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Technical Report

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APPLICATION OF ELECTRO-OPTICAL TECHNOLOGY TO SATELLITE RECONNAISSANCE

A Survey of Capabilities and Status

DIRECTORATE OF SCIENCE & TECHNOLOGY
Office of Special Projects

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SUMMARY

This report has the dual objective of reviewing the status of Electro-Optical Imaging Technology and of assessing the performance of [redacted] A performance analysis is conducted for both the warning/indications problem as defined by the Warning/Indications Task Force and the current high resolution surveillance requirement established by the United States Intelligence Board. (b)(1) (b)(3)

The performance analysis concludes that electro-optical imaging systems can, in general, meet the target coverage requirements for warning/indications. However, [redacted] are required, and even so, the winter coverage may be marginal. (b)(1) (b)(3)

Because of the continuous on-orbit capability of electro-optical imaging systems, the current surveillance requirement can be accomplished with ease. In addition, such systems appear to offer several additional advantages not available with current photographic satellite systems.

Electro-optical technology has progressed to the point where a system development program could be initiated within approximately one year. However, this date is contingent upon the decision to proceed with a concerted program to develop and qualify the return-beam vidicon image tube. Alternative imaging devices are also under development and could be available for application within two to three years. In either case, system development will require approximately three years.

This report also contains a discussion of some of the more important design and performance trade-off considerations involved in electro-optical systems.

CHAPTER 1: INTRODUCTION

The principal objective of this report is to assess the application of Electro-Optical Imaging Technology to strategic satellite reconnaissance. The status of the technology is reviewed, and the application of electro-optical techniques is described in terms of several alternative reconnaissance system configurations. The performance capabilities of these systems are measured against the warning/indications requirement as expressed in a study released by USIB (USIB-D-46-4/3) and against the current USIB high resolution surveillance requirement (USIB-D-46-4/13). This report is summary in character and is intended to provide a conceptual framework to support policy decisions governing electro-optical imaging technology program objectives. Each of the major technologies and analyses presented in this report is supported by definitive documentation developed by the Office of Special Projects.

Electro-Optical Imaging Systems

All satellite-derived imagery to date has been collected by systems using specially developed silver halide films as the basic image medium. Image recovery is accomplished by physical recovery of the exposed film. While in many regards silver halide film is extraordinarily well suited to this task, all such systems have a number of inherent and well-known limitations. The rapid growth of electro-optical imaging technology in recent years is on the verge of making possible a new and radically different type of image-forming satellite reconnaissance system.

Imagery collected using electro-optical techniques will be displayed for photo-interpretation on silver halide film and will be largely indistinguishable in general appearance from imagery collected by present-day photographic systems. As in current photographic systems, electro-optical systems will operate in the visual portion of the spectrum using reflected sunlight as the source of scene illumination. However, in functional and engineering terms, electro-optical systems will bear little resemblance to current photographic systems. From the standpoint of strategic satellite reconnaissance, electro-optical imaging systems present several advantages as compared to current photographic reconnaissance systems. First, electro-optical imaging systems have no inherent useful-lifetime constraints. The only practical lifetime limitation is the reliability of the electrical and mechanical subsystems of the satellite vehicle. Technology as it is now developing should lead to system lifetimes 10 to 20 times longer than current photographic systems with substantial growth potential to even greater lifetimes. This capability could readily provide continuous on-orbit availability of [redacted] reconnaissance systems at a launch rate considerably below the rate typical of current programs. The second key feature of electro-optical imaging systems is the method of image recovery. In these systems the image information is available in the form of an electrical video signal. This signal is transmitted to the ground station via a data link where the image information is stored and reconstructed for visual analysis. This method of image recovery results in a relatively smooth and continuous flow of imagery from the reconnaissance satellite to the ground based photo-interpretation facilities. This contrasts with the image recovery flow typical of photographic systems utilizing a necessarily limited number of recovery vehicles. The use of a data link to recover the image information results in a number of additional potential system advantages associated with the image reconstruction process. These advantages depend upon the fact that electronic techniques can be employed to process and reconstruct the image information to provide a visual display which is optimum for the photo-interpretive tasks to be performed. Image processing techniques which could be employed offer the very real potential of deriving substantially more useful information from the imagery than that collected by normal photographic systems with comparable optical characteristics.

(b)(1)
(b)(3)

On the other side of the ledger, there is at least one performance area in which electro-optical imaging technology cannot compete with photographic technology--at least not for the foreseeable future. Because of a number of fundamental data handling limitations associated with such systems, they will be suitable only for discrete target coverage applications. The rate of information collection and the total quantity of information collected by current and planned medium and high resolution panoramic reconnaissance systems is well beyond the current electro-optical state-of-the-art. Major new advances will be required before electro-optical systems can begin to compete with photographic systems for large area coverage missions.

Strategic Reconnaissance Applications

The Office of Special Projects has been actively investigating the application of electro-optical imaging technology to satellite reconnaissance for the past several years. This activity has been directed towards furthering the state-of-the-art in critical areas and studying the capabilities and limitations of this class of system against strategic reconnaissance requirements. It is unlikely that electro-optical imaging techniques will ever be truly competitive with photographic techniques if ground resolution is used as the exclusive figure of merit. However, the unique characteristics of the electro-optical imaging systems described above do offer very real potential to provide high resolution imagery together with a number of additional advantages which could result in significant gains when measured in a broader context. These potential gains can be categorized under four headings:

a. Lower costs in meeting high resolution target surveillance requirements.

b. Improved operational flexibility and responsiveness to intelligence needs.

c. Acquisition of high resolution imagery on a time schedule consistent with warning/indications requirements.

d. Rapid response to intelligence needs in crisis situations.

The potential cost advantage of electro-optical imaging systems is a direct result of the capability of these systems to achieve long mission durations, thereby reducing launch vehicle procurement. These systems can be designed with a nearly zero use-rate of expendables so that, as mentioned earlier, space vehicle useful mission lifetime will be limited only by reliability considerations. At the same time, long mission durations will not result in corresponding penalties in the timeliness of data recovery. A detailed quantitative assessment of actual cost savings depends upon a careful analysis of achievable reliabilities and an assessment of the total satellite reconnaissance program in terms of the mix of systems required to meet intelligence requirements for imagery. Although these issues will not be discussed as such in this paper, studies indicate that substantial dollar savings can be realized.

The nearly exclusive drive to develop systems with better and better photographic resolution performance has led to a situation where the operational characteristics of photographic satellite systems are not particularly well suited to the nature of intelligence requirements for imaging. Programmatic considerations limit the flexibility with which the rate of collection of imagery can be adjusted or reoriented to follow the changing needs for information. Consequently, long-range planning must be done largely in terms of a general level of effort. Mission planning and operations considerations complicate the detailed tasking of current systems and make it difficult to direct and modulate the flow of imagery. Furthermore, while current systems have a capacity for collecting quantities of imagery, they tend to be limited by active mission days on orbit, access considerations, and cloud cover in their ability to collect against specific priority objectives on a timely basis. Consequently, much of the imagery collected relates to low-priority objectives when measured against immediate needs. The continuous on-orbit availability of electro-optical imaging systems together with the relatively rapid recovery of imagery can be exploited to great advantage, both in insuring timely collection of critical imagery and in controlling the rate and quantity of imagery collected so as to better match real Intelligence Community needs. With an electro-optical imaging system on orbit, there will be no need to target a given objective until an intelligence problem results in a specific need for coverage of this objective. Furthermore, once the need for imagery is identified, there is a high assurance that such imagery will be available within a matter of days. The value to the Intelligence Community of the flexibility and responsiveness characteristic of electro-optical imaging systems is difficult to quantify. It can only be treated as one factor in the total planning equation.

The current recovered-film systems have not proven very useful in support of the warning/indications problem. While satellite photography is invaluable in assessing the military capability of a country such as the USSR, the flow of photography from satellite collection systems into the Intelligence Community is generally much too erratic to contribute to an assessment of impending military action. The recent warning/indications study released by USIB concludes that a more timely flow of imagery would in fact make a valuable contribution to indications intelligence. The following sections of this report will discuss this problem in some detail.

As in the case of indications intelligence, operational constraints severely limit present satellite systems in their ability to provide timely information in a cold war crisis situation. Here too, the unique ability of electro-optical imaging systems to recover imagery rapidly and continuously is essential. Although there is little doubt that high resolution imagery, if it could be made available on a timely basis, could contribute valuable intelligence information in a crisis situation, the worth of this contribution must be judged against the inherent disadvantages of satellite platforms for this mission. Whether or not the cost associated with developing an electro-optical imaging system can be justified exclusively on this basis of a crisis management mission, a crisis potential would be a valuable fall-out should an electro-optical imaging system be developed for more general application.

Preliminary System Design Requirements

The four general considerations discussed in the preceeding paragraphs have led to the formulation of a broad set of design requirements to guide electro-optical study and technology work. This design requirement is intended to bracket the systems capabilities which appear to be necessary if any of the above advantages are to be realized. It should be emphasized that considerable analysis is yet to be done to define specific performance specifications needed to meet any given intelligence needs.

The five most critical design requirements are summarized in Table I. The resolution requirement of two to four feet refers to the resolution of the system when imaging a target directly below the space vehicle. While there is considerable technical difficulty in relating electro-optical systems to photographic systems in terms of a precise measure of image quality (and even in comparing different electro-optical imaging systems), an image acquired by an electro-optical system rated at two foot resolution should be capable of supporting the same level of detailed interpretation which can be accomplished with a silver halide image rated by current standards at a two foot resolution. Electro-optical imaging systems of the type discussed in this paper are inherently framing systems. The frame size refers to the ground coverage capability of a system targeted at a point directly below the space vehicle. The frame size projected on the ground will, of course, increase as the optical system is pointed at targets off nadir. A size of 3 x 3 nautical miles

TABLE I
PRELIMINARY DESIGN REQUIREMENTS

Nadir Resolution:	2 - 4 feet
Nadir Frame Size:	3 x 3 nautical miles - 10 x 10 nautical miles
Space Vehicle Lifetime:	Failure limited
Reliability:	High probability of operating for [redacted] (b)(1) (b)(3)
Image Recovery Response Time:	Less than 12 hours

was selected as the smallest useful frame size in view of target dimensions and targeting errors. Larger frame sizes are desirable, and the selection of 10 x 10 nautical miles as the maximum for study purposes was based on an early feasibility judgment. The specification of space vehicle lifetime as "failure limited" indicates the design objective of minimizing the expendables required for the operation of the system. This objective provides for maximum growth potential and insures maximum return per dollar cost invested in each satellite launch. The reliability objective of [redacted] was selected on the basis of a cost effectiveness study which indicated that useful mission durations of this order would be required to realize substantial cost gains over photographic systems. Image recovery response time is the time lapse between the acquisition of an image in the space vehicle and the time at which that image is available for viewing at the ground station. This time can range [redacted] in the case of systems configurations using relay satellites up to approximately 12 hours when the data is read out directly from the imaging satellite to a single U.S. ground station. The design requirement is intended to leave open for consideration the entire family of potential systems configurations with and without various kinds of relay satellite nets. In addition to the requirements specified in Table I, some consideration has also been given to a [redacted]

(b)(1)
(b)(3)

(b)(1)
(b)(3)

(b)(1)
(b)(3)

The design requirements in Table I were formulated to focus attention on a relatively narrow range for each of the major performance parameters. Nonetheless, there is a tremendous spread in size and complexity between a system with two foot resolution and a 10 x 10 nautical mile frame size and one with a four foot resolution and a 3 x 3 nautical mile frame size.

One of the major technical problems associated with electro-optical imaging systems is the image transducer. A number of such devices are under development all of which are more or less attractive depending upon what specific resolution and frame size numbers are selected to define a design point. Systems outside the general guidelines of Table I are also possible. As is the case with photographic systems, the optical system, and therefore the space vehicle, rapidly decreases in size as the resolution specification is relaxed. However, the equivalent of a photographic panoramic system for large area coverage will not be feasible in the near future independent of the resolution desired. Moving in the other direction, resolutions better than two feet are also possible. However, some potentially undesirable trade-offs begin to occur. These are discussed below.

Some of the basic design trade-offs will be discussed in Chapter 2. The engineering implications of these trade-offs in the context of the warning/indications problem and the high resolution surveillance problem will be developed more fully in Chapters 3 through 5.

Warning/Indications

COMIREX document D-13.7/4 is the final report of the special Warning/Indications Task Force established to examine the potential utility of satellite imagery to the warning/indications intelligence problem. This task force report concludes that satellite reconnaissance can contribute vital information applicable to warning/indications of a maximum weight attack or an attack combining weight with surprise. The task force developed a list of 505 specific targets divided into 14 categories, as summarized in Table II. These targets were selected on the basis that abnormal military activity should be observable at these installations if the Soviets were to prepare for a "maximum weight" attack. A "maximum weight" attack is distinguished from a "maximum surprise" attack, which by definition would involve only the quick reaction offensive missile forces, which do not present any observable indication of impending action.

