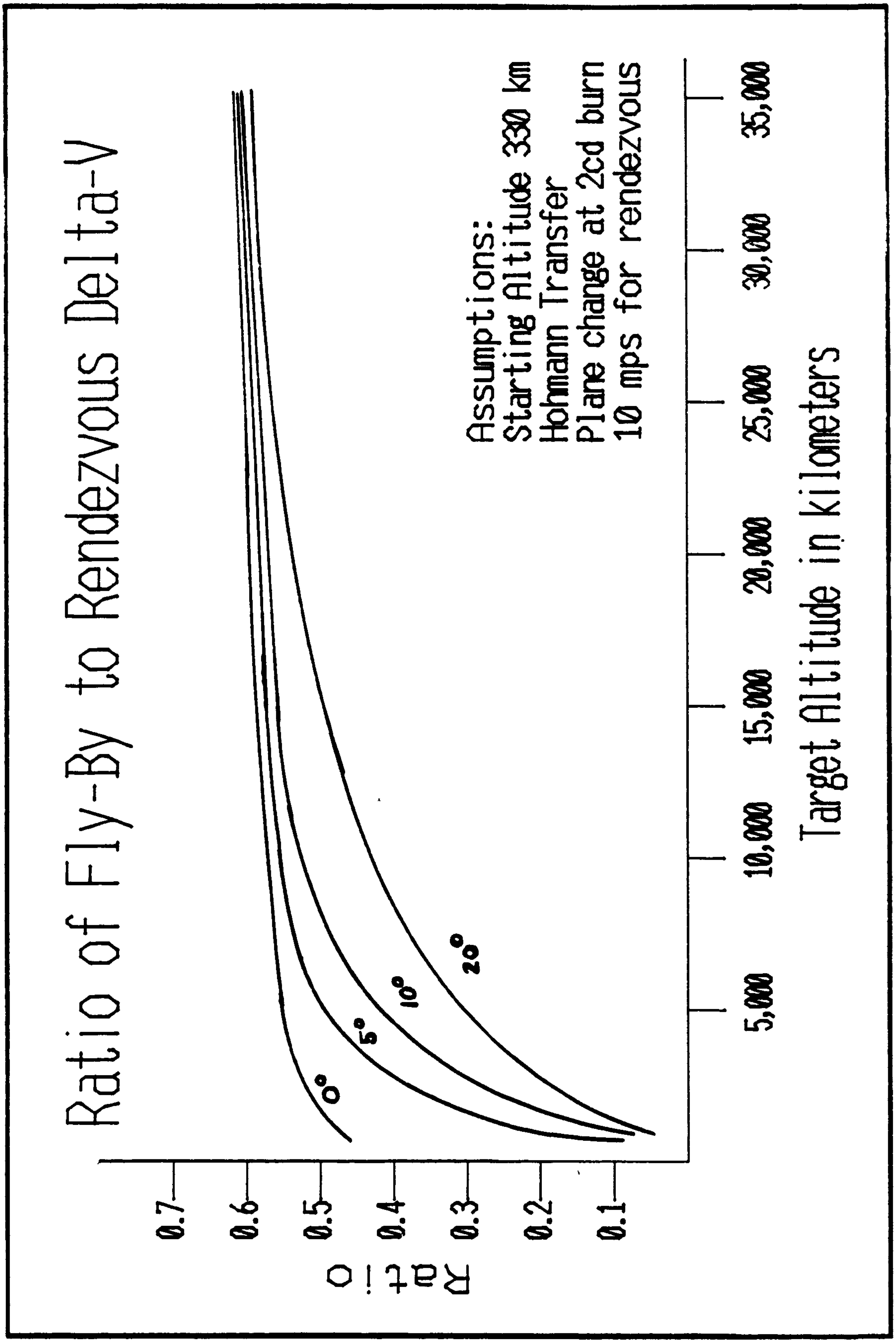


Figure 9. Ratio of Flyby to Rendezvous Delta-V

Appendix F

Orbital Maneuvering Vehicle

NASA is developing two reuseable space vehicles that could serve as the host platform for the sensors of an orbital inspection satellite. The vehicles are the Orbital Maneuvering Vehicle (OMV) and the Orbital Transfer Vehicle (OTV). These vehicles are unique in their ability to maneuver repeatedly and in their capability for reuse. The OMV is designed to operate in low earth orbit (LEO) while the OTV will operate from LEO to geosynchronous LEO orbit. The OTV is currently being researched and no operational date has been approved. The OMV is under development and should begin operations in the 1990's (30:305). The rest of the discussion will concern the use of the OMV as an orbital inspection satellite.