The task force also presented an analysis of the level of sampling of the 505 targets that would be required in order to provide a given confidence level of detecting abnormal military preparation. The 70 per cent confidence level daily sample rate and the 90 per cent confidence level daily sample rate are also summarized in Table II. The task force concluded that imagery

TABLE II
WARNING/INDICATIONS TARGET COVERAGE REQUIREMENTS

Target Category	Number of Targets	Daily Sample for: 70 Percent Level of Confidence	90 Percent Level of Confidence
Submarine Bases			
Nuclear Powered Ballistic Missile Sub Bases	14	5	6
Other Missile Sub Bases	24	6	10
Aviation			
LRA Heavy Bomber Home Bases	6	3	4
LRA Staging Recovery Bases	23	6	9
Medium Bomber Bases	22	6	9
Fighter Deployment Bases	22	6	9
Airborne Transport Bases	17	5	8
Ground Forces			
Military Depots	43	8	15
Tank & Motorized Rifle Units	77	9	18
Airborne Regiments	23	6	9
Transloading Yards	5	2	3
Missiles (Ground Based)			
Tactical Missile Support Facilities	8	3	4
Soft ICBM Sites	77	9	18
Soft MRBM Sites	144	9	20
TOTAL	505	83	142

must be recovered for analysis in near real time, which is defined as approximately [redacted] maximum from the time the imagery is acquired in the reconnaissance satellite. In the case of most of the 505 targets, the task force concluded that monoscopic imagery is adequate. The exceptions to this are the two submarine categories which require stereoscopic coverage. (b)(1) (b)(3)

On the basis of the ground rules developed by the warning/indications task force, a 70 per cent confidence level of detecting abnormal activity at a specified military installation requires 83 cloud free images per day. This level of coverage increases to 142 cloud free images per day to obtain a confidence level of 90 per cent. These levels of collection would lead to a total number of target coverages of 30,295 per year at a 70 per cent confidence level and 51,830 targets per year for the 90 per cent confidence level. The ability to achieve this high rate of coverage is complicated by a clustering of a large fraction of the warning/indications targets in the northwestern sector of the USSR. The performance capability of several alternative electro-optical imaging systems against this requirement is analyzed in Chapter 2.

Surveillance

The current USIB high resolution surveillance requirement calls for a periodic surveillance of approximately 5,200 targets plus 1,200 SAM sites. These targets are summarized by category in Table III. The requirement calls for 3,878 target coverages per year. Approximately 70 per cent of these coverages are called for in stereo giving a total requirement for 6,600 cloud free target images per year.

In order to provide a basis of comparison between current photographic satellite systems and electro-optical imaging systems, Chapter 2 includes a brief analysis of the performance of several alternative electro-optical imaging systems assuming that such systems were tasked with meeting the current USIB surveillance requirements.

TABLE III

CURRENT USIB HIGH RESOLUTION SURVEILLANCE REQUIREMENT

CATEGORY	NO. OF TARGETS AS OF JAN 1968	ANNUAL GROSS (COVERAGE LOOKS)
Missiles	1687	1145
Aviation	657	697
Nuclear	174	165
Naval	159	201
BW/CW	52	29
Electronics	203	152
Ground Forces	2177	1474
Urban/Industrial	122	*
Unidentified	15	15
TOTAL	5246	3878

*Normally collocated with targets of higher priority interest in the other categories.

CHAPTER 2: PERFORMANCE ANALYSIS

The first part of this chapter is devoted to a discussion of the primary design considerations associated with electro-optical imaging systems. These considerations differ in several important regards from those normally associated with photographic reconnaissance satellite design. This especially true for the class of electro-optical imaging systems of interest in the context of this paper where long mission duration is a key consideration. The latter sections of this chapter are concerned with the definition of two generic electro-optical imaging systems (i.e., Multiple Vidicon and STX Systems) and the performance analysis of these systems against both the warning/indications problem and the high resolution surveillance problem. These two systems are selected in order to illustrate important performance characteristics. Here, the systems are treated functionally, while a more detailed description of the component subsystems is developed from an engineering viewpoint in Chapter 3.

Primary Design Considerations

The central engineering problem associated with electro-optical imaging systems is the handling of large volumes of information at high rates. Two alternative overall system configurations are currently under active study. The first configuration involves storing the image information on board the electro-optical imaging satellite and later reading out this information either directly or indirectly to a ground station via a data link. The second configuration relies on the use of relay satellites arranged so that the image information need not be stored on board the image forming satellite but rather is relayed to a ground station [redacted] Although this approach requires a (b)(1)
complex relay satellite net, the availability of a [redacted] data link (b)(3)
to and from the imaging satellite has a number of potential engineering advantages. However, the functional aspects of both configurations are comparable in regard to collection capability. As this paper is primarily concerned with analyzing the functional performance of electro-optical imaging systems and surveying the electro-optical engineering state-of-the-art, [redacted] relay options, as distinguished (b)(1)
from deferred relay options, will not be considered further herein. (b)(3)

The selection of a transducer and a data storage technique is dominated by the overall system performance required. In practice, all of the major imaging satellite design parameters are interdependent. The following paragraphs discuss several of the more critical functional tradeoffs in order to develop a background for the discussion of two particular systems (Multiple Vidicon and STX).

For a given ground resolution the quantity of information per image frame depends only upon the number of square miles covered by that frame. Total information per frame can be measured in terms of the number of resolution elements contained in that frame. Figure I shows the dependence of resolution elements on frame size for two and three foot ground resolutions. The number of resolution elements increases directly as the area of the frame and as the square of the ground resolution. As the data storage and data transmission requirements increase directly as the number of resolution elements that must be handled by the system, there is a strong engineering trade-off associated with the selection of frame size and resolution.

There is also a direct geometric relationship between the area framed (frame size) on the ground and the format size required of the transducer in the image plane of the optical system. The format size required is dependent upon the inherent resolution capability of the transducer. Figure II displays this relationship for two ground resolutions and two transducer resolutions. This relationship is particularly critical in the case of the return-beam vidicon where format size for a given tube cannot be made arbitrarily large because of engineering limitations. When the tube is operated at a conservative resolution level, more than one tube is required to meet even the minimum ground frame size requirements established in Table I. The class of solid state array transducers is not specifically limited in format size in that these arrays are modular and can be built up to any desired physical size. However, sensitivity and readout rate limitations combine to limit in practice the array lengths that can be employed with reasonable optical systems. The STX is more flexible in this regard. Not only does it possess an inherently high resolution (which tends to minimize the format size required for a given ground frame size), but it also can be fabricated in reasonably large pieces. The ultimate limitation is not known at this time, but a practical limit will be set by fabrication considerations.

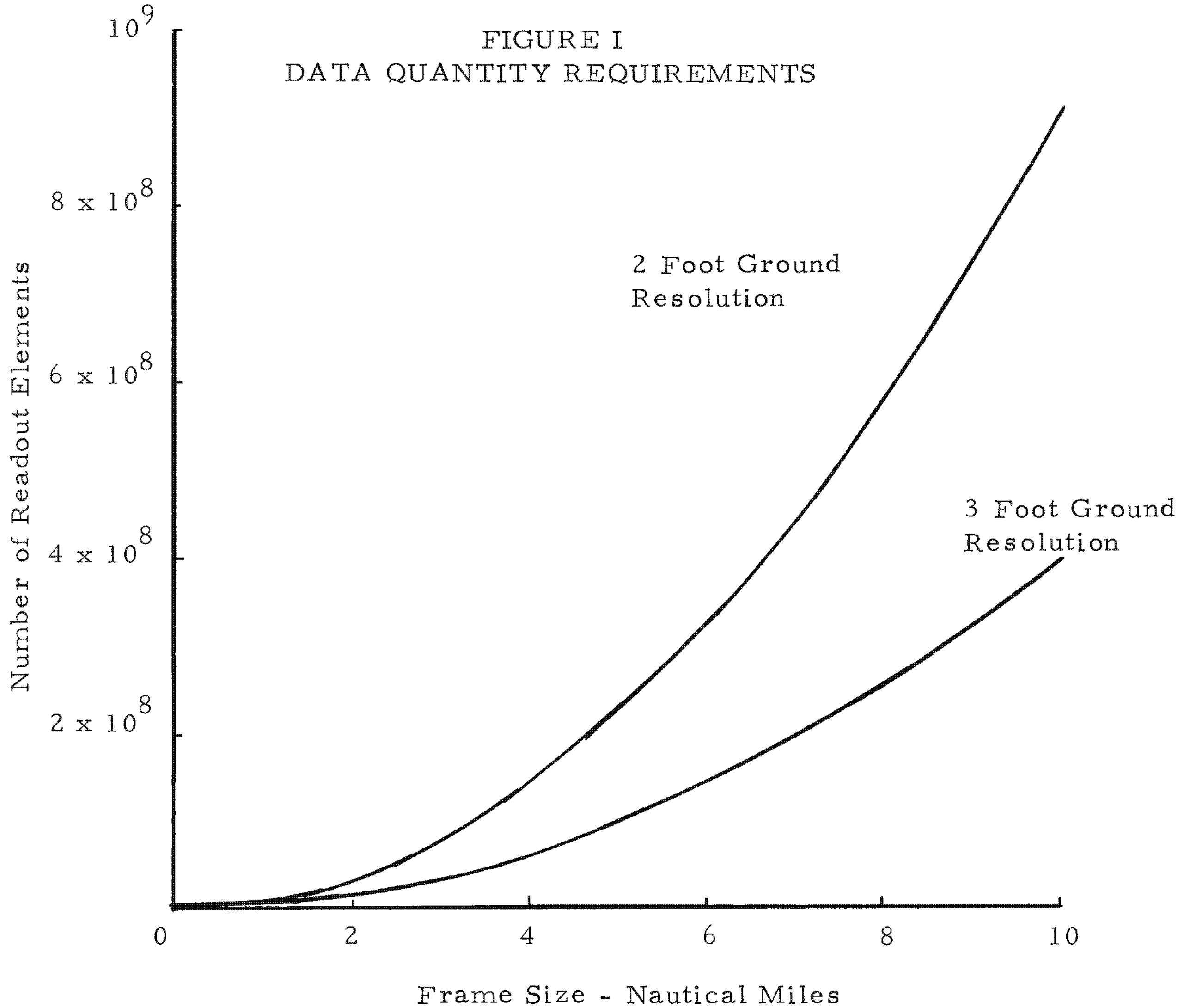
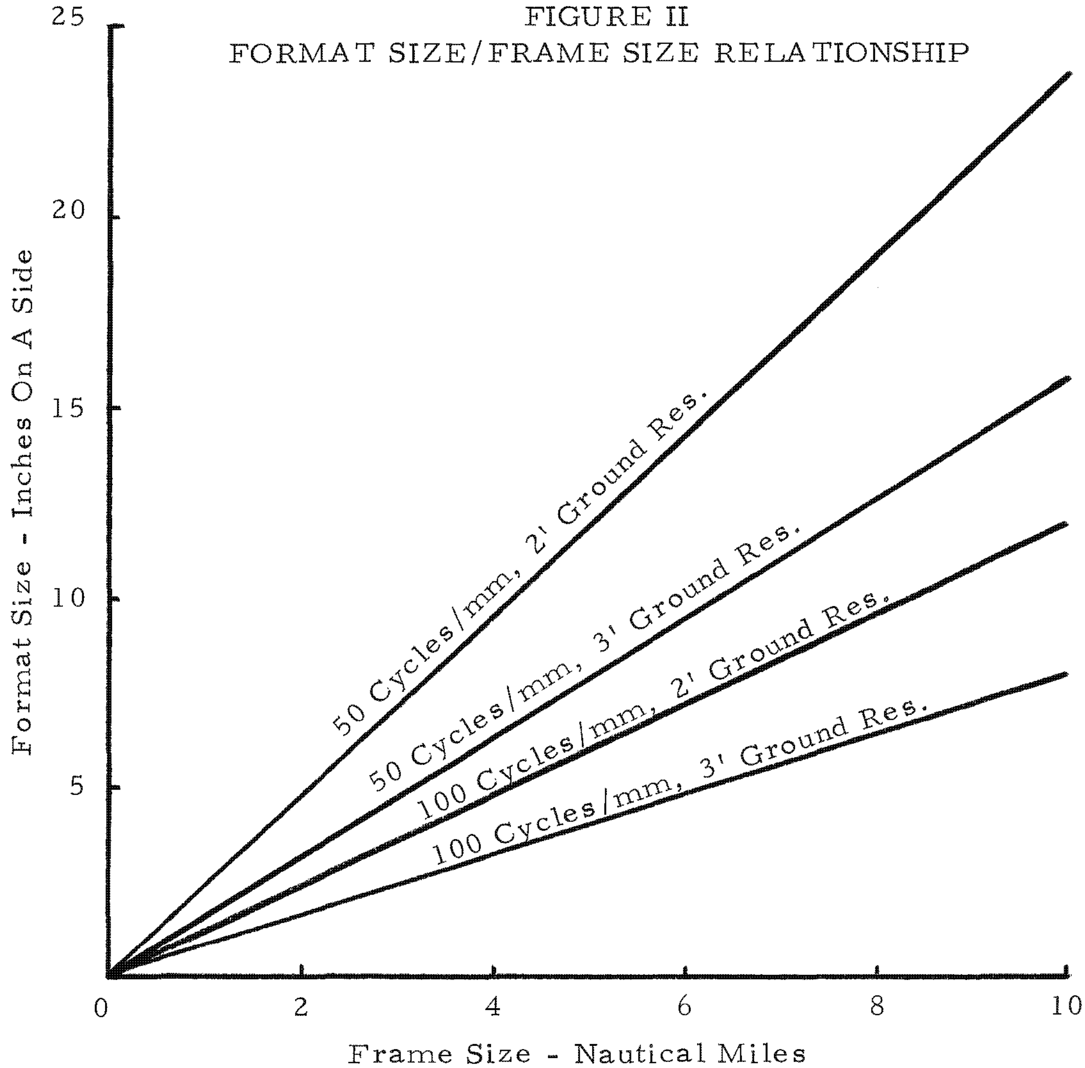


FIGURE I
DATA QUANTITY REQUIREMENTS
10^9
8×10^8
6×10^8
4×10^8
2×10^8
Number of Readout Elements
2 Foot Ground Resolution
3 Foot Ground Resolution
0
2
4
6
8
10
Frame Size - Nautical Miles

FIGURE II
FORMAT SIZE/FRAME SIZE RELATIONSHIP



The total quantity of imagery which can be stored in and read out from an imaging satellite does not generally appear to be a limiting design consideration. Geographic target distribution and cloud cover considerations lead to a practical upper limit on the requirement for image data storage which is well within the bounds of storage and data link technology, at least down to resolutions of two feet. However, there are potential engineering constraints which may limit the maximum rate at which some systems configurations can take consecutive images. This is particularly true in the case of vidicons where the rate at which a vidicon can be read out into magnetic tape recorders is limited both by vidicon considerations and by tape recorder considerations.