The OMV's function is to deploy, retrieve, and inspect space vehicles. It could not be launched from current expendable boosters due to its large width (180 inches) (30:97). It will be launched from the space shuttle, and The baseline vehicle will deploy a satellite and return to the space shuttle within 48 hours (due to limited battery life).

The OMV uses a modular concept of design to accommodate the needs of various users. Solar panels and a more sophisticated guidance package will be used in a space-based version of the OMV. All OMVs will be controlled from the Marshall Space Flight Center through the Tracking and Data Relay Satellite System (TDRSS) ground station at White Sands, New Mexico.

The baseline OMV does not have sufficient propulsion to fly-by or rendezvous with space objects at geosychronous altitude (with a payload of 1000 pounds). The following table is based on an empty OMV operating with various payloads (sensors) and provides the resulting delta-V.

Payload (lbs)	Delta-V (km/s)
0	2.74
500	2.54
1000	2.11
1500	1.85
2000	1.60

The delta-V required to fly-by and rendezvous from a 330 km altitude 28.5° inclination parking orbit is 2.42 km/s and 4.25 km/s respectively (Hohmann transfer). The OMV may be boosted to geosynchronous altitude with an expendable upperstage (PAM, IUS, Centaur, etc.). Once at geosynchronous altitude relatively little propulsion is needed to inspect the satellites there.

The OMV represents a considerable expenditure of money and time. NASA has invested 42 million dollars in the development of the OMV and its' antecedent the Teleoperator Retrieval System (TRS). The TRS program was begun in 1976. The estimated cost for two flight vehicles and support equipment is 150 million dollars (24:354).

Due to the similarities between the OMV and the orbital inspection satellite, any development should build on OMV technology and experience. The OMV with the planned enhancements for space-basing will meet the needs of a host vehicle for an inspection satellite in low earth orbit.

Appendix G

Space-Based Telescopes

The United States has designed and deployed several telescopes in low earth orbit. The x-ray telescope is currently in operation. The Hubble space telescope will be launched as soon as the space shuttle is ready. These instruments and others like them will not be useful for orbital inspection without some modifications.

There are three basic areas that may need modification if space telescopes are to be used for orbital inspection. These areas are focusing limits, tracking and pointing, and security. The telescopes are designed to look at sources very far away. Some instruments cannot focus on objects in low earth orbit. The telescopes are designed to track a point in space that is essentially fixed during the time observation. Therefore, only the telescope moves as it orbits the earth. The angular change is small since the source is many light-years away. The tracking and pointing requirements for low earth orbit satellites will exceed the telescope's capabilities. The third consideration is data security. Since most telescopes are operated by civilian universities on behalf of the government, data security may require enhancement.

The use of space telescopes for orbital inspection may be an inexpensive mode of operations. However, these instruments need modification before they become effective as orbital inspection satellites.

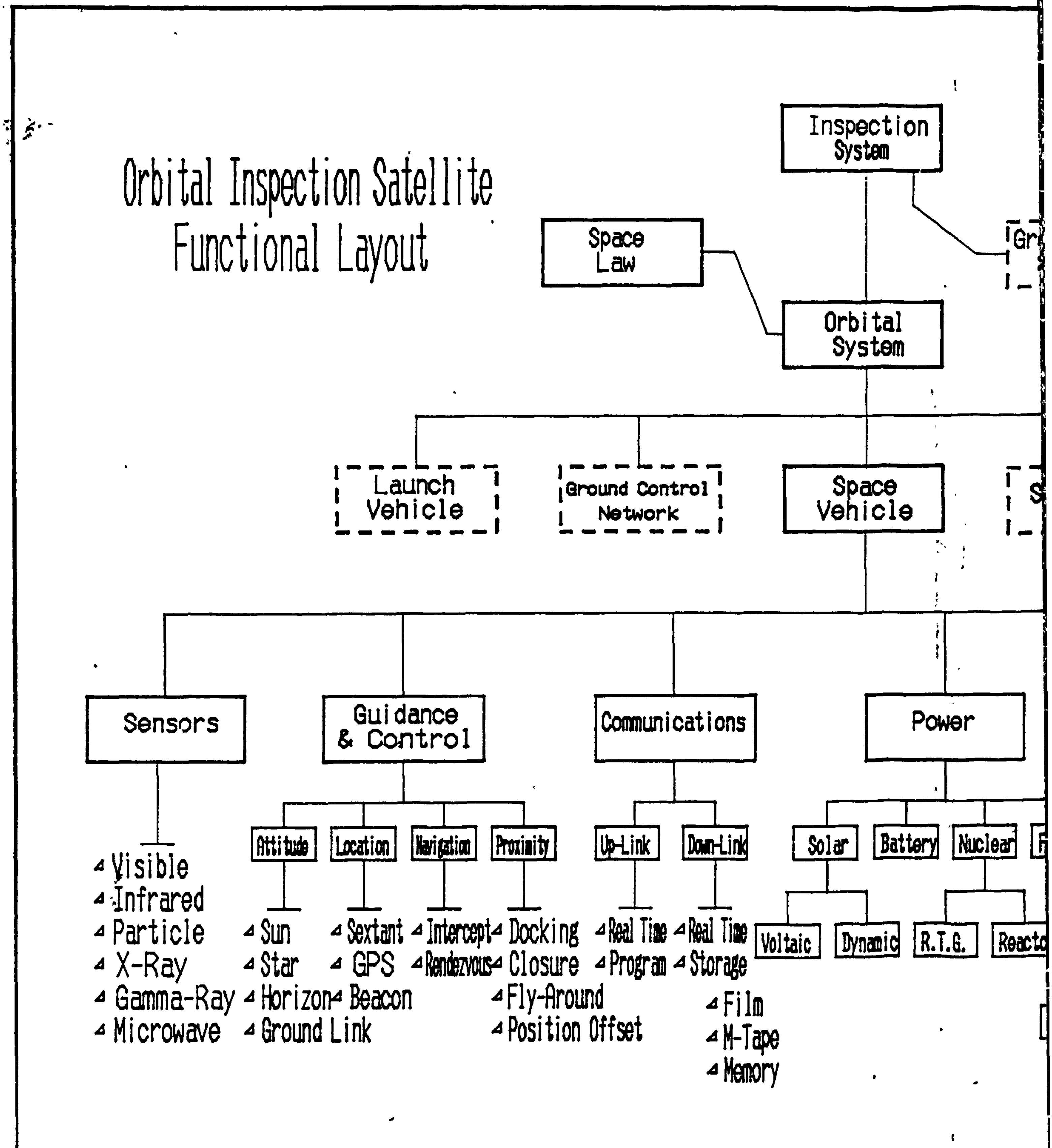
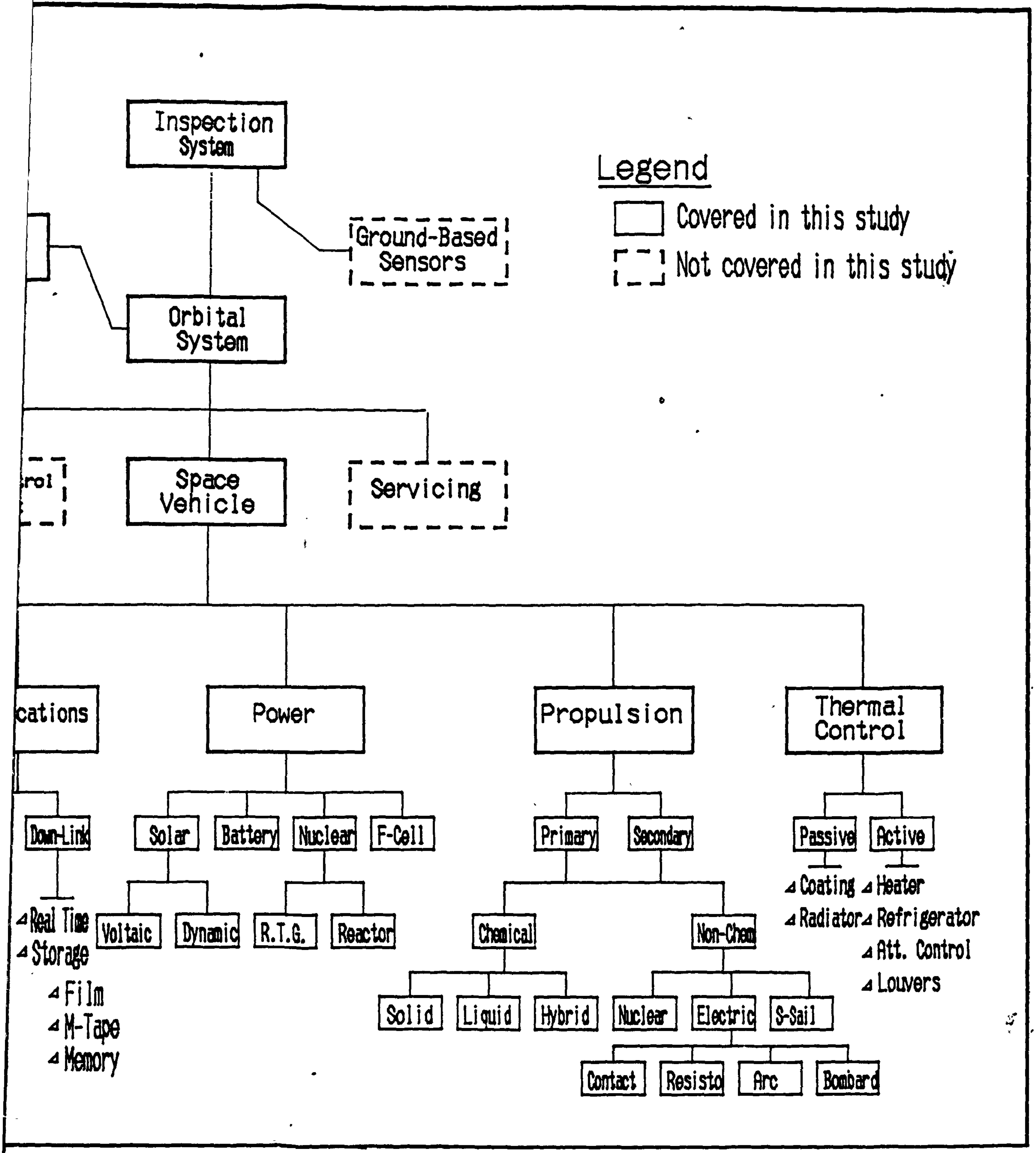