The general problem of orbit selection contains a number of important performance trade-offs. The family of potential orbits is immediately limited by two considerations, both associated with the long life design requirements. In general, the orbit plane of the satellite rotates so that the local time at which the satellite appears over a given target area slowly changes from day to day. For near polar orbits and short missions, this limitation is not usually of critical importance. However, with missions longer than several weeks the inclination of the orbit plane must be selected so that this orbit plane rotation matches the rate of rotation of the earth around the sun. When this condition is satisfied, the scene illumination will vary only with the season of the year. For low-altitude satellites, this inclination is approximately 97 degrees (7 degrees off polar) and is often referred to as a sun-synchronous inclination. A second problem associated with the orbital mechanics of long missions is that generally the location of perigee will rotate within the plane of the orbit so that after a period of time, perigee and apogee will change places and consequently the satellite will pass over targets on the sunlit side of the earth near apogee rather than perigee. This rotation can be controlled by utilizing a propulsion system on board the satellite, but for missions of many weeks duration, this results in an unacceptable rate of expenditure of propellent. This constraint requires that only circular orbits be used so that perigee rotation will not result in appreciable variation in altitude over the target areas.

In view of the two constraints discussed in the previous paragraph, the only orbital parameter which remains to be selected is altitude. The altitude selected will control the period of the orbit and therefore control the pattern of the orbit traces on the surface of the earth. The period must be selected so that the entire land mass of the world is accessed on a cyclic basis within the access swath of the imaging satellite. Aerodynamic drag will cause the orbital period to decay slowly, thus changing the coverage pattern of the imaging system. This period decay will require orbit maintenance at the expense of propellent weight. Above 250 nautical miles altitude the orbital period is sufficiently constant so that no propellent is required for mission durations up to a year. As the altitude selected is reduced below 250 miles, increasing amounts of propellent will be required. Since atmospheric density varies exponentially with altitude, propellent utilization considerations are an important factor in orbit selection.

For a given ground resolution the diameter of the optical system increases with increasing altitude. As optical system diameter has a strong impact on space vehicle weight, this consideration competes with the desire to fly a higher orbit with the objective of minimizing propellent weight. While the optical system diameter required for a particular ground resolution depends on the transducer selected as well as a number of other trade-offs in other vehicle subsystem areas, conservative design practice tends to result in a relationship between orbital altitude and optical system diameter which is dependent only on the ground resolution desired. Figure III displays this relationship at two ground resolutions. Current optical system technology limits feasible optical system diameters somewhere between six and eight feet.

Another weight consideration is the fact that the space vehicle weight that a given launch can inject into orbit decreases with increasing altitude. This consideration also tends to favor lower altitude.

While the above trade-offs tend to drive the orbital altitude selection to somewhere around 150 nautical miles, there are several additional competing factors which tend to drive it up. For a given cross-track roll angle capability, the access swath within which a target may lie in order to permit targeting increases with altitude as shown in Figure IV. Access swath is one of the most critical parameters in determining the time required to obtain good quality cloud free imagery of a given target and in determining the periodic level of coverage that can be maintained of any given list of targets. The time between successive target accesses is plotted in Figure V as a function of target latitude for several access swath widths.

FIGURE III
OPTICAL SYSTEM APERTURE REQUIREMENT

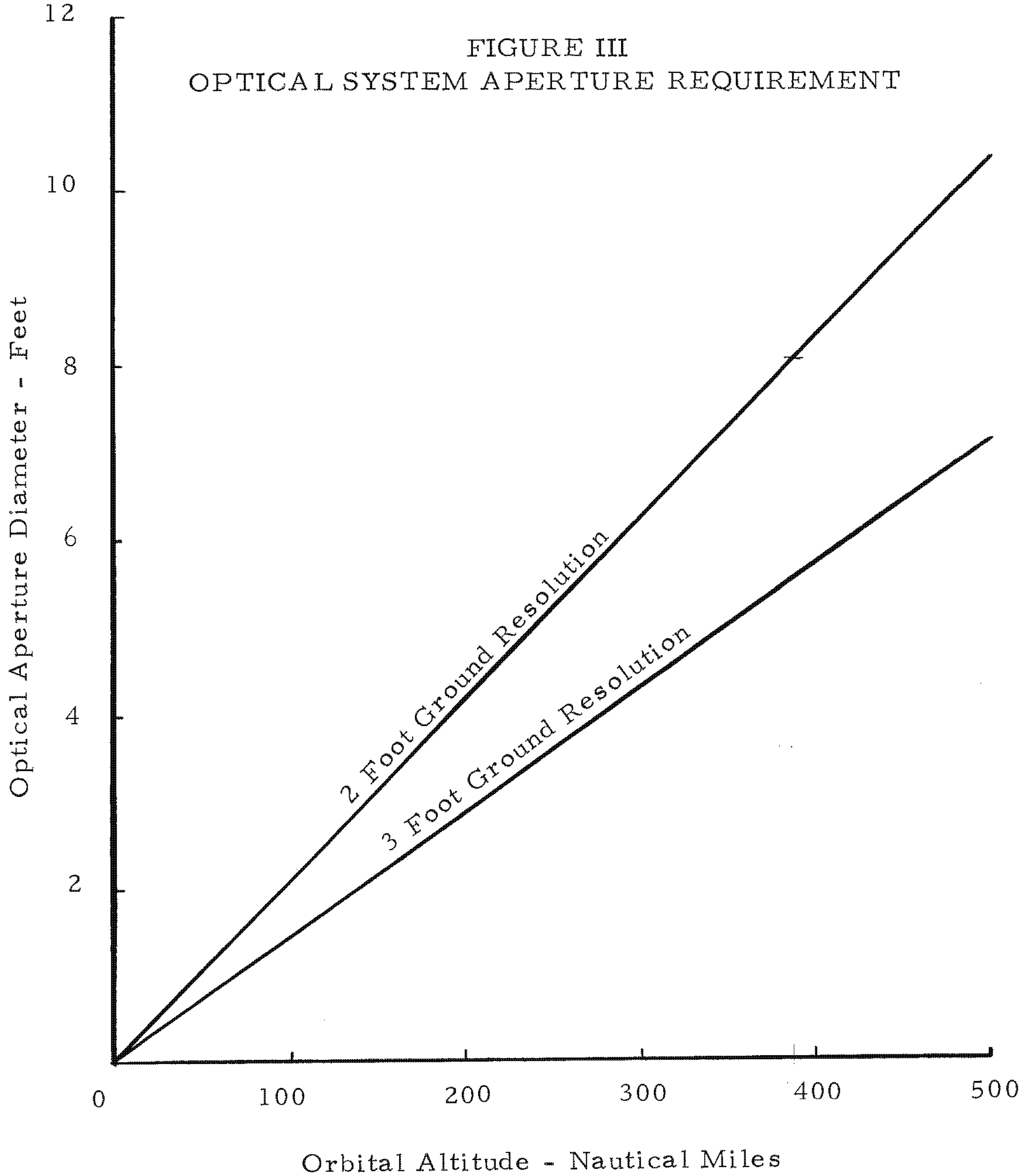


FIGURE IV
TARGET ACCESS SWATH

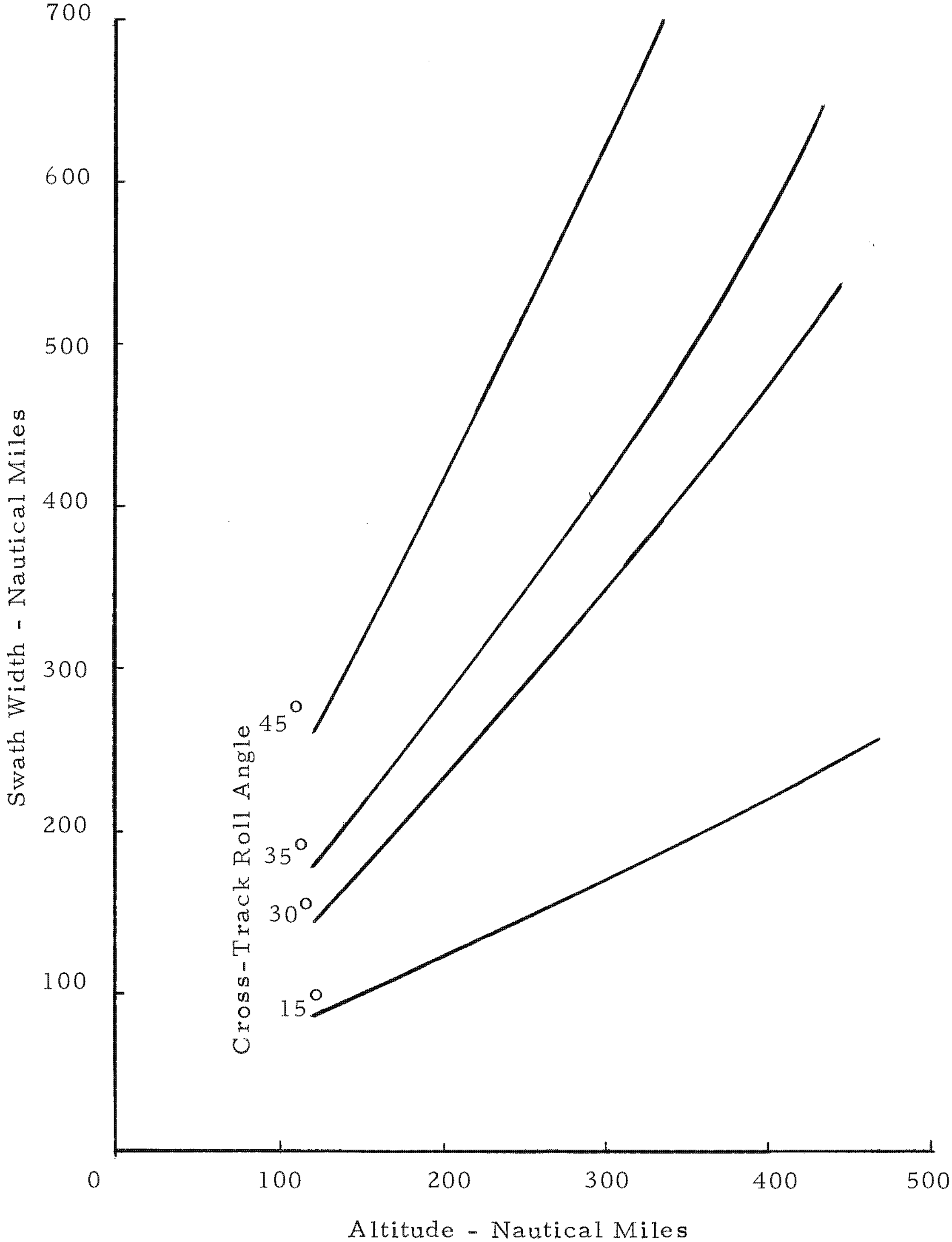
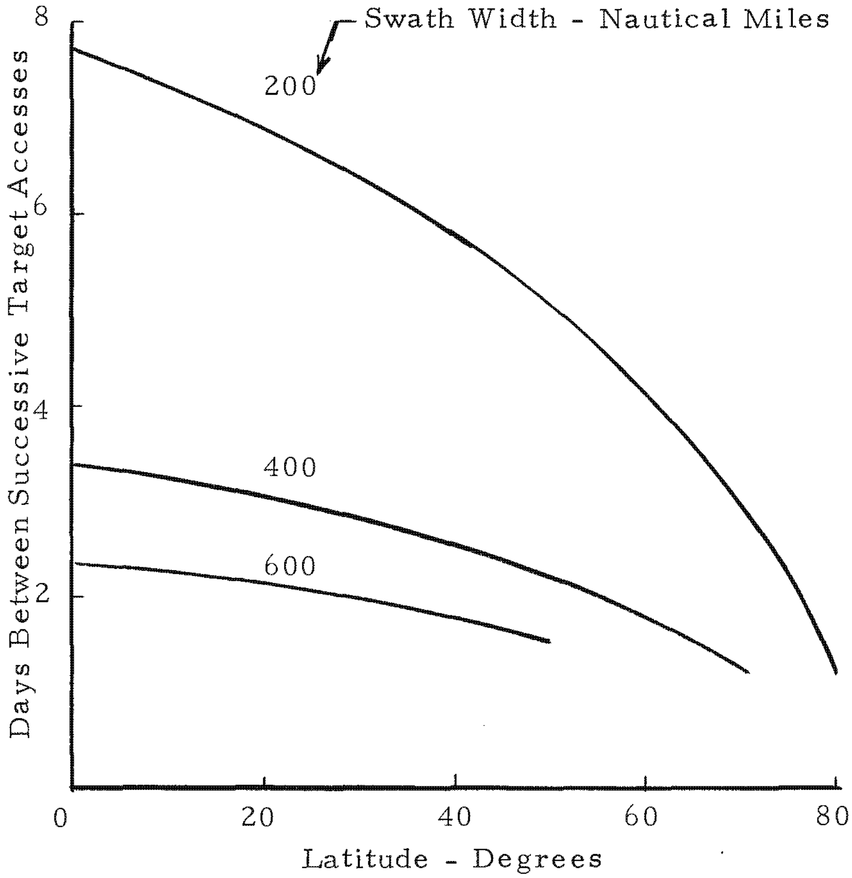


FIGURE V
TARGET ACCESS INTERVAL



A large access swath is of particular importance in the case of the warning/indications problem where a relatively high rate of daily coverage is needed.

There are two additional considerations which tend to favor higher altitude of operation for the imaging satellite. The first of these is associated with the imaging time available on a given pass over a target complex. For an imaging satellite which has the capability to point the optical system in pitch as well as in roll, more than one target within a closely bunched complex can be imaged during a given pass. In the same way it is also possible to obtain multiple images of a given target as the imaging satellite passes by the target location. The time available for acquiring multiple images of a target or a closely grouped target complex increases with altitude and pitch angle agility as shown in Figure VI. In addition, as the altitude increases, the time required to repoint the optical system from one target to another target decreases assuming the angular rate at which the optical system can be rotated remains constant. Figure VII shows the pointing velocity of the intersection of the optical axis with the ground versus altitude for several angular pointing rates. The number of images of a given target that can be obtained or the number of targets in a complex that can be imaged will increase directly with the pointing velocity until transducer cycle time becomes the limiting factor. However, there is another attitude control requirement which competes with the desire to have an agile system. As the altitude of the imaging satellite increases, the angular accuracy with which it must be pointed also increases if the pointing error on the ground is to remain constant. As the alternative is increasing frame size to accommodate larger pointing errors, the orbital altitude is ultimately limited by the accuracy with which the attitude of the optical system can be measured and controlled.

As there are many secondary interrelationships amongst the various parameters discussed above and additional considerations which have not been mentioned at all, the final task of selecting the best configuration will not be addressed in this paper. In fact, work in the electro-optical systems area has not progressed to where the final design optimization can be accomplished. In any case, this optimization is dependent upon establishing a definitive set of collection requirements against which to evaluate systems performance. However, based on work to date, a number of alternative configurations have been examined, and two of those will be discussed in the remainder of this paper.

FIGURE VI
TARGET DWELL TIME
(Target Located on Space Vehicle Ground Track)

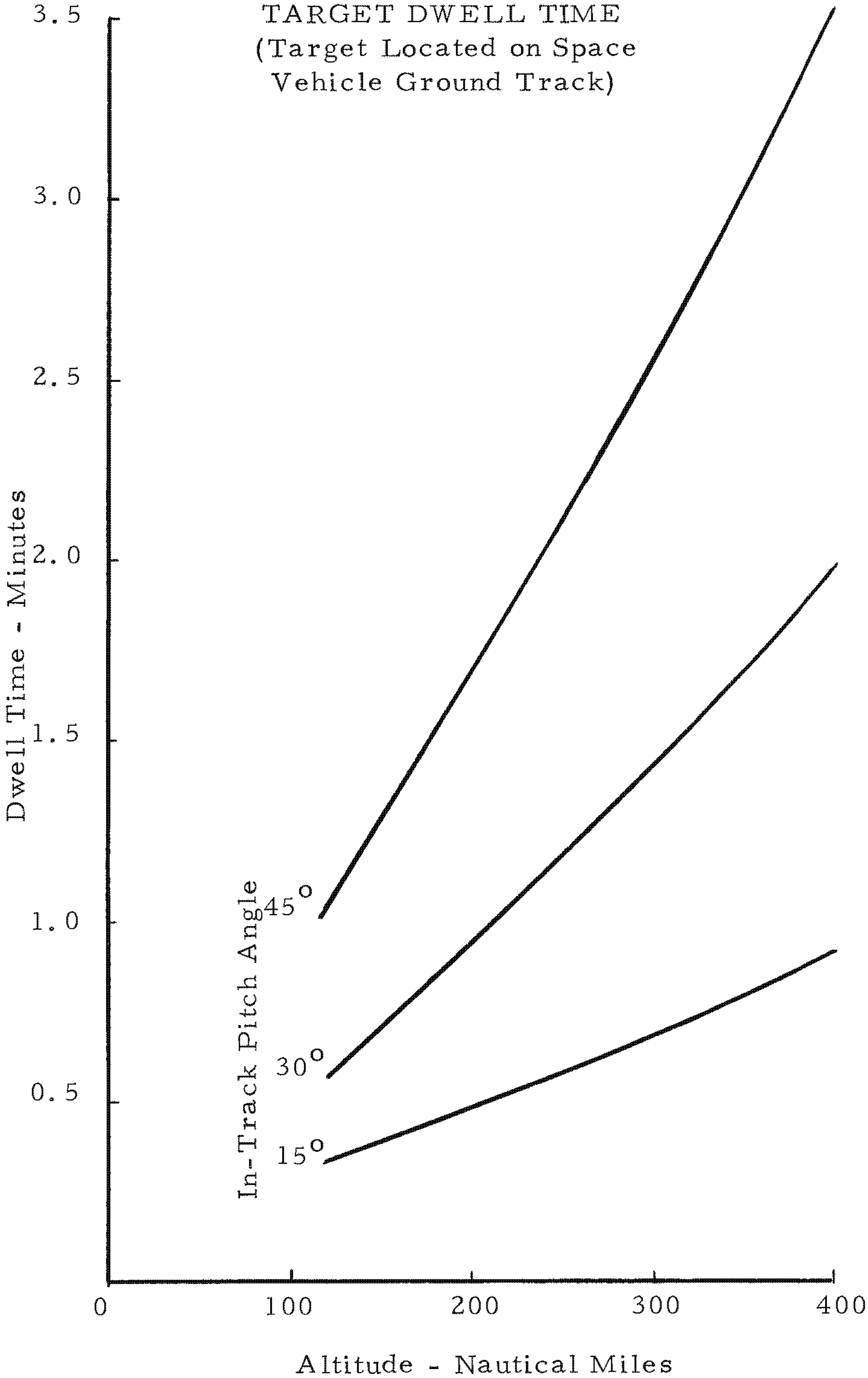
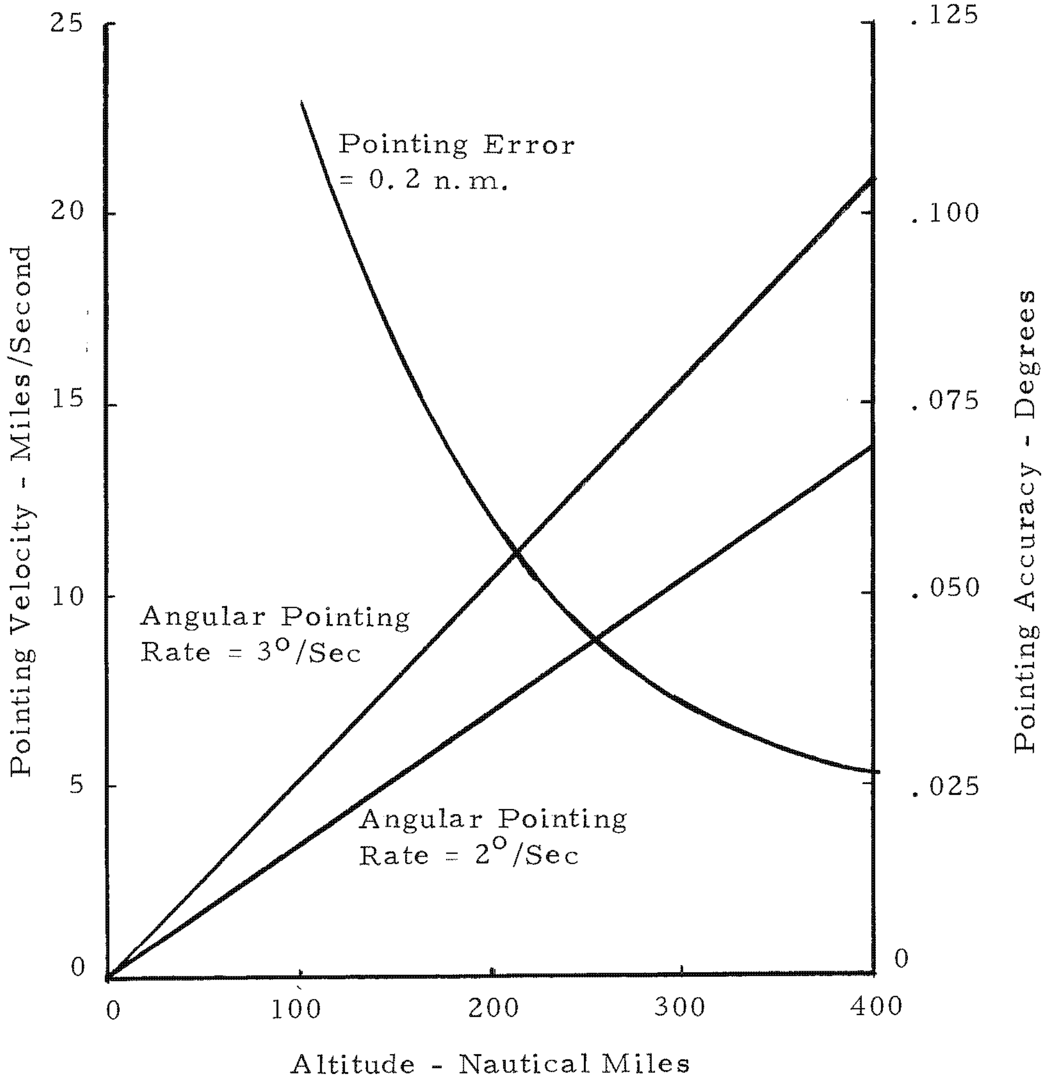


FIGURE VII
RETARGETING RATE/POINTING ACCURACY TRADEOFF
(Computed for Nadir Viewing)



Generic Systems Definition

From an overall systems point of view, the specific system arrangement selected for analysis is the deferred relay configuration. This employs one data relay satellite working in conjunction with the imaging satellite. [redacted] (b)(1) (b)(3) image data is passed through the relay satellite to a ground station which can be located anywhere within the continental United States (in fact, anywhere in view of the relay satellite). The imaging satellite is launched so that the sunlit passes over the Sino-Soviet Bloc occur as the imaging satellite passes from south to north. The imaging satellite comes into view of the relay satellite as soon as it crosses into the western hemisphere, and at this time readout of the imagery can begin. As mutual visibility constraints are satisfied approximately half of the time, data relay can be performed at a relatively slow rate, minimizing the data link requirements. In addition, since data readout can occur on every imaging satellite revolution, delay in recovery of the imagery at a continental United States ground station can be reduced [redacted] (b)(1) (b)(3)

Aside from all other considerations, a relay satellite is required if the [redacted] recovery lag requirement specified by the Warning/Indications Task Force is to be met. Direct [redacted] Independent of the delay time consideration, (b)(1) (b)(3) the data link bandwidth would have to be considerably greater to read out a useful number of pictures per day directly to [redacted] as compared to relaying this imagery through a second satellite. However, it does not appear that the data link will prove to be a serious limitation in either case.

The functional performance characteristics for the two systems of interest in this paper are summarized in Table IV. The two systems are differentiated by the use of a multiple vidicon transducer arrangement in one and STX in the other. The solid state array is not treated as a major option in that its functional characteristics lead to a coverage capability somewhere between that of the vidicons and the STX. This is not to imply that the solid-state-array transducer may not be selected for an electro-optical imaging application. It has a number of potential engineering advantages, both in terms of reliability and design flexibility, which will be mentioned later in this paper.

The nadir resolution selected for the two systems is two feet in both cases. This resolution was chosen both in terms of the specific resolution requirements specified by the Warning/Indications Task Force and by the general requirements of high resolution surveillance. The frame size for the multiple vidicon system is limited to 3 x 3 nautical miles by the current state-of-the-art in

TABLE IV
SYSTEMS CHARACTERISTICS

Nadir Resolution:	2 feet
Nadir Frame Size:	
Multiple Vidicon System	3 x 3 nautical miles
STX System	6 x 6 nautical miles
Time/Image:	
Multiple Vidicon System	
STX System	
Operating Altitude:	
Access Swath:	
Image Recovery Response Time:	
Peak Image Capacity:	

(b)(1)
(b)(3)

vidicon design and the engineering judgment that no more than four vidicon tubes can be conveniently packaged at the focal plane of an optical system. The STX frame size of 6 x 6 nautical miles is not so limited. This corresponds to an 8 x 8 inch format size, and the capability to fabricate plates up to this size has been demonstrated. There is no obvious limitation at this dimension. The time required per image in the case of the multiple vidicon system [redacted] is (b)(1) limited by the time required to read the image from the vidicon (b)(3) faceplate into magnetic tape recorders and then erase this image and prepare the vidicon for the next. The STX image time [redacted] is based on an estimate of the time required for material transport. On the average, the STX advantage in this regard over the multiple vidicon system is not as great as it may appear. In general, some time will be required to repoint the optical system before the next image can be accepted. Since repointing can occur while the vidicon is being read out and erased, only a fraction of the [redacted] can be counted as waste time. For a reasonable attitude control system, (b)(1) studies have indicated an average repoint time of approximately (b)(3) [redacted] The operating altitude of [redacted] miles was selected to give slightly better than worldwide access in a [redacted] coverage cycle with the [redacted] mile access swath. This access swath requires (b)(1) a plus or minus 45 degree roll angle capability. The information (b)(3) bandwidth of the data link through the relay satellite is selected so that all images acquired from a given pass over the Sino-Soviet Bloc can be recovered to a [redacted] The peak image capacity per day specified at [redacted] images (b)(1) per day does not represent a firm limitation; however, it is difficult (b)(3) to see where greater capacity than this might be required.

Performance Analysis

As is summarized in Chapter 1, the Warning/Indications Task Force report calls for 83 images per day to realize a 70 per cent confidence level of detecting abnormal activity at any of the 505 Soviet military installations. A 90 per cent confidence level calls for 142 target coverages per day. The second requirement addressed in Chapter 1, high resolution surveillance, can be satisfied by approximately 3,900 target coverages per year. Approximately 70 per cent of these coverages are required in stereo giving a total number of annual target images of approximately 6,600. The following paragraph discusses the performance of the systems described in Table IV against these two requirements.

The three important parameters which influence coverage performance are: access swath, cloud cover statistics, and target distribution. Target distribution is particularly important in discrete target coverage systems of the sort being discussed here in that limitations of pointing agility will inhibit target coverage performance in high density target areas. Table V shows the distribution of the two target lists by latitude. Also shown in Table V are the average daily accesses per target in each latitude band. The strong clumping of both target lists in the northern latitudes has both positive and negative implications. On the one hand, the more northerly latitudes are covered more frequently since the spacing between successive imaging satellite ground tracks decreases with increasing latitude. On the other hand, this concentration in northern latitudes also implies a high density target distribution which will give rise to potential targeting conflicts due to systems agility

TABLE V
TARGET DISTRIBUTION BY LATITUDE

Latitude	Number of Warning/Indications Targets	Number of Surveillance Targets	Avg. Daily Access Per Target
0 - 10	-	1	.43
10 - 20	-	16	.45
20 - 30	-	329	.50
30 - 40	2	594	.53
40 - 50	114	1,535	.62
50 - 60	326	2,331	.71
60 - 70	56	203	1.00
70 - 80	5	11	2.50
80 - 90	2	2	-
TOTAL	505	5,022	-

limitations. High density target distribution is particularly critical in the case of the warning/indications problem since a high daily coverage rate is required. Table VI shows the distribution of warning/indications targets by longitude. From these two tables it can be seen that over 400 of the 505 targets lie between 20 degrees and 50 degrees east longitude and 40 degrees and 70 degrees north latitude.

Table VII displays the two target distributions in another form. In this table are shown the number of targets accessed on each of the eight active passes per day. Since the orbit selected repeats the same ground track on a three day cycle, the data in Table VII is representative of a complete mission. The peak target numbers which characteristically occur on pass six or seven are again symptomatic of the high target density in the western Soviet Union.

For the warning/indications target list, an average of 450 targets fall in the [redacted] nautical mile access swath of the imaging (b)(1) satellite per day. Averaged over a year, 129 of these target accesses (b)(3) will be cloud free. However, there is a considerable variation about this average for various times of the year. In November and December the bimonthly average number of daily cloud free opportunities falls to 72, whereas in March or April the daily average rises to 165. During the winter months, in particular, there will be large deviations from the mean on a daily basis.

The image frame size and systems agility limitations will further degrade system performance below that estimated on the basis of cloud cover and access only. Figure VIII is a graph showing the performance of the multiple vidicon system and the STX system against the warning/indications target list based on the mean bimonthly cloud cover conditions. The multiple vidicon shows a poor performance both because of its smaller frame size and because of the longer mean time between sequential images. On a bimonthly average basis it can be seen that the STX system will meet the coverage level required for 70 per cent confidence during the best times of the year; whereas the multiple vidicon system falls well short of this objective. However, it should be noted that in order to reach this coverage level the STX system has to take full advantage of its capability to point plus or minus 45 degrees in both roll and pitch, and some fraction of the imagery will be degraded not only by obliquity, but also by systematic uncompensated image motions characteristic of oblique photography in framing systems. The amount of this image motion degradation will depend upon the level

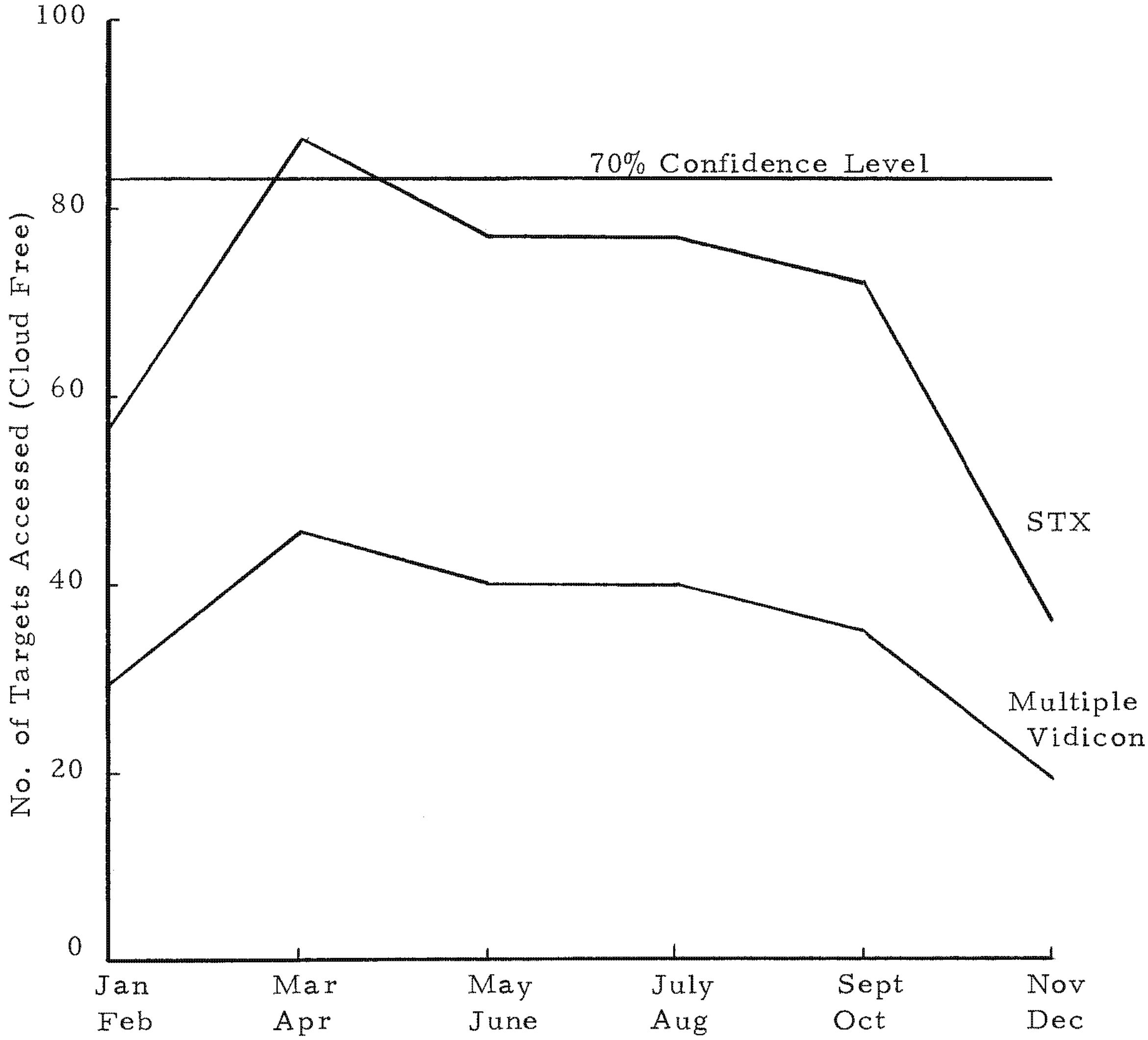
TABLE VI
WARNING/INDICATIONS TARGET DISTRIBUTION BY LONGITUDE

East Longitude	Number of Targets
19 - 30	249
31 - 40	105
41 - 50	48
51 - 60	14
61 - 70	10
71 - 80	6
81 - 90	8
91 - 100	4
101 - 110	1
111 - 120	4
121 - 130	17
131 - 140	26
141 - 180	11
181 - 190	2
	505

TABLE VII
TARGET DISTRIBUTION BY PASS OVER SINO-SOVIET BLOC
(Access Swath - [redacted] Nautical Miles) (b)(1) (b)(3)

Surveillance Targets			Warning/Indications Targets		
Pass	Number of Targets Accessed	Seconds Per Pass	Pass	Number of Targets Accessed	Seconds Per Pass
Day 1			Day 1		
1	39	360	1	7	240
2	639	300	2	37	180
3	517	720	3	7	240
4	194	720	4	15	360
5	818	780	5	94	360
6	1,555	360	6	297	300
7	148	240	7	-	-
8	11	120	8	-	-
	3,921			457	
Day 2			Day 2		
1	34	120	1	4	180
2	81	360	2	12	240
3	845	540	3	10	120
4	444	800	4	11	180
5	420	720	5	28	480
6	1,129	600	6	136	540
7	1,385	360	7	288	240
8	5	60	8	-	-
	4,343			489	
Day 3			Day 3		
1	15	240	1	8	120
2	62	300	2	25	360
3	183	360	3	6	240
4	743	720	4	13	240
5	337	840	5	38	480
6	332	660	6	296	600
7	1,680	720	7	17	180
8	617	300	8	-	-
	3,969			403	

FIGURE VIII
COVERAGE PERFORMANCE AGAINST WARNING/INDICATIONS TARGETS
(Average Cloud Conditions)



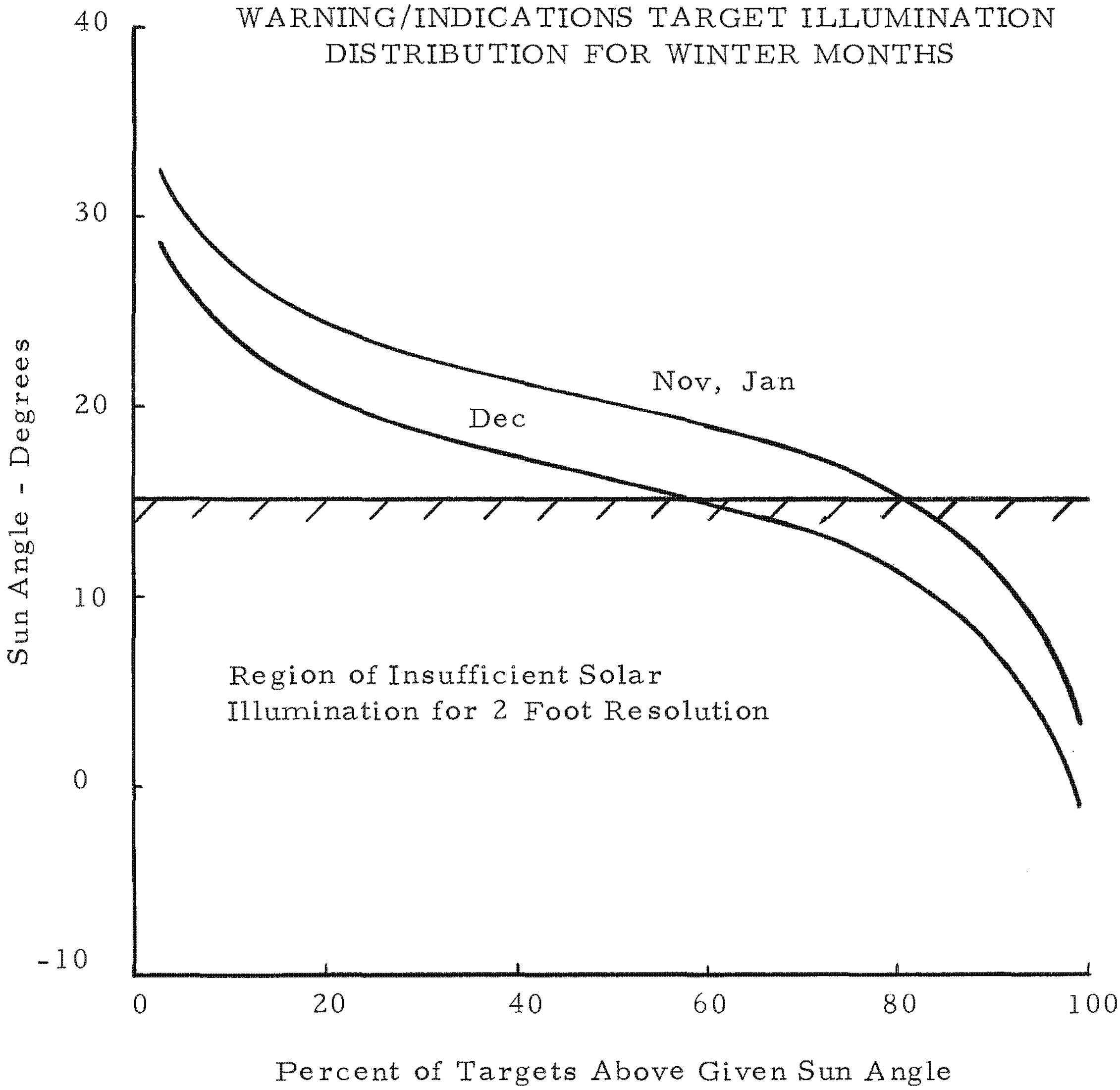
of complexity of the compensation mechanization. If both translational and rotational image motion compensation is used, low smear rates can be achieved even at 45 degree pitch angles. However, this is a complexity which would be introduced only if essential.

Another problem associated with the warning/indications target list is the low scene illumination level during the winter months in the northern latitudes. Figure IX shows that in December 40 per cent of the warning/indications targets fall below 15 degrees sun angle. At an operating altitude of [redacted] nautical miles an optical aperture large (b)(1)
enough to provide two foot nadir resolution at zero degrees sun angle (b)(3)
is impractical. The optics for the systems summarized in Table IV have been designed for the scene illumination characteristic of 15 degrees sun angle. Therefore, during the winter months not only will the system performance be degraded due to cloud cover conditions, but also the image quality will be degraded on some fraction of the targets due to scene illumination limitations.

The above discussion of systems performance against the warning/indications target deck has been for the case of one imaging satellite. A second satellite will approximately double the performance. The second satellite will also tend to smooth the daily fluctuations of target coverage performance due to cloud statistics. With two systems operating on orbit simultaneously, the multiple vidicon system can meet the 70 per cent confidence level coverage requirement for much of the year, and the STX system will generally exceed the 90 per cent confidence level coverage requirement. In the case of the STX system in particular, the second imaging satellite will reduce the amount of high obliquity coverage, but in neither case will the second vehicle help the problem of low scene illumination in the winter months.

While one imaging satellite is marginal against the level of coverage required by the warning/indications requirement, the situation is quite different in the case of the target surveillance requirement. For the surveillance targets there are an average of 1,223 cloud free target opportunities per day. In order to achieve the annual coverage level of approximately 6,600 target images, the daily average rate is approximately 18 cloud free images per day. Therefore, it is clear that either system defined in Table IV has a considerably greater coverage capability than is needed to meet the current Sino-Soviet target surveillance requirement. Because of the systems' relatively high access rates, it is possible to realize tremendous flexibility in responding to the needs of the Intelligence Community for high resolution imagery. For example, in the case of a target which lies north of

FIGURE IX
WARNING/INDICATIONS TARGET ILLUMINATION DISTRIBUTION FOR WINTER MONTHS



40 degrees latitude, there is a greater than 90 per cent assurance that an image of that target will be obtained in less than 10 days from the time of the decision that coverage is required. Furthermore, the problem of conflicting targeting requirements in high density target areas is to a large measure eliminated because all target complexes north of 40 degrees are accessed at least twice every three days.

In addition to these considerations, the peak daily systems capability is more than a factor of 10 higher than that required for an average day. Therefore, a large reserve capability exists for responding to unanticipated imagery needs. In general, the functional characteristics of electro-optical imaging systems should permit a more orderly collection and exploitation process in every regard. This should result in a more efficient utilization of Intelligence Community assets as well as the dollars allocated to satellite reconnaissance collection.

If an electro-optical imaging system were to be targeted primarily against the warning/indications problem, some residual capability would remain to be used against the high resolution surveillance problem. A quantitative analysis of the interaction between these two requirements has not been made. However, it is clear that in the sector of the Sino-Soviet Bloc between 40 degrees and 70 degrees north latitude and 20 degrees and 50 degrees east longitude, the warning/indications target list will be largely in conflict with surveillance targets. Although this same area is also the high density area for surveillance targets, it may well be possible to adjust priorities so as to in large measure meet the surveillance requirement.

CHAPTER 3: GENERIC SYSTEMS DESCRIPTION

This chapter summarizes performance characteristics of the various subsystems associated with the imaging satellites defined in Table IV. The engineering choices outlined below are based on a preliminary analysis of the technical requirements the various subsystems must meet but do not necessarily represent the optimum choice in every case. The detailed engineering design studies necessary to define fully specific hardware configurations have yet to be performed. Nonetheless, the configurations are clearly workable, if not necessarily optimum. Each of the major subsystems will be further discussed in Chapters 4 and 5.

Table VIII presents in summary the various subsystems selected. There are two alternatives in this table depending upon the selection of either the multiple return-beam vidicon transducer or the screened thermoplastic transducer (STX). The multiple vidicon transducer is a [redacted] (b)(1) (b)(3)

The optical system required to achieve two foot ground resolution from an altitude of [redacted] miles has an aperture of [redacted] (b)(1) A possible optical design is a [redacted] (b)(3) system operating in conjunction with a reimaging optics train for each vidicon. The quadrisectioning of the image is accomplished by a beam splitting technique. Exposure is controlled by focal plane shutter. Good image motion compensation can be achieved over the full range of pitch and roll angles by programmed rotation and translation of each vidicon during exposure.

After exposure, [redacted] vidicons are read out in parallel at an information bandwidth of [redacted] per vidicon. There is a separate [redacted] tape recorder for each vidicon. Each tape (b)(1) recorder has the capacity to store up to [redacted] images. To accomplish (b)(3) image recovery, [redacted] tape recorders are read out in parallel at an information rate of one MHz per recorder using 8:1 tape recorder

TABLE VIII

ELECTRO-OPTICAL IMAGING SATELLITE SUBSYSTEMS

Transducer:	Multiple Vidicon or STX
Optical System Diameter Multiple Vidicon: STX: Optical System F/Number Multiple Vidicon: STX:	[redacted] (b)(1) (b)(3)
Image Data Storage:	Magnetic Tape Recorder or STX
Storage Capacity:	[redacted] (b)(1) (b)(3)
Data Link Information Bandwidth Primary (through relay): Backup (to Ground Station):	[redacted] (b)(1) (b)(3)
Attitude Control System:	[redacted] (b)(1) (b)(3)
Command System Link: Storage:	 Through relay or direct from Ground Station Integral with Attitude Control System Computer
Power:	Solar Cells and Batteries
Space Vehicle Weight:	~10,000 lbs.

speed-reduction on playback. The resulting video signal is relayed through a stationary communications satellite to the ground station in the continental United States. In addition to the primary mode of data recovery through the relay satellite, there is a separate backup mode which permits readout from the imaging satellite directly to the ground station at an information rate of eight MHz per tape recorder. Recovery of one image through the primary relay link requires approximately [redacted] (b)(1) (b)(3)

The system option employing STX does not use tape recorders since STX has an image storage capability. The STX configuration discussed in Chapter 2 uses an 8 x 8 inch format size. The STX may be handled either in the form of thin glass plates or a flexible belt. The optical system required to meet the two foot ground resolution requirement has an aperture diameter of [redacted] and an [redacted] The operational sequence involves applying (b)(1) a surface charge to the STX material, exposing the material, re- (b)(3) charging the material, and developing the latent electrostatic image by heating the thin plastic layer. The image information can then be read out at any subsequent time with an optical scanner. After readout, the stored image can be erased by a second heating of the plastic layer. The primary mode for recovering imagery is through a relay satellite as in the case of the multiple vidicon configuration with a backup link directly to the ground station. Because of the larger frame size, a higher readout data rate may be required than that needed for the multiple vidicon system if a [redacted] image/day capacity is required.

[redacted] (b)(1) (b)(3)

Programming of the imaging satellite is by stored ground command. Commands can be transmitted to the space vehicle either through the relay satellite or directly from a ground station. The power is provided by a combination of solar cells and rechargeable nickel cadmium batteries. The total space vehicle weight is estimated to be on the order of 10,000 pounds. While a detailed study to support a launch vehicle selection has not been made, a space vehicle of this weight and size is compatible with the capabilities of the Titan III class launch vehicles for low earth orbit missions.

With the exception of the transducers, all of the subsystems discussed above are currently within the existing state-of-the-art. The optical systems, although large, can be fabricated with current technology. In addition, new fabrication and test techniques are now under development which will greatly improve the capability for fabricating large optical systems of this class. The data link requirements are modest and are well within demonstrated capability. The tape recorders required for the multiple vidicon system have not yet been developed and space qualified; however, six MHz bandwidth recorders have been successfully flown in other space programs. The eight MHz recorder with 8:1 record to playback ratio can be developed using the technology of the current six MHz recorders. Depending upon the exact size of the space vehicle, [redacted] development program may be required. However, [redacted] (b)(1)
[redacted] of this general size class are currently available. (b)(3)
Design studies have not progressed far enough to determine whether or not existing flight computers can be adapted to the requirements of this application. However, even if a computer development program is required, it will not represent any extension in the state-of-the-art. The solar cell/battery power system is typical of power supplies currently in use in other space programs.

Both the return beam vidicon and STX are developmental items. The three inch return beam vidicon, however, is a direct extension of the [redacted] two inch return beam vidicon and does not (b)(1)
represent a major developmental program. A detailed evaluation (b)(3)
of this particular tube has been conducted. A vigorous development effort could produce a prototype tube for the requirements discussed in this paper in approximately 12 months. STX is a longer term development. A substantial program in this area has been underway for the past 10 months, and it is estimated that another two years will be required before a systems development program could be initiated based on this transducer.

CHAPTER 4: TRANSDUCER DESCRIPTION

This chapter describes the design and function of the three transducers introduced earlier in this report: the Return-Beam Vidicon, the Screened Thermoplastic Transducer (STX), and the Solid State Array. None of these devices is currently available in flight-qualified form. The amount of development work which is required before the initiation of an imaging satellite acquisition program is different for each of the devices. The return-beam vidicon is the most mature of the three in that a flight-qualified prototype tube can be developed in approximately 12 months. The solid state array is currently somewhat earlier in its development cycle and will require two to three more years of work before an imaging satellite program could be initiated based on it. The STX development required is critically dependent on the specific design requirements it must meet. A carefully planned development program is now under way for STX which will lead to an initial capability to produce minimum-standard materials in about two years and an expanded capability yielding higher performance materials in three years. Another image tube under development by [redacted] will also be discussed briefly. (b)(1) (b)(3)

Return-Beam Vidicon

The return-beam vidicon is a new type of image tube developed by [redacted] In outward appearance, the tube is not far different from the picture tube of a five-inch oscilloscope. The overall size is about two feet in length and less than a foot in diameter, including deflection coils. The tube employs a glass faceplate with a photosensitive surface and an electron gun which reads out the image from the faceplate and converts it to an electrical signal. (b)(1) (b)(3)

Light from the target passes through the optical system and is focused on the face of the vidicon tube. The inner surface of the glass faceplate has a very thin layer of photoconductive material deposited on it. The inner surface of this layer is initially negatively charged by spraying it with electrons from the gun located in the tube neck. This places a negative electric field across the photoconductive layer. A shutter opens to permit light to fall on the tube, causing the charges on the inner surface of the photoconductor to leak off. The brighter the light, the more charge leaks away. Following exposure, a replica of the image exists on the tube face in the form of an electric charge pattern.

The charge pattern must then be converted into a video signal. This is done by scanning the surface with a low-energy electron beam. The electric charge pattern representing the optical image repels some of the incident electrons from the scanning beam. The fraction of the beam electrons repelled is related to the electric charge density on the photoconductive layer being scanned. The repelled electrons are collected and amplified in an electron multiplier stage and converted to an electrical signal. After the entire tube face has been scanned, the surface is erased and prepared for the next image by restoring the uniform potential on the photoconductor.

Exposure times for the vidicon are of the same order as those for photographic film, i.e., about a hundredth of a second. Readout time is five to ten seconds, depending upon the conditions of operation. Readout speed is limited by the maximum current available from the electron gun and by the bandwidth capability of the electron multiplier. Both of these components are being continually improved. Erasing the tube requires three to five seconds, limited by electron gun current and the time constant of the photoconductive surface.

Though the details of the optical system design to be used with a vidicon are different from those of a system to be used with silver halide film, size and complexity are nearly equal. Two foot ground resolution from [redacted] miles altitude requires approximately (b)(1)
[redacted] optical aperture diameter, a large but feasible size, and (b)(3)
approximately equivalent to the optics used in a system currently under development.

The sensitivity and resolution properties of the return-beam vidicon are adequate. For satellite reconnaissance, the transducer must also be capable of recording a large target area. Unless a major tube development is undertaken, vidicons must be grouped together in order to obtain a 3 x 3 mile frame size. It appears likely that with an adequate development effort the vidicon performance can be improved somewhat over that currently obtainable. In particular, some electron gun improvements can probably be made. However, no dramatic breakthroughs are expected. Thus, the total number of picture lines that can be stored on a single tube is constrained.

Vidicons with a 2 x 2 inch format have been operating in the laboratory. A large base of experience has been gained in the setup and operation of these tubes. Vidicons of a 1 x 1 inch format have been flight-qualified for aircraft, which due to the vibration environment represents a more stringent requirement than space qualification for this item. Though the 2 x 2 inch tubes have operated only in the laboratory, there appear to be no major problems involved with adapting them for space use. The 3 x 3 inch format vidicon, discussed elsewhere in this paper, is felt to be only a small extrapolation from existing technology.

To summarize, while the return-beam vidicon has practical limitations on frame size, reliability, and readout time, it offers a near-term solution as an electro-optical transducer having adequate resolution, sensitivity, and general mechanical and electrical properties.

Screened Thermoplastic Transducer (STX)

The development of the STX is predicated on the fact that light reflected from highly deformed surfaces can be collected to form imagery. If the deformations occur in an orderly pattern, the imagery contains useful information content. The ability to control the deformation patterns imposed on the surface of thin plastic films coated on a class of photosensitive materials known as photoconductors (materials which become electrically conductive when exposed to light) provides the basis for STX.

The transducer, in its present configuration, consists of a 1/8 or 1/16 inch thick glass plate on top of which is deposited a thin metallic layer which serves as an electrical ground. Adjacent to this is a metallic screen which contains approximately 300 parallel lines per millimeter. The next layer consists of the light-sensitive, photoconductive material. This is coated with a thin outer layer of thermoplastic which forms the surface of the device.

In operation, the surface of the plastic is negatively charged to a uniform potential of several hundred volts by sweeping it with an electron beam. When the photoconductive layer is exposed to light, charge conduction through the photoconductor occurs, thereby altering the initially uniform potential. The electric field exerts a compressive force on the thin plastic layer which is proportional to the magnitude of this potential. If the viscosity of the plastic is reduced to its flow point by heating, the higher compressive force level in the light-exposed areas becomes sufficient to overcome the surface tension of the plastic, and deformation occurs. Charge potential and viscosity of the plastic are controlled so that unexposed areas remain smooth or specularly reflecting, whereas the light-exposed areas deform to provide the light reflecting surfaces for image formation. Readout is accomplished by scanning the STX surface with a light beam. Light scattered by the deformed plastic is collected and imaged on a photocell. The electrical output of this cell forms a video signal containing the desired image information. After readout the STX can be erased for reuse by reheating the plastic layer. The usefulness of the device derives from the fact that changes in conductivity, surface charge, and deformation density are proportional to the intensity of the exposing light. The function of the screen is to provide a high frequency carrier whose signal is amplitude modulated by the lower frequency signal of the image. The use of a screen improves the response, sensitivity, dynamic range, and contrast characteristics of the transducer. In practice STX is comparable in sensitivity-resolution performance to silver halide film. Furthermore, current experimental STX devices can probably be substantially improved, particularly in resolution performances as the R&D program progresses.

A format size of 8 x 8 inches is the current goal. However, there is no technological barrier to prevent enlarging the format. The fabrication of larger area screens is the major problem in this respect, but experience to date indicates that this can be accomplished if required.

The selection, fabrication, and testing of optimum components of the transducer are currently under way. Primary emphasis has been on photoconductor and thermoplastic materials studies, and indications are that optimum solutions are in hand. Similar progress has been achieved in key fabrication and technology areas, and it is expected that all key technical milestones will be achieved on schedule. The follow-on R&D phase will emphasize the development of fabrication techniques necessary to produce components in reasonable quantities with the objective of producing integrated devices for component compatibility evaluation and extensive image quality analysis. The final phase of the development effort will be geared to establishing fabrication and materials specifications and to demonstrate the capability of producing operationally acceptable transducers on a pilot plant scale.

The objective of the R&D program described is to produce a fast, high-resolution, reusable photoreceptor whose operation does not require use of expendable materials and which will have a useful plate lifetime of 18 months. Each plate will be capable of multiple reuses. The achievement of this basic goal offers significant advantages for future long life electro-optical reconnaissance systems in addition to those mentioned. The sensitivity-resolution data are conservative estimates of potential performance. Unlike film, the resolution is not limited by grain size, and the speed of the transducer is nearly a direct function of the photoconductor efficiency. Experimental photoconductors have demonstrated sensitivities several times better than those of the best film available today. In addition, the STX has a built-in storage capability; images can be retained for several hours if necessary before being read out. This feature could ease the data transmission problem considerably. Probably the most desirable long-range goal for STX is the development of a flexible base material having physical characteristics similar to film. Achieving this goal is dependent upon developing techniques for applying photoconductors, which are glass-like in nature, to optical quality plastics in configurations which permit the materials to be twisted around at least moderate radii of curvatures.

Solid State Array

The solid state array is a grouping of solid state detectors arranged in the image plane of the optical system. The detectors are placed in a line which is perpendicular to the satellite velocity vector. Thus, at any instant of time, the array looks at a line on the ground which is at right angles to the satellite ground track. As the vehicle moves, this line is swept across the ground.

In operation, the amount of light falling on each element of the array is converted to an electrical signal which is sampled and either recorded or transmitted directly to the ground. Thus, the electrical signal coming from the array consists of sequential readings from each element across the array. The array can, therefore, be pictured as scanning the ground in the cross-track direction as the satellite moves along its orbit. This is the same geometry as a television raster scan. The difference is that, in this case, the line scanning is achieved in the optical focal plane, with the line traversal being taken care of by the satellite movement over the ground.

To date, the best performing solid state array has been fabricated using phototransistors. Higher resolution arrays can be built employing photodiodes or photoconductors, but they have not yet shown adequate sensitivity.

Resolution in the cross-track direction is determined by the spacing of the individual elements in the array. Along-track resolution is determined, in part, by how often each element is sampled. Ground resolution of two to three feet appears to be feasible. Resolution better than two feet may not be possible within state-of-the art optical design unless the more optimistic sensitivity predictions are achieved. At the scan rate induced by the satellite velocity, each photosensor has a very short time to look at each ground resolution element (the satellite moves one foot in about 50 microseconds). Consequently, even a perfect detector (the ideal photon counter) will not have adequate sensitivity for two foot ground resolution with feasible optical systems. In order to relax this optical problem, the effective satellite velocity is reduced by slowly pitching the satellite forward during the picture taking time. This permits each photodetector to look at each ground resolution element for a longer time. This slowdown technique permits smaller optical systems and less stringent photodetector designs. The price for this improvement is an increased time required to image each frame, and a slightly increased satellite attitude stability requirement. Slowdown factors of between five and ten (b)(1)
appear to be feasible for implementation. Optical diameters of (b)(3)
[redacted] are then adequate to obtain two foot resolution from an altitude of [redacted] nautical miles. (b)(1) (b)(3)

Cross-track format size is determined by the number of individual photosensors making up the array, up to the point where the angular field-of-view of the optical system becomes limiting. Format size in the along-track direction is limited by the image velocity reduction described in the previous paragraph. Frame sizes of 10 x 10 miles are quite reasonable with this system.

Small-scale solid state arrays have been operated in the laboratory. Performance predictions for operational designs have been extrapolated from data measured on these arrays. Barring unforeseen development problems, solid state arrays can be built to meet the overall system performance requirements discussed in Chapter 3.

Solid state linear arrays are attractive because of their construction, consequent high reliability, and large format possibilities. Other advantages include an electrical output that is compatible with data transmission systems. The small physical size and shape of the linear array permits optical system designs not possible with other transducers such as film, which requires a complicated transport mechanism to be located near the focal plane.

[redacted] Image Tube

A new image tube is currently under development [redacted] as a United States Air Force sponsored effort. The design specifications for this development are specifically oriented to the requirements of high resolution reconnaissance. (b)(1) (b)(3)

[redacted] tube is an electrostatic device akin to the vidicon, but unlike the vidicon, it has a capability of storing a number of images in the form of electron charge distributions on a moving belt or drum. The image data is read out with an electron beam.

This tube will probably require several more years of development before it is available for application.

CHAPTER 5: SUPPORTING TECHNOLOGY

The image transducer is the only system element which represents a major developmental problem. The technology required for the remainder of the system poses no serious feasibility problems, although several of the subsystems will require supporting engineering development programs. This chapter presents a brief review of each of the major subsystems associated with the imaging satellite, the relay satellite, and the ground station. As had been mentioned in Chapter 3, the detailed engineering design for the total system has not been accomplished; therefore, the subsystem discussions are concerned only with establishing the engineering feasibility against the general design requirements discussed earlier in this paper. Specific hardware examples mentioned below are included as being representative only and should not be construed as specific design choices.

Optics

Preliminary optical design studies have been conducted for the various transducers of interest. The unique features of these transducers introduce a number of degrees of freedom in the optical design which are not normally available for photographic systems. This factor coupled with the desire to operate at orbital altitudes higher than those usually associated with photographic systems lead to classes of optical designs not previously encountered in satellite reconnaissance. However, the basic problems of optical element fabrication and optical system mechanical design and alignment are very much the same as those encountered in the more usual photographic systems technology.

Both [redacted] have been considered. For the vidicon and STX transducers, the [redacted] system appears to be one of the more favorable design options. However, in the case of the solid state arrays, a broader range of optical system selections is available. This is largely due to the fact that solid state arrays are physically small, and can therefore be placed directly within the optical system. In addition, the solid state arrays do not require complex image

(b)(1)
(b)(3)

motion compensation systems or exposure control and shuttering mechanisms. Against these design requirements, one of the several three mirror optical systems configurations may be most desirable.

In all cases for an operating altitude of [redacted]nautical miles, optical systems with aperture dimensions in the [redacted] range are required. Optical elements of this size can be manufactured with current fabrication and figure evaluation technology. In fact, a system which requires folding flats and primary mirrors of approximately [redacted]n diameter is now under development. The optical requirements in the electro-optical imaging system are somewhat eased from a manufacturing point of view since a high production rate will not be required. Furthermore, new optical element fabrication techniques are now being developed which will result in substantial improvement in the capability to figure large mirrors even when aspheric surfaces are required. Various schemes for mechanizing the active alignment of large optical systems after the space vehicle has been placed in orbit are also under active investigation. As these techniques are developed to the point where they can be incorporated in the systems design, the problems associated with the mechanical alignment of optical systems will also be alleviated. (b)(1) (b)(3) (b)(1) (b)(3)

In summary, there is no fundamental problem associated with the design and acquisition of the large optical systems required to meet the proposed performance objectives.

Magnetic Tape Recorder

Systems incorporating the return-beam vidicon and the solid state array will require either [redacted] data relay from the imaging satellite or on-board storage of the image data. In the latter case, the storage requirements can be met by the current state-of-the-art in magnetic tape recorders. A number of manufacturers are actively pursuing space-qualified tape recorder development work. In particular, [redacted] has developed a line of tape recorders which most nearly match the requirements of the systems of interest here. (b)(1) (b)(3) (b)(1) (b)(3)

[redacted] recorders use a rotary recording head technique very much like that used in broadcast television tape recorders. [redacted] recorder is space-qualified and is now in active use in a satellite program. This recorder has a six MHz (b)(1) (b)(3)

information bandwidth and records on two inch wide magnetic tape with oxide coating on both sides. The recorder weighs 94 pounds and uses 135 watts of power when operating at a head-to-tape speed of 125 inches per second. [redacted]s currently developing and qualifying the [redacted] recorder which is a direct extension of the [redacted] technology. This recorder has an eight MHz information (b)(1)
bandwidth and incorporates the capability for 8:1 slowdown upon (b)(3)
playback. It has a 48 minute record capacity which is more than adequate for storing [redacted] images from the multiple vidicon system discussed in earlier chapters. The instrument weighs about 80 pounds and has a power consumption of 100 watts. In addition, the dynamic range is more than adequate for recording the video signal from the return-beam vidicons. Similar experimental recorders with information bandwidths in excess of 10 MHz have been fabricated in breadboard form and tested in the laboratory.

In the past there has been considerable question concerning the reliability of space-borne tape recorders. However, recent developments in mechanical configuration and techniques for maintaining adequate cleanliness in the vicinity of the recording heads has resulted in substantial reliability improvements. Recent flight experience has been very encouraging and leads to increased confidence that the requirements of the electro-optical imaging systems can be met.

In summary, recorder technology is well developed and continues to advance. No basic feasibility or engineering problems are anticipated in this subsystem area.

<u>Image Recovery</u>

There are three basic data links associated with image recovery from the electro-optical imaging satellite. The primary mode of image recovery involves the relay of data from the imaging satellite through a stationary relay satellite to a ground station located in the continental United States. The first data link of interest is the up-link from the imaging satellite to the relay The second data link connects the relay satellite with the ground station. The third link is a backup mode which permits direct readout of imagery from the imaging satellite to the ground station.

In this arrangement, the relay satellite is a simple communications transponder very similar in general arrangement and design requirements to conventional communication satellites.

The primary mode of image recovery takes advantage of the relatively large amount of time available for reading out the imagery information. Since there are many hours per day during which the imaging satellite is visible from the relay satellite, the data bandwidth requirements are quite modest. In the case of the multiple vidicon system, a [redacted] image per day total capacity can be recovered by [redacted] (b)(1) through the relay satellite. With the larger format size of the (b)(3) STX system, [redacted] images per day could be relayed with the same [redacted] capacity. However, in this case, a more (b)(1) optimum design would probably call for a somewhat higher channel (b)(3) capacity. The backup data link in the case of the multiple vidicon systems consists of [redacted] for a total information bandwidth [redacted] This is the maximum rate at which the tape recorders can be read out. In the backup mode, there will be a loss in timeliness of image recovery and a reduction in the total image capacity per day from [redacted] to approxi- (b)(1) mately [redacted] (In the relay case, [redacted] channel capacity will (b)(3) permit recovery of almost [redacted] 3 x 3 nautical mile images per day; (b)(1) however, this appears to be a far larger total capacity than would (b)(3) reasonably be required.) A [redacted] information bandwidth backup in the case of the STX system will result in a total daily image capacity of approximately 30 images. However, the STX can be read out at a higher information rate, and the data link technology does not set the [redacted] limit. (b)(1) (b)(3)

Various RF modulation schemes are available. Both digital techniques and FM modulation techniques have been examined, and both appear feasible. The antenna sizes on the imaging satellite and the relay satellite are in the [redacted] and (b)(1) pose no particular problem. Antenna pointing from the imaging (b)(3) satellite to either the ground station or the relay satellite is quite straightforward in that the attitude control system required for optical system pointing provides more than adequate accuracy for antenna control. However, the pointing of the antenna on the relay satellite associated with the link to the imaging satellite does pose a potential engineering problem. This link requires a relatively high-gain, narrow-beam antenna. Since the attitude control accuracy of the relay satellite is not sufficiently accurate to point this high-gain antenna at the imaging satellite, this antenna must execute a programmed search mode at the beginning of each data relay interval. After the relay satellite antenna has acquired the imaging satellite, it must then automatically track the imaging satellite. (However, antenna control is not judged to be a key feasibility problem area.)

The radio frequency for the data links can be placed anywhere in the [redacted] Modulators and power amplifiers for these frequencies are already available. There are advantages to be gained by using a [redacted] frequency for the imaging satellite/ (b)(1)
relay satellite data link, but the component technology at these (b)(3)
frequencies is not fully developed. Table IX summarizes a representative set of characteristics for the three links discussed above.

In summary, there is no basic feasibility problem associated with the data links. The one new engineering feature which must be incorporated in the relay satellite portion of the link is the search and track mode on the high-gain antenna linking the relay to the image satellite.

The issue of data security has not yet been explored in any detail since communications security guidelines for the various links have not been established. There are a number of potential ways of providing various degrees of security for these links. First, the geometry of the situation provides a considerable degree of inherent security. The imaging satellite data link to the relay satellite could be intercepted from a ground site with relative ease; however, since the imaging satellite traverses the entire western hemisphere during the process of relaying one day's take, no single ground station could intercept more than a small fraction of the total images read out. The incorporation on the imaging satellite of a low power noise transmitter radiating at the data link frequency would inhibit the ability of a ground site to intercept even this amount of imagery without introducing corresponding penalties for the United States ground station.

If digital modulation is employed, it appears feasible to incorporate in the imaging satellite some level of encryption. Encryption would complicate the imaging satellite and would therefore be undesirable. If the imaging satellite/relay satellite link used a frequency o [redacted] (b)(1)
(b)(3)

TABLE IX

TYPICAL DATA LINK CHARACTERISTICS

	Imaging Satellite to Relay Satellite	Imaging Satellite to Ground Backup Mode	Relay Satellite to Ground
Carrier Frequency	[redacted]		
Information Bandwidth Per Channel			
Bandwidth (RF) Per Channel			
Transmitting Antenna Diameter			
Receiving Antenna Diameter			
RF Power			
Half-power Beam Width			
Modulation			

(b)(1)
(b)(3)

[redacted] (b)(1) (b)(3)

The link from the relay satellite to the United States ground station does not appear to pose a major security problem even without encryption. A relatively high-gain, narrow-beam antenna will be employed on the relay satellite so that the ground area illuminated by this antenna can be confined to United States territory. In addition, a large (60 foot) high-gain antenna will be used at the ground station. Therefore, the RF power transmitted by the relay satellite can be reduced to a low level. It should be possible to provide adequate security to prevent the construction of a sufficiently large antenna close enough to the ground station to intercept the imagery signal at an adequate signal-to-noise ratio. The security considerations for the backup link are similar to those for the imaging satellite/relay link.

Attitude Control System

[redacted] (b)(1) (b)(3)

A stellar reference approach appears to be required to derive attitude to the accuracy needed for targeting from an orbital altitude of [redacted] miles. The more conventional and in some ways simpler horizon scanner systems appear to be inherently limited to an accuracy several times poorer than that needed for the small frame size electro-optical transducers. Several stellar reference systems are available, and the selection of an optimum technique will require considerable further study. However, one scheme which appears simple and adequate has been evaluated in some detail. This concept calls for stabilizing the space vehicle attitude in inertial coordinates once per revolution. A Sun sensor and a star sensor are located on the space vehicle so that in this attitude an attitude measurement can be taken by sightings on the Sun and the star Canopus. [redacted]

(b)(1)
(b)(3)

An attitude reference system based on inertial measurements requires an on-board computer to combine ephemeris information derived from ground tracking of the space vehicle with the inertial reference information to compute control signals for pointing the space vehicle at specified target locations. This computer also serves as the command programmer and stores in its memory targeting commands transmitted to the satellite from the ground station. The design requirements for this computer are readily achievable. The magnetic core memory capacity needed is approximately 8,000 twenty-four bit words. The computer clock rate is about 1 MHz. A computer of this capability weighs about 75 lbs and requires about 75 watts of power. A number of computers of this general capacity are either currently available or under development. Although reliability requirements will probably necessitate incorporation of two such computers in the system, the computer does not represent a basic engineering problem.

Relay Satellite

The relay satellite basically functions as a transponder for information transmitted from the imagery satellite to the ground station. The antenna and RF power requirements for the relay satellite were discussed in an earlier section of this chapter. The basic tasks of the remaining relay satellite subsystems are to provide an earth stabilized platform, power, and station keeping propulsion.

The relay satellite required for this application is very similar to communications satellites now under development. Intelsat III is probably closest in general capability. Intelsat III is a spin stabilized satellite with a mechanically despun antenna. It is being designed for a five-year active life. The antenna gains of Intelsat III are lower than those required for the image relay application. Also, this satellite does not incorporate the capability for antenna search and track that will be required in the case of the data link from the electro-optical imaging satellite. However, these features do not appear to present serious engineering problems.

Another approach to meeting the requirements of the relay satellite is to use the Multi-mission Support Stage currently being
developed by [redacted] This stage is designed to operate at synchro- (b)(1)
nous altitudes and provides a three-axis stable platform which (b)(3)
will be more than adequate to carry the antenna and electronics required for data relay. This stage also contains the required propulsion system for final orbit injection and for station keeping as well as housekeeping electronics. It is designed for a three year active life.

In general, the relay satellite for this application is closely related to an evolving family of communications satellites and therefore does not represent a difficult engineering task.

Ground Station

The basic functions of the ground station are to record, process, and reconstruct for visual analysis the recovered imagery. The ground station can be configured in a straightforward manner with little special purpose equipment development. What special equipment will be required can draw on techniques already developed or currently in use.

In the case of the multiple vidicon system and the STX system the image data received at the ground station will be initially recorded on magnetic tape recorders. The video data will then be read out of the tape recorders, processed, and reconstructed on silver halide film using a laser recorder. Reconstruction can be accomplished at data rates eight or ten times higher than those employed in the data readout from the imaging satellite through the relay satellite. Before reconstruction, electronic filtering techniques can be used for one dimensional image processing such as aperture correction and contrast enhancement. More complex image enhancement techniques, if required, involve two dimensional processing and will therefore have to be accomplished digitally. Considerable techniques development work is yet to be accomplished; however, it is clear that substantial gains in image quality can be realized even with simple one dimensional techniques.

In summary, the ground station from a hardware point of view poses no real development problem. However, much remains to be accomplished if full advantage is to be taken of the basic electronic characteristic of the image information.

CHAPTER 6: EXTENDED CAPABILITY OPTIONS

All of the earlier discussion in this paper was concentrated on electro-optical imaging systems based on a design resolution of two feet. The multiple vidicon approach gives a ground frame size of 3 x 3 nautical miles, while the STX approach with its larger format results in a 6 x 6 nautical mile frame size. The two foot ground resolution is not a fundamental limitation of electro-optical imaging techniques. Also, the 3 x 3 nautical mile frame size of the multiple vidicon system results from limitations of the current vidicon technology and is not a limitation of the basic technique.

Return beam vidicon is proceeding at [redacted] with the (b)(1)
objective of designing a tube with the capacity of a larger number (b)(3)
of scan lines per frame. An advanced vidicon may be feasible having approximately twice the number of lines per tube as that used in the definition of the multiple vidicon system as presented in Chapter 3. This improved capability could be exploited to achieve a 6 x 6 nautical mile frame size at two foot resolution or a higher ground resolution at the 3 x 3 nautical mile frame size.

The format size of STX depends only on fabrication technology limitations. However, even the 8 x 8 inch plate size which can currently be fabricated is not a particularly critical limitation. With this same plate size a system could be configured giving a ground resolution of 1 foot with a frame size of 3 x 3 nautical miles.

The problem immediately encountered in going to higher ground resolution with either the vidicon or STX is that the optical system aperture dimension doubles if the operating
altitude of [redacted] nautical miles is retained. Optical elements of (b)(1)
this size are not currently feasible. Therefore, the operating (b)(3)
altitude would of necessity have to be lowered to approximately 140 nautical miles. Substantial quantities of propellant would be required at this altitude to sustain the [redacted]
[redacted] All this would result in a considerable system weight increase (b)(1)
but does not pose any new engineering feasibility problems. (b)(3)
However, with the lowered altitudes the access swath would also

be halved, and the dwell time per target would be correspondingly reduced. In addition, the time available for readout of the image data directly to a ground station would be reduced, although the data recovery time would be unchanged for the systems employing a relay satellite.

As in the case of photographic systems, electro-optical imaging techniques offer a broad range of performance capabilities depending upon basic collection requirements and over-all design objectives. These issues can only be fully assessed in the context of the mission assigned this class of system.

CHAPTER 7: SCHEDULE AND COSTS

A three-year development program will be required for either of the electro-optical imaging systems defined in Chapter 3 of this paper. The program costed below includes [redacted] (b)(1)
[redacted] two relay satellites, and a ground control station. (b)(3)
Although only one relay is required for operation, a backup capability is considered necessary.

The cost estimate of system development, excluding launch vehicles, is [redacted] broken down as follows:

Ground Control Station	[redacted]
Systems Engineering	
Relay Satellites	
Imaging Satellites	
TOTAL	

(b)(1)
(b)(3)

Subsequent imaging satellites are estimated at [redacted] each, and relays at [redacted] (b)(1)
(b)(3)

The multiple vidicon and the STX both require a transducer development program before initiation of the total system development program.

The vidicon development program will require 12 months and will cost [redacted] STX will require 30 months and (b)(1)
[redacted] Therefore, assuming decision to proceed with the (b)(3)
vidicon, beginning 1 July 1968, the resultant system could be operational in FY 1973. If the STX alternative is chosen, the system could be operational in FY 1975.

An additional cost factor, common to both transducer alternatives, is the requirement for supporting technology and engineering effort. This level is estimated at [redacted] per year. (b)(1)
(b)(3)