Figure 10. Orbital Inspection Satellite Functional Layout



Inspection System
Ground-Based Sensors
Legend
Covered in this study
Not covered in this study
Orbital System
rol
Space Vehicle
Servicing
cations
Power
Propulsion
Thermal Control
Down-Link
Solar
Battery
Nuclear
F-Cell
Primary
Secondary
Passive
Active
Coating
Heater
Radiator
Refrigerator
Att. Control
Louvers
Real Time
Storage
Film
M-Tape
Memory
Voltaic
Dynamic
R.T.G.
Reactor
Chemical
Non-Chem
Solid
Liquid
Hybrid
Nuclear
Electric
S-Sail
Contact
Resisto
Arc
Bombard

l Layout

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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

AD-A179 115

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS
none

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
AFIT/GSO/AA/86D-4

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
Engineering

6b. OFFICE SYMBOL *(If applicable)*
AFIT/EN

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
Air Force Institute of Technology
Wright-Patterson AFB, Ohio
45433-6583

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
DESIGN OF AN ORBITAL INSPECTION SATELLITE (Unclassified)

12. PERSONAL AUTHOR(S)
Harold D. Getzelman, Captain, United States Air Force

13a. TYPE OF REPORT
MS Thesis

13b. TIME COVERED
FROM ________ TO ______

14. DATE OF REPORT *(Year, Month, Day)*
December 1986

15. PAGE COUNT
114

16. SUPPLEMENTARY NOTATION

Approved for public release: IAW AFR 190-1/.
LYNN E. WOLAVER 13 Mar 87
Dean for Research and Professional Development
Air Force Institute of Technology

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
22	02	none

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Satellite Inspector, Space Propulsion, Spacecraft Cameras, Rocket Propulsion, Rocket Engines
Space Navigation

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Chairman of Advisory Committee: Joseph W. Widhalm, LtCol, USAF
Deputy Head, Department of Aeronautics and Astronautics

The need for the inspection of space objects by satellite is identified. The historical and legal context of the inspection satellite is discussed and implications for the design of the satellite are understood. Systems engineering tools are used to identify the basic design of an orbital inspection satellite. The satellite is partitioned into six major subsystems for analysis. The interactions between subsystems and among competing technologies for each subsystem is investigated. An orbital inspection satellite composed of the best systems and supporting subsystems is described. Finally, recommendations for further study and the impact of key decisions are described.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
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21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

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DD Form 1473, JUN 86 — *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified