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REPORT G 864

15 JANUARY 1969

IMAGE MOTION STABILIZATION REQUIREMENTS FOR DYNAMIC VISUAL TASKS IN SPACE

SUBMITTED TO
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA 94035

PERFORMED UNDER CONTRACT NO. NAS2-4985

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IMAGE MOTION STABILIZATION REQUIREMENTS FOR DYNAMIC VISUAL TASKS IN SPACE

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PREFACE

This study was performed under NASA Contract No. NAS2-4985 by the Human Performance Laboratory of the Engineering Psychology Department, McDonnell Douglas Corporation, St. Louis. Charles O. Hopkins was the program manager and Barry J. Cohen the principal investigator. Robert J. Randle of the NASA Ames Research Center was the technical monitor.

Kieth J. Maxwell initially defined the physical properties of an orbiting optical system. He also developed a major portion of the Functional Description of the IMS system.

Wilbert N. Manzelli helped determine the navigational tasks and aided in establishing the Functional Requirements for the Stabilization Subsystem.

ABSTRACT

An analytical study was performed to determine the requirements for stabilizing images of visual targets to be detected and observed by astronauts in future NASA space missions. An Earth resources survey mission, a Moon landing mission, and a Mars landing mission were used to define physical characteristics that would influence the performance of visual tasks. Expected image velocities of targets in each task were compared with the image velocities defining smear thresholds for human vision, photographic films, and electronic sensors to determine image motion stabilization (IMS) requirements. These requirements were used to develop the functional requirements for an IMS system and a plan for its laboratory and airborne testing.

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INTRODUCTION

Some of the most important tasks performed by crew members of manned spacecraft are visual ones involving visible objects (targets) outside the spacecraft. Certain characteristics of man's vision, in conjunction with his decision-making capability, make him a potentially highly effective subsystem for performance of tasks that require detection, recognition, and identification of visual targets. The sensitivity of the human eye is so great that man can detect as few as three light quanta (ref. 1). Man's visual acuity is somewhat less remarkable, but nevertheless, he is often capable of resolving a line separation of approximately 168 microradians (35 seconds of arc)(ref. 2). This degree of acuity can be achieved only under ideal conditions of illumination, brightness contrast, atmospheric transmissivity, and stability of the target image. The determination of requirements for achieving acceptable values for this last condition was the purpose of this study.

Relative motion between a spacecraft observer's eye and a viewed target results in instability of the target image. At certain critical rates of relative motion the target image will blur.

When the target is on the planetary surface, the direction and rate of relative image motion depend, in part, upon the characteristics of the orbit that determine spacecraft velocity and upon the spacecraft attitude rates. With this type of relative motion the image appears to translate across the field of view. Another source of relative image motion is vibration (relatively small amplitude, high frequency oscillatory movements) of the line of sight. For example, if the observer were using a hand-held optical device, muscle tremor and other extraneous vibrations might cause the image to "jump" around independently of any translational movements.

Increasing magnification affects both types of image motion adversely. Vibratory motion is increasingly exaggerated with increased magnification. In fact, at high magnifications, vibratory relative image motion could be a problem, even if the optical device was mounted to the spacecraft, rather than being hand held. In the case of translatory image motion, as magnification is increased, the field of view is decreased proportionately, thereby causing the apparent velocity of the image to increase.

Image Motion Stabilization

Image motion stabilization (IMS) refers to the stopping or slowing down of relative image motion. We will distinguish two types of IMS. One type is concerned with stopping target image motion due to vibration of the line of sight. A stabilization system using angular-rate-sensing gyros would be used to damp out vibrations with certain amplitude and frequency characteristics. This might be called "damping" IMS.

The other type of IMS is concerned with stopping target motion resulting from rotation of the line of sight due to the orbital velocity of the spacecraft and to the spacecraft attitude rates. If the observer follows or "tracks" the target with a line of sight rotation rate proportional to the target's velocity, image blur can be eliminated. This is "tracking" IMS.

In addition to eliminating image blurring, tracking IMS increases the time that a given area is in the field of view. If the observer is searching for a target in a given area, tracking IMS will increase the probability of his detecting the target. Thus, tracking is a type of image motion stabilization that is generally applicable to a wide variety of visual tasks performed by crew members during a manned space mission. This study is concerned with the requirements for tracking IMS.

Study Objectives

An objective of this study is to correlate human dynamic visual acuity with the visual tasks that are expected to be performed by astronauts in some typical NASA space missions. By bringing together minimum task performance requirements and maximum human performance capabilities, we identified those tasks requiring some form of image motion stabilization. Thus, for each visual task this study has asked two basic questions:

(1) Is image motion stabilization required for successful visual task performance?

(2) If IMS is required, what are the requirements for achieving it?

Study Approach

The study was approached from three base areas of interest:

Area I - The capabilities and limitations of human, electronic, and photographic sensor systems for gathering data about the visual environment likely to be encountered in manned space missions.

Area II - The visual tasks to be performed by man in these missions.

Area III - The design and evaluation of an image motion stabilization system.

In Area I, the question was asked, "What potentially useful auxiliary capabilities do man and his equipment have to assist him in extending his capability to gather visual information beyond the limitations of the naked eye?"

In Area II, we asked,"What does man have to see during a typical NASA space mission?" Finally, in Area III, we attempted to reconcile the differences between what man may be required to do and what he is capable of doing unaided.

Study Methods

A deductive, rather than inductive, approach was used to derive IMS requirements for future manned space flight. We began with a review of human visual characteristics and of other sensor characteristics. The general missions likely to be flown in the next few decades were analyzed to select the most typical missions for further study. Within each selected mission, all visual functions were identified and broken down into their most critical visual tasks.

Each task was evaluated in terms of the physical characteristics of each visual target, the altitude and velocity of the observer, the amount of magnification required to resolve the target and the relative velocity of the target with respect to the observer's line-of-sight. The resulting target movement, stated in terms of angular velocity, was then compared with the "smear threshold" for each sensor system, including the human eye. The tasks were then analyzed for criticality and defined in tabular format. A specification for an image motion stabilization system was developed and a test plan written. Figure 1 outlines the basic steps taken to accomplish the present study.

Determination of human visual characteristics.- The ability of an observer to see the target is affected by the size, brightness, and contrast of the target, and by the amount of time the observer has to detect the target before it passes from his field of view. The observer's ability to resolve the details of the target is affected by the target's angular velocity with respect to his line of sight. The factors which may degrade the observer's vision, and the upper and lower limits of static and dynamic visual acuity, are discussed under Human Visual Characteristics.

Resolution of aerial film and electronic sensors.- Relative target motion degrades the resolution of both photographic and electronic sensors. High speed photographic films are typically grainy and are therefore unable to resolve fine detail. In order to increase the resolving power of a camera system, it is necessary to use a fine-grain, low-speed film. Thus the higher the resolution, the lower the film speed, and the greater the likelihood of image smear as a function of target movement with respect to the camera line of sight. Similarly the signals of various electronic sensors that will be used in the missions considered in this report are also subject to degradation as a function of relative target movement. The image motion criteria for both photographic and electronic sensors are described under Electronic and Photographic Characteristics.

Mission selection.- A large number of potential manned space missions were reviewed to select the most appropriate missions for this study. Those chosen were the Earth Resources Survey Mission, the Lunar Landing Mission, and the Mars Landing Mission. This effort is described in Mission Analysis.

Identification of visual functions.- The selected missions were broken down on functional flow diagrams into a sequence of visual functions and tasks. A single flow diagram was developed for each mission and each diagram was, in turn, divided into mission segments. The visual functions were arranged sequentially beneath each segment and were alpha-numerically coded. The diagrams are contained in Mission Analysis.

Analysis of visual tasks.- Once the visual tasks were identified, they were analyzed into sequential task elements which described the nature of the task, the task performance requirements, and the modes and possible results of

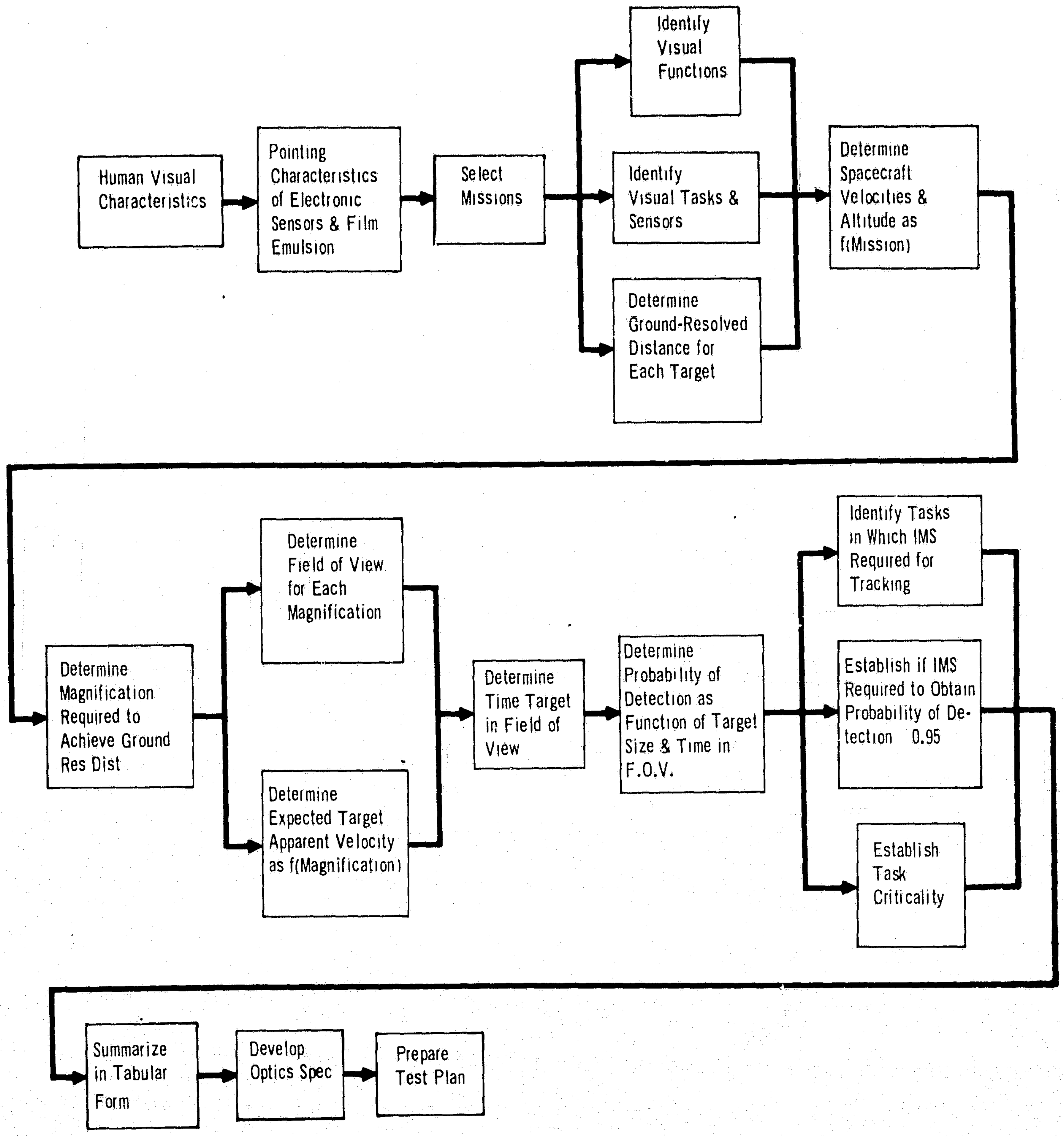

FIGURE 1
METHODOLOGY OF THE PRESENT STUDY

incorrect task performance. The task descriptions are contained in tables in the section titled Task Analysis. Once defined, the tasks were evaluated in terms of resolution requirements and sensor classification. Next the magnification required to achieve the desired resolution was determined. Once the magnification requirements were defined, two separate analytical efforts were initiated. One was aimed at determining the amount of IMS required to insure a 95% probability of target detection (assuming the target would be above threshold under completely static conditions) and the other was aimed at determining the amount of IMS required to maximize the resolution of the visual, photographic, and electronic sensors. The steps used are shown in Figure 1.

Determination of task criticality.- Once the visual tasks requiring image motion stabilization were identified, they were arrayed in order of task criticality. This was done to aid NASA in deciding the nature of priorities that should be used in future mission planning. The task criticality coefficients are presented in tabular form arranged in order of magnitude in Table 72 under Determination of IMS Requirements. This section also contains a tabular summary of the IMS requirements for optical tracking and target detection (Table 73).

Development of the IMS system functional description.- Following the determination of IMS requirements is the IMS System Functional Description. This description was written in general terms rather than in terms of detailed design requirements. It was developed on the basis of the image motion stabilization requirements defined by this study and provides an acceptable target acquisition system in terms of light gathering power, magnification range, field of view, and resolution capability.

Development of the IMS system test plan.- As the last step in the study, a test plan was developed for evaluating the effectiveness of the image motion stabilization system described in the previous section. The plan encompasses both airborne and laboratory testing of the system under conditions designed to represent the relative target velocities experienced by the observer.

Review of the literature.- During the study, we reviewed the literature in the fields of dynamic visual acuity, visual perception, target detection, mission requirements, sensor capabilities and limitations, and space navigation. The references compiled during the literature search are contained in the last section.

Assumptions

The conclusions that were developed in this study were based upon a combination of analytic and empirical data. This approach necessarily involves certain assumptions about the physical environment and man's performance characteristics in this environment. The following set of assumptions was used in this study:

a. The visual tasks performed during an Earth Resources Survey Mission, a Lunar Landing Mission, and a Mars Landing Mission are representative of the majority of visual tasks that will be performed in manned space missions in the next two decades.

b. The smallest object that can be detected subtends a visual angle of 2.9 milliradians (ten minutes of arc) under worst-case viewing conditions, namely 0.0032 candela/meter^2 (.001 Foot Lamberts), 10% brightness contrast, 50% atmospheric transmission, and 75% cloud cover.

c. The spacecraft will be in a circular, equatorial orbit about a flat non-rotating body beneath the spacecraft nadir.

d. The probability of target detection will be largely a function of the amount of time the target is in the observer's field of view. A 1.31 radian (75°) field of view will allow greater than chance detection of an above-threshold target for all three missions. Also, there is an equal probability of target detection anywhere within the field of view.

e. A small, hand-held monocular optical device (telescope) that can be mounted in the spacecraft will provide the primary visual information considered in this study. Weight and volume will constrain the overall size of the optical device, limiting it to 6.8 kilograms (15 pounds) overall with optics weighing between 1.81 kilograms and 2.27 kilograms (10 pounds) and being 22.9 centimeters (9 inches) in length, and 7.62 centimeters (3 inches) in diameter.

f. The sensor smear thresholds are applicable to both tracking IMS and damping IMS.

g. The ground resolved distances selected represent reasonable and useful values that will be within the sensor state of the art during the time period of the missions described in this study.

h. The values of task criticality that were derived are numerically additive and represent at least an interval scale of measurement.

HUMAN VISUAL CHARACTERISTICS

Human vision depends on the complex interaction of many physiological, psychophysiological, and physical factors. A great deal of research has been devoted to assessing the effects of aircraft and spacecraft environments on the functioning of the human visual system in general, and on the visual tasks of detection, identification, and interpretation in particular.

Classes of Visual Tasks

It was recognized at the beginning of this study that image motion stabilization might be required for the following types of visual tasks:

a. Target Search and Acquisition - Detection, recognition, and identification of surface and aerial targets.

b. Optical Tracking - Sustained visual surveillance of surface and aerial targets in order to aim another sensor system at the target.

Figure 2 summarizes the classes of visual tasks considered in the study.

Target search and acquisition.- In this type of task the observer must visually locate an object that may be embedded in a highly complex background, or in an area filled with geologically similar surface features. The activity consists of the following:

a. Detection - The perceptual segregation of the visual field into two parts - figure and ground (i.e., the determination that there is "something of possible interest there.")

b. Recognition - The assignment of the object to a general class (e.g., "It looks like a river.")

c. Identification - The determination that the object is a specific member of the general class based on various perceptual and navigational cues (e.g., "It is the Mississippi River between Natchez and New Orleans.")

Optical tracking.- To perform optical tracking, the observer attempts to keep the target within his field of view (FOV) by compensating for the motion of its image. In this study, all image motion compensatory-tracking tasks are referred to as image motion stabilization (IMS). As the spacecraft approaches a target and passes over it, apparent movement is a function of the speed, altitude, and attitude rates of the spacecraft, and the magnification of the target. Image motion stabilization is accomplished by moving the center of the optical system (e.g., the naked eye, a telescope, a camera platform, or a multispectral sensor system) in the same direction as, and at a rate proportional to, the image movement, thus stabilizing the image with respect to the observer. In addition to improving the visual capability of the observer,

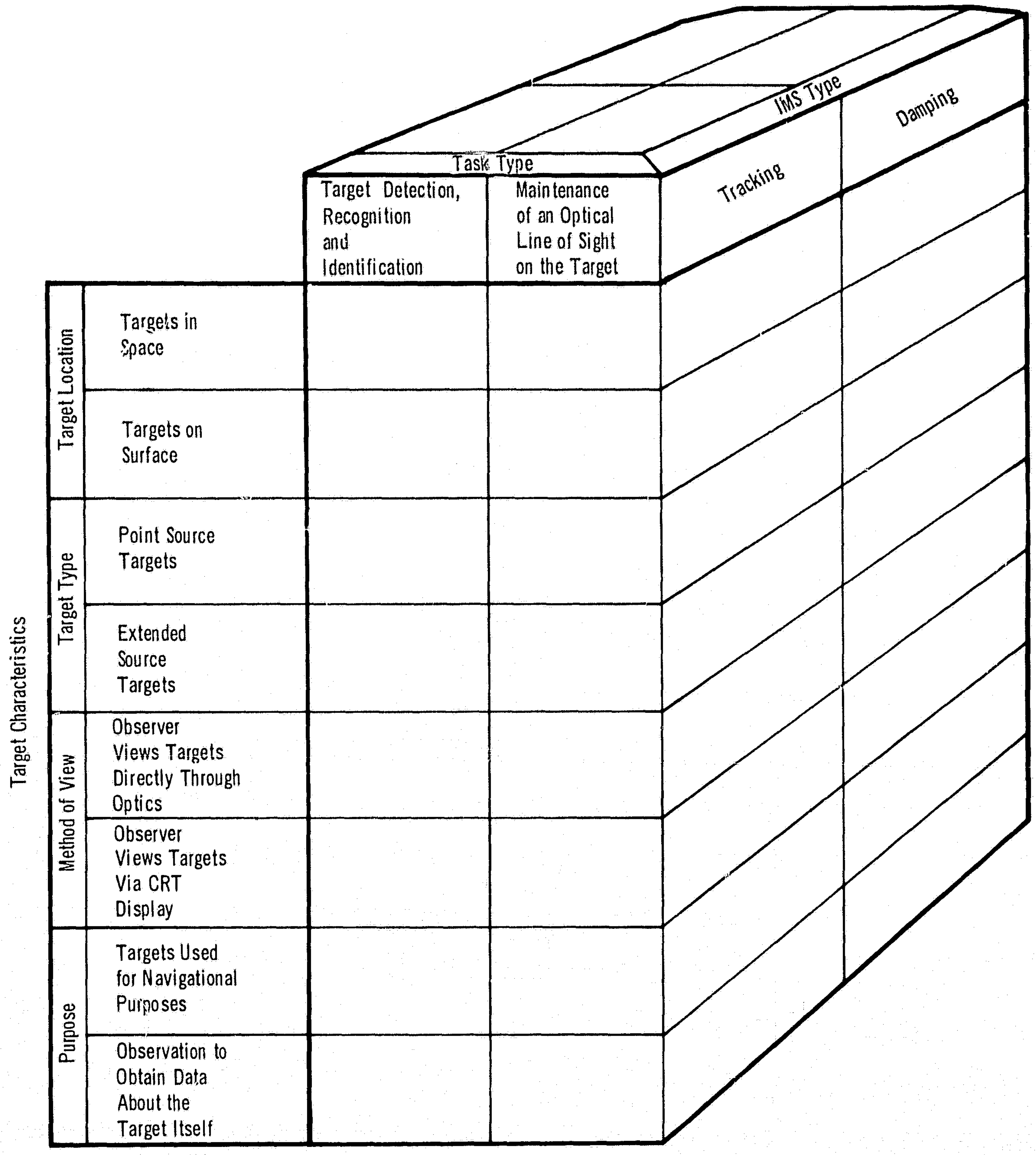

FIGURE 2
CLASSES OF VISUAL TASK VARIABLES CONSIDERED
IN THE PRESENT STUDY

IMS also minimizes any photographic smear that might be caused by the long exposure interval required of high resolution film.

IMS is applicable to many sensor-pointing tasks, because the effective use of many sensor subsystems will depend on critical adjustment and alignment between the sensor and the area under examination. For example, in radar mapping, the antenna line of sight angle must be maintained within ±17.45 milliradians (1°) pitch and ±34.9 milliradians (2°) in roll or yaw. In addition, a present state-of-the-art radar system requires that spacecraft attitude rates be held to less than 872 microradians (0.05°) per second (ref. 3).

IMS requires that a high contrast area be available on the earth as a visual reference to enable the observer to determine if he has effectively stabilized the image (ref. 4).

Navigation.- Navigation is a special category of visual tasks containing elements of both detection and tracking. The importance of navigation tasks can be inferred from the fact that they are consistently judged to be critical (See the Criticality Analysis). Although onboard navigational tasks in earth orbit missions are often given a back-up role, in the event of ground track failures, these tasks were considered in the present study because certain situations could arise in which this secondary function would supply vital information for mission success and crew safety (e.g., an abort entry.) There are also certain missions for which the onboard system is more accurate than earth-based tracking (e.g., orbiting about a distant planet). In this case, the navigation system onboard the spacecraft could supply the primary source of information.

Depending on the type of mission and the mission phase, the navigation task will be one of the following general types:

a. Orbital Navigation - A vehicle's state (position and velocity) relative to the planet about which it is orbiting must be estimated. This navigation task is important for the determination of sensor pointing commands, deorbit maneuver for re-entry, or perhaps a trans-planetary injection maneuver for an interplanetary mission.

b. Rendezvous Navigation - The primary interest in rendezvous navigation is in determining the relative state of a target vehicle. Rendezvous guidance maneuvers can then be calculated to accomplish the rendezvous.

c. Midcourse Navigation - The aim of midcourse navigation is to define the vehicle's state during the transplanetary phase of an interplanetary mission. Midcourse maneuvers can then be determined which would guide the vehicle into specific approach corridors at the destination planet.

Different measurements are required for each of the above navigation tasks. The measurements depend upon the information required by the task and the availability and accuracy of data. Measurements containing the most basic information are those which have the greatest change with time (i.e., the most dynamic ones). These rapidly changing measurements are more difficult to observe, however, resulting in poorer accuracy. In this study, the data that have evolved for these tasks represent a trade-off between the information in the more dynamic measurement and the projected accuracy of that measurement.

As a navigator, the astronaut is exposed to particularly dynamic viewing conditions. In addition, vehicle attitude changes make observation more difficult.

The navigation task requires the acquisition of two celestial bodies, and a measurement of the angle subtended by them in relation to the space vehicle An alternative method is the measurement of the angle subtended by the perimeter of a single planetary body. These measurements require highly accurate instruments and readings, and precise determination of the time intervals between measurements.

To gather the data the observer must first locate a planetary body or the limb of a planet, and a known star in a scanning telescope. The observer then uses a sextant to bring one of the objects to a reticle type reference by orienting the space vehicle until the required reticle placement is achieved. The optical system then superimposes the second celestial body over the primary one and the resultant angle is noted. Once obtained, these data are inserted into an onboard computer, to be compared with pre-designated "true" flight paths or with ground-supplied navigational updates (refs. 5, 6, 7, 8, 9, 10, and 11).

A probable sextant accuracy of ±4.8 microradians (10 arc sec) would be required for the missions described herein, although a ±2.4 microradian (5 arc sec) measurement accuracy would be more desirable. A 1970 state-of-the-art sextant would probably have a resolution capability of slightly less than 4.8 microradians (10 arc seconds) with a 34.9 milliradian (2°) field of view (ref. 12). These accuracies have not yet been obtained, however, in either simulation studies or in actual orbital flights.

The sources of variance are extensive and only a relatively few can be adequately controlled in an experiment which attempts to simulate navigational tasks. For this reason, the accuracies obtained in simulations are higher than those obtained in actual missions. In short, dynamic viewing conditions increase the complexity of the navigator's task, and indicate that image motion stabilization would be beneficial. Table 1 (refs. 8, 10, 11, 13, 14, and 15) compares some representative results of navigational accuracies obtained under both operational and simulated conditions. This table also summarizes some of the more desirable types of measurements that can be obtained during the three missions that have been considered in the present study.

Factors Affecting Visual Performance

Man's ability to perform the required visual tasks depends, to a large degree, on the characteristics of visual perception. As pointed out by Gibson (ref. 16), visual perception is the processing of information about the visual

TABLE 1. NAVIGATIONAL CHARACTERISTICS

MISSION	FUNCTION	POSSIBLE TYPES OF MEASUREMENT	OBTAINED ACCURACIES			
			SIMULATOR		OPERATIONAL	
			MICRORADIANS	ARC SECONDS	MICRORADIANS	ARC SECONDS
Earth Resources, Lunar, Martian	Orbital Navigation	a) Star-Horizon	±288(ref.13)	±60	3.7-22.3(ref.15)	18-108
		b) Star-Beacon	±99(ref.10)	±20	-	-
		c) Star-Local Vert.	-	-	-	-
		d) Star-Landmark	-	-	-	-
		e) Landmark L.D.S.	-	-	-	-
		f) Star-Occultation	-	-	-	-
Lunar, Martian	Midcourse Navigation	a) Star-Planet	±99(ref.11)	±20	±38.4(ref.11)	±8
		b) Star-Star	±57.6(ref.11)	±12	±48(ref.15)	±10
		c) Diameter of Planet	-	-	-	-
Lunar, Martian	Rendezvous Navigation	a) Star-Vehicle	-	-	±288(ref.14)	±60
		b) Star-Flashing Light	±288(ref.8)	±60	-	-
		c) Vehicle-Horizon	-	-	-	-
		d) Vehicle-Local Vertical	-	-	-	-

environment, and is a function of the characteristics of the visual field which allow the observer to reduce any uncertainties about this environment. The characteristics which segregate the target from its surroundings will naturally enhance the observer's ability to detect and identify the target. This process is influenced by the following factors:

Brightness contrast.- If the brightness of targets does not differ greatly from that of the background, target contours will blend into the background and detection will be difficult.

Ambient illumination.- Under low lighting conditions, detection will be less likely, particularly if the eyes are not yet dark-adapted. In viewing the moon, this problem is aggravated by the sharp brightness gradient between the shadowed and unshadowed portions. The sensitivity available to scotopic vision and the acuity of photopic vision will both tend to be compromised. If segregation of figure from ground is based upon color cues, the Purkinje shift phenomenon will minimize this discrimination capability, particularly on the long end of the visible spectrum.

Atmospheric transmission.- The environment outside the spacecraft may influence man's visual capabilities. The effects of varying levels of clouds, glare, and haze upon image motion stabilization performance have been studied under simulated conditions (ref. 4). Although these factors have detrimental effects on the image motion stabilization task, such effects can be almost eliminated with extensive training. A related study (ref. 17) has indicated that image motion compensation skills, when acquired through overlearning, show a minimal decrement for up to 200 days.

Reports of orbital observations have emphasized the visibility restrictions imposed by natural and artificial pollutants and cloud coverage over the earth's surface (refs. 18, 19, 20, and 21). The amount of light falling on the eye is greatly attenuated by the transmission properties of the atmosphere, with the transmission coefficient varying from .56 to .83 (refs. 22, 23, 24, and 25). The atmosphere is a colloidal system of water vapor in various forms, plus solids, liquids, and gases in complex combinations. The sun's energy must penetrate this conglomerate, hit the earth, and reflect back to the observer's eye. The result is that the observer sees only about 4% of the original solar electromagnetic energy from direct ground reflectance (ref. 26). When photons of light from the sun move through the atmosphere and a high proportion of their energy is refracted, an intervening layer of light is effectively superimposed over the earth. This phenomenon is called "air light", and is the prime cause of atmospheric glare.

Cloud cover is another atmospheric hinderance to light transmission. The mean cloud cover for the entire earth is estimated at 54% and the cloud concentration over a particular area on successive orbits can range from complete to nil. The amount of light energy reflected depends on the thickness and water content of the cloud formation, with a wide cloud albedo (reflectance) range of .05 to .85 (refs. 27, 28, and 29). Clouds lead to a significant attenuation in light transmission and produce shadows on sparsely illuminated ground areas.

A number of investigators (refs. 22, 30, 31, and 32) have singled out figure-ground contrast as the most crucial determinant of visual observation of objects on the ground from orbit. Glare and clouds both effectively reduce figure-ground contrast. It is safe to assume, therefore, that both glare and cloud cover will have an adverse effect on visual performance, with their combined effect being particularly detrimental.

Figure-ground differentation.- An isolated object (such as a super-highway) contrasted against a visually homogeneous background (such as a desert) tends to stand out, even under very adverse viewing conditions. If the figure is embedded in a complex background, the probability of detection is lowered considerably, since highly articulated background provides a large amount of information which overloads the observer, making it less likely that he will be able to resolve the uncertainty in the visual field.

Image magnification.- Some form of image magnification improves the contour discrimination between figure and ground and thus enhances target detection. As Morgan (ref. 2) has pointed out, the probability of detection increases as an ogive function of the size of the visual angle subtended by the target. However, as image magnification is increased beyond certain values, the probability of detection begins to decrease. A recent study (ref. 33) demonstrated that 10-power magnification was significantly more effective than 30-power at the .005 level of significance. On the basis of that study, it was concluded that the following factors contributed to the advantage of lower magnification:

a. Contextual Cues Available - With 30-power magnification, the field of view covered only one-ninth of the area obtained under 10-power magnification. Thus, the number of natural and man-made surface features available as positional cues in searching for a specific target was reduced 89 percent. Also, the paucity of contextual cues under high magnification tends to shift an observer's perceptual set from terrestial surroundings to the configuration of specific targets and their immediate surroundings. Previous investigators (ref. 34) have indicated that superior observers gained cues from the entire visual field, whereas the inferior observers memorized specific routes and tried to find specific targets.

b. Relative Target Velocity - The second contributing factor is the apparent relative velocity of ground objects with respect to the observer. This factor has previously been pointed out by another set of investigators (ref. 35) who summarized the effects of this factor as follows: "Angular velocities of objects across the display are inversely proportional to the field of view."

Method of viewing the target.- Although the present study considers visual search and acquisition only in terms of imagery being presented directly to an observer, research has been conducted in which a television link was placed between the observer and the telescope optics. Such studies have demonstrated that such a link can be used successfully in some tasks with appropriate magnification, training procedures, and control-display directional relationships (refs. 35 and 36).

Eye-hand coordination.- Target detection, recognition, and identification rely on man's visual perception, but they also involve certain psychomotor skills that control the optical system in search, and maintain image motion stabilization once the target is acquired. One such study (ref. 36) has shown that the directional relationship between telescope and hand control movement significantly influences target search and acquisition performance.

Static and dynamic visual acuity.- Under given physical conditions, the absolute threshold of vision can be defined as the visual angle subtended by an object that can just be detected 50% of the time by an observer with normal emmetropic vision. The term "visual acuity" has been used by many researchers such as Graham (ref. 37) as a method of uniformly expressing the observers "capacity to discriminate the fine details of objects in the field of view," and is "conventionally defined as the reciprocal of the threshold visual angle, in minutes ...." On the other hand, most of the people who have studied the effects of target motion on vision such as Ludvigh and Miller, (ref. 38) have, by convention, made the term "visual acuity" synonymous with "the smallest visual angle that can be resolved" (ref. 2). This convention has been used in the present study.

Target acquisition and tracking is directly related to the observer's visual acuity, which is in turn a function of the following factors:

a. Illumination of the target.

b. Target contrast with its background.

c. Atmospheric transmissivity.

d. Fidelity of the viewing system.

e. Relative motion of the target with respect to the observer.

The last factor brings into consideration the differences between static and dynamic acuity. A target that is stationary or whose relative angular velocity is stabilized with respect to the observer's line of sight is more likely to be resolved than a moving target, which is subject to blur, accommodation error, possible impingement of the center of the image on the peripheral retina, and lateral inhibition (refs. 38 and 39).

In other words, if the relative motion is stabilized, target acquisition may be treated as being a function of those factors affecting static visual acuity (SVA). The term "dynamic visual acuity" (DVA) is used to designate the ability of an observer to discriminate an object when there is relative movement between him and the object. Recent increased interest in DVA is an outgrowth of the realization that discrimination of moving objects (or of stationary objects while one is moving) plays a key role in many activities, such as driving and flying, and that DVA may be more closely correlated with task performance than is SVA.

Regardless of the basic differences between SVA and DVA, there are certain fundamental characteristics common to both types of visual acuity. For example, visual acuity gets better as the illumination on the target is increased and also as the contrast ratio of the target and its background is increased[1]. There are three ways of expressing visual acuity; namely, minimal separable acuity, minimum perceptible acuity, and vernier acuity (ref. 2). Minimal separable acuity or "gap resolution" is the visual angle subtended by the smallest difference between two lines or the smallest gap in a Landolt ring that can be detected 50% of the time. The effects of variations in illumination and brightness contrast on minimum separable acuity are shown in Tables 2 and 3 (ref. 2).

Minimum perceptible acuity or "spot resolution" is the visual angle subtended by the smallest target that can be detected 50% of the time. The effects of variations in illumination and brightness contrast on minimum perceptible acuity are shown in Table 4 (ref. 2).

The third type of acuity, vernier acuity, is a special case that probably has limited applicability to the present study. It is defined as the minimum lateral displacement of one segment of a broken straight line that can be detected 50% of the time. Table 5 (ref. 2) shows the relationship between illumination and vernier acuity.

Because of the particular relevance of DVA to the present study, an extensive review of the scientific literature was accomplished to investigate the capabilities and limitations of human vision under dynamic viewing conditions. In our literature search we found that the most frequently used methods of producing real or apparent motion of the test object are: (1) movement of the object of interest, (2) movement of the observer, (3) filming real movement of the object for use with observers, (4) use of an optical device to produce apparent motion of the object, and (5) use of a movable projector or background. The test objects typically employed consist of: Landolt rings, Snellen letters, checkerboard transparancies, numerals, highway signs, Morse code characters, and two-bar resolution figures. Most of the experiments reviewed here have employed these motion-producing methods and test objects.

Blackburn (ref. 40) moved an object subtending 0.58 milliradians (2 min) of arc in a horizontal plane, and noted the angular velocity above which visibility was seriously impaired. He found that the target was barely visible at an angular velocity of 436.3 milliradians/sec (25°/sec), and disappeared completely at 872.5 milliradians/sec (50°/sec).

Warden, Brown, and Ross (ref. 41) conducted an experiment to assess the effects of varying angular velocity and level of illumination on DVA, and to determine if there was any correlation between DVA and static visual acuity.

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1 $$\% \text{ contrast} = \frac{\text{Background Brightness - Target brightness}}{\text{Background Brightness}} \times 100$$

TABLE 2
MINIMUM SEPARABLE ACUITY AS A FUNCTION OF BACKGROUND BRIGHTNESS[1]
(FROM MORGAN ET AL, REF 2)

Background Brightness (mL)	Minimum Visual Angle (Minutes of Arc)
0.001	10'
0.01	3'
0.1	1'10"
1.0	42"
10.0	33"
100.0	27"
1000.0	25"
10000.0	24"

[1]All values shown are the minimum visual angle subtended by a target that will be seen 50% of the time. To determine the size target required to be detected nearly 100% of the time, multiply the tabled angles by two.

TABLE 3
MINIMUM SEPARABLE ACUITY AS A FUNCTION OF BRIGHTNESS CONTRAST[1]
(FROM MORGAN ET AL, REF 2)

Contrast Ratio (%)	Background Brightness		
	1 Ft-L	10 Ft-L	100 Ft-L
2	11'	8'30"	4'45"
5	5'	3'54"	2'20"
10	3'12"	2'20"	1'36"
20	2'20"	1'36"	1'6"
50	1'30"	1'	48"
100	1'6"	48"	30"

[1]All values shown are the minimum visual angle subtended by a target that will be seen 50% of the time. To determine the size target required to be detected nearly 100% of the time, multiply the tabled angles by two.

TABLE 4
MINIMUM PERCENTABLE ACUITY AS A FUNCTION OF BACKGROUND BRIGHTNESS AND BRIGHTNESS CONTRAST[1]
(FROM MORGAN ET AL, REF 2)

Background Brightness (Ft–L)	Contrast Ratio		
	1%	10%	100%
.00001	–	–	88'
.0001	–	–	52'
.001	–	1°40'	16'
.01	–	16'	4'24"
.1		6'48"	2'48"
1.0	40'	4'18"	56"
10.0	9'18"	3'42"	49"
100.0	8'6"	3'15"	46"

[1]All values shown are the minimum visual angle subtended by a target that will be seen 50% of the time. To determine the size target required to be detected nearly 100% of the time, multiply the tabled angles by two.

TABLE 5
VERNIER ACUITY AS A FUNCTION OF BACKGROUND BRIGHTNESS[1]
(FROM MORGAN ET AL, REF 2)

Background Brightness (mL)	Minimum Visual Angle (Seconds of Arc)
.05	6"
.08	4.5"
.3	3.3"
1.0	2.8"
6.0	2.6"
130.0	2.6"

[1]All values shown are the minimum visual angle subtended by a target that will be seen 50% of the time. To determine the size target required to be detected nearly 100% of the time, multiply the tabled angles by two.

Dynamic visual acuity decreased as a function of increasing angular velocity and decreasing illumination, and showed no relationship to static visual acuity.

Low (ref. 42), using moving objects, investigated simple form acuity in the peripheral retina. The test objects were Landolt rings, moved in a horizontal meridian by means of a modified perimeter so as to produce a constant angular velocity of 261.8 milliradians/sec (15°/sec). It was found that form discrimination deteriorated as a function of object movement.

Ludvigh (ref. 43) determined foveal visual acuity during ocular pursuit. It was found that movement of the test objects (Snellen letters) in the horizontal plane led to a marked deterioration in visual acuity as angular velocity increased from 0 to 2.18 radians/sec (0 to 125°/sec). Ludvigh (ref. 44), using Landolt rings as test objects, found a marked decrement in DVA performance as a function of increasing angular velocity from 436.3 to 3490.0 milliradians/sec (25 to 200°/sec). In a subsequent series of investigations, Ludvigh (ref. 45) determined visual acuity while the test object moved through a circular path in a plane perpendicular to the line of sight. In these experiments a rotating prism was placed between the observer's eyes and the test objects (Landolt Rings) to achieve the circular path. Visual acuity deteriorated more rapidly when the movement was in a circular path in a frontal plane than when the movement was linear. In addition, it was observed that high-intensity illumination improved visual acuity.

O'Hara (ref. 46) determined the maximum distance at which various test objects were visible from an automobile moving at various speeds. It was found that visual acuity decreased as vehicle speed increased.

Rose (ref. 47), using Morse code characters as test objects, measured visual acuity during ocular pursuit in the horizontal plane. The test objects were moved by means of a projector mounted on a rotating turntable. A sizable decrement in visual acuity was noted as a function of increasing test-object angular velocity in the range 349.0 to 1745 milliradians/sec (20 to 100°/sec), with maximal deterioration occurring at angular velocities greater than 1745 milliradians/sec (100°/sec).

Ludvigh and Miller (ref. 38) investigated the general relationship of visual acuity to angular velocity. For the purpose of analysis, the observers were assigned to one of three groups on the basis of the rate at which visual acuity deteriorated as a function of increasing angular velocity of the test object. Group I consisted of five observers tested at angular velocities of 1919.5 milliradians/sec (110°/sec), Group II of eight observers tested at up to 2443.0 milliradians/sec (140°/sec), and Group III of five observers tested at up to 2966.5 milliradians/sec (170°/sec).

The results of this investigation indicated that when a test object moving in a horizontal plane attains an angular velocity of approximately 872.5 milliradians/sec (50°/sec), the ability of the eye to pursue it accurately is seriously impaired. (See Figure 3).

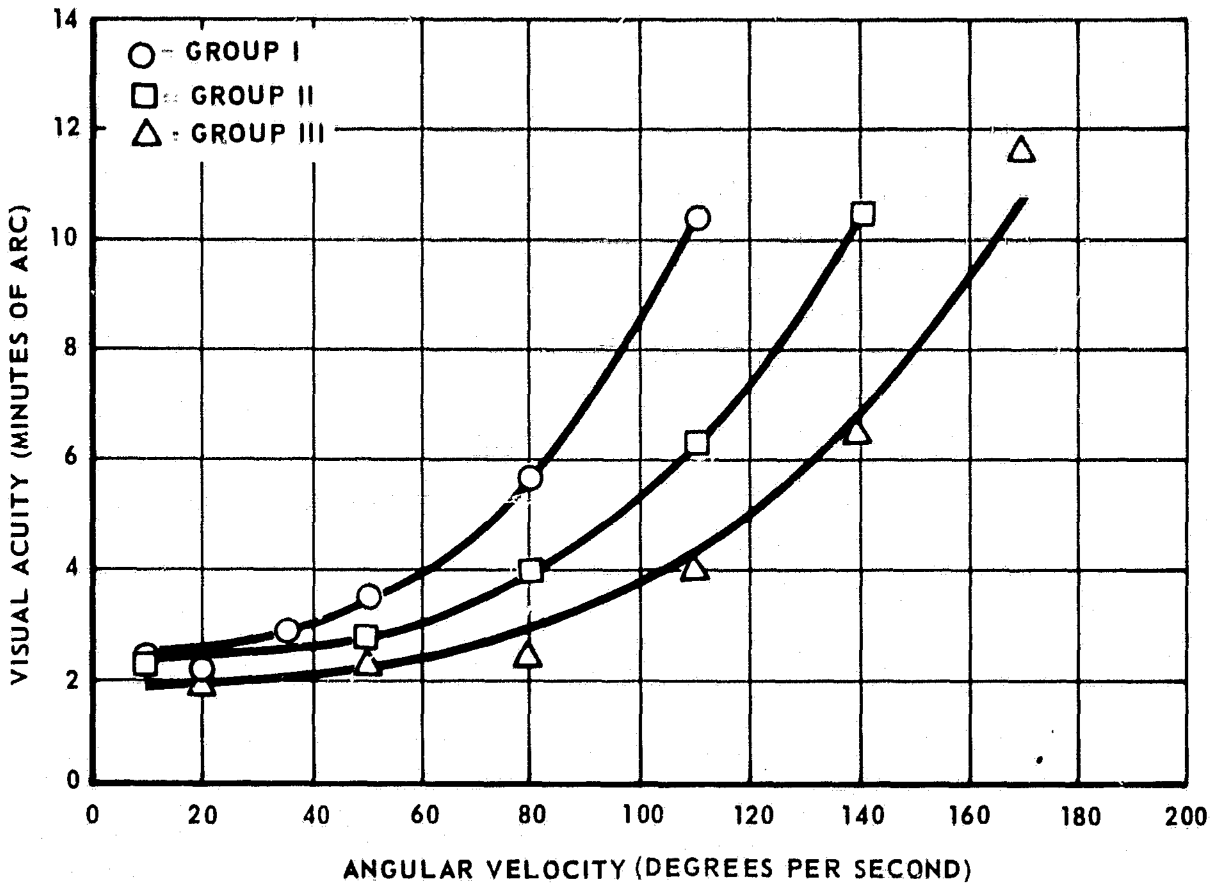

FIGURE 3 – DEPENDENCE OF VISUAL ACUITY ON ANGULAR VELOCITY OF THE TEST OBJECT (FROM LUDVIGH AND MILLER, REF 38)

Miller and Ludvigh (ref. 48) examined the effect of direction of test-object motion on DVA. The results of DVA testing for nine observers with the test object moving in the horizontal plane are presented in Figure 4. The corresponding results for these same observers obtained with the test object moving in the vertical plane are plotted on the same axes. These findings indicate that movement along the vertical meridian of the retina is somewhat easier to perceive than movement along the horizontal meridian. Pollock (ref. 49) has presented evidence indicating that, even in the absence of pursuit, motion along the vertical plane is better perceived than motion along the horizontal plane. Monocular luminance thresholds were determined for a spot of white light moving, in either the vertical or horizontal plane, at angular velocities ranging from 872.5 to 34900.0 milliradians/sec (50 to 2000°/sec). A consistent difference between the vertical and horizontal thresholds was evidenced. For seven of the eight speeds examined, the thresholds for vertical movement were lower than those for horizontal movement.

Ludvigh and Miller (ref. 50) sought to evaluate the reliability of DVA test scores. Twenty successive DVA thresholds were determined with a test-object angular velocity of 349.0 milliradians/sec (20°/sec), and another 20 were established at 1919.5 milliradians/sec (110°/sec). Half of the observers were tested first at 349.0 milliradians/sec (20°/sec) and then at 1919.5 milliradians/sec (110°/sec), and the remaining half were tested first at 1919.5

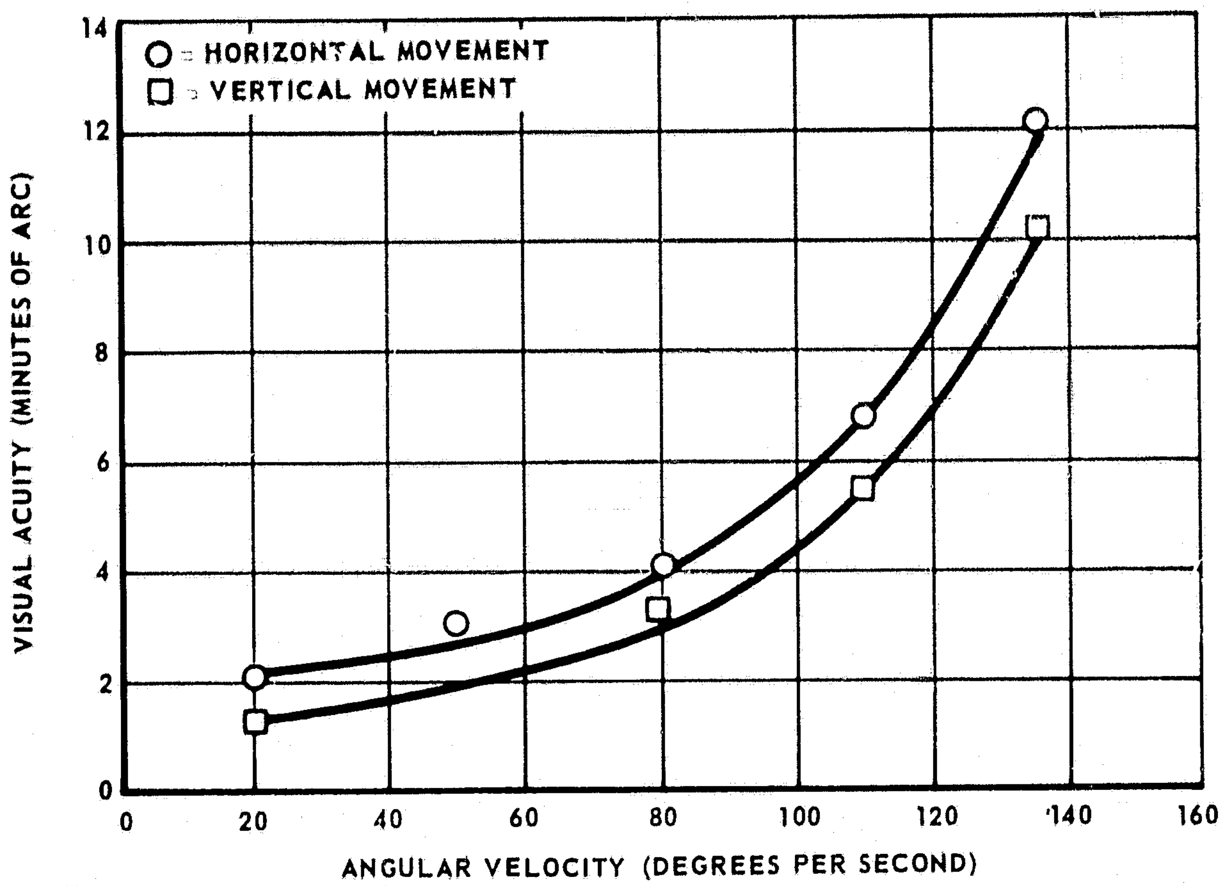

FIGURE 4 – EFFECT OF DIRECTION OF MOTION OF THE TEST OBJECT (FROM MILLER AND LUDVIGH, REF 48)

milliradians/sec (110°/sec) and then at 349.0 milliradians/sec (20°/sec). The relaibility of this method of assessing DVA was examined by correlating the means of the odd- and even-numbered thresholds obtained at an angular velocity of 1919.5 milliradians/sec (110°/sec). The resulting product-movement correlation coefficient was 0.99. An additional 120 observers were then utilized to determine whether a test-retest measure of reliability would yield a result similar to that obtained with the split-half method, and it did. It was concluded that the method of determining DVA utilized by Ludvigh and Miller was internally consistent and highly reliable.

Ludvigh and Miller (ref. 51) investigated the effect of practice on DVA. The DVA thresholds for 200 naval aviation cadets tested at 349.0 and 1919.5 milliradians/sec (20 and 110°/sec) test-object velocities are shown in Figure 5. Examination of the curves indicates that the effect of practice at 1919.5 milliradians/sec (110°/sec) was substantial, while the effect of practice at 349.0 milliradians/sec (20°/sec) was negligible. In addition, it is obvious that a substantial amount of the improvement at 1919.5 milliradians/sec (110°/sec) occurred during the initial four test trials. So it appears that when improvement in DVA performance does occur with practice, it occurs quite rapidly.

Ludvigh and Miller then took the 20 best and 20 poorest performers and determined the effect of practice at 1919.5 milliradians/sec (110°/sec) on DVA performance. It can be seen from Figure 6 that practice at 1919.5 milliradians/sec (110°/sec) was much more beneficial for good performers than for poor per-

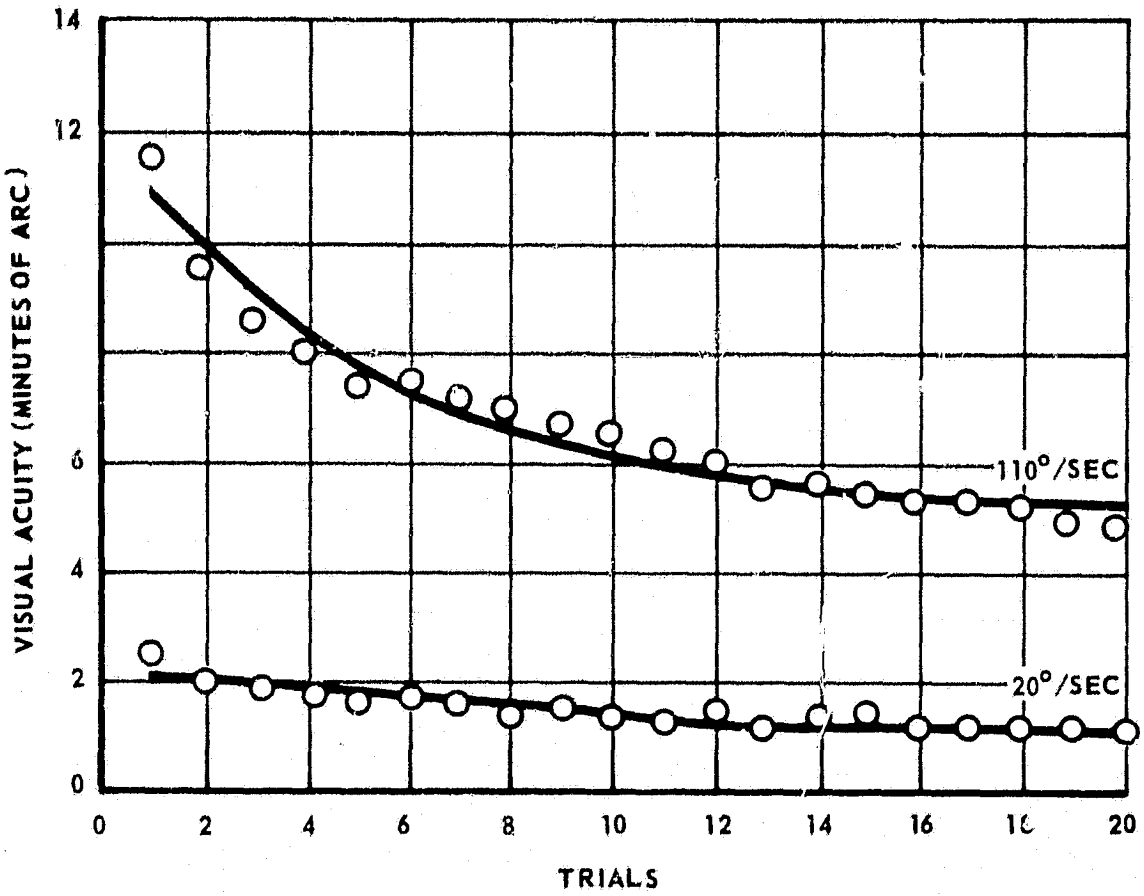

FIGURE 5 – THE EFFECT OF PRACTICE ON DYNAMIC VISUAL ACUITY (FROM LUDVIGH AND MILLER, REF 50)

formers. The question remained, however, as to whether the rapid improvement shown in the initial trials represented asymptotic performance or merely a plateau on the learning curve for the average observer. Figure 7 shows the effects of greatly prolonged training on DVA skill. Extending training over a three week period did not improve DVA performance. In brief, it appears that any improvement in DVA performance as a result of practice occurs rapidly, that practice has a differential effect for good and poor performers, and that extended training does not enhance DVA skills.

Ludvigh and Miller (ref. 52), using two groups of observers, studied the problems of retention and transfer of training within the context of a DVA task. Substantial retention of the DVA skill was found after seven months. With regard to transfer, practice at 349.0 milliradians/sec (20°/sec) produced a very slight improvement in performance at 1919.5 milliradians/sec (110°/sec). Practice at 1919.5 milliradians/sec (110°/sec) resulted in a still smaller improvement in performance at 349.0 milliradians/sec (20°/sec). This is probably because angular velocities of less than 436.25 milliradians/sec (25°/sec) have little effect upon DVA performance.

Miller (ref. 53) compared the results of testing visual acuity in the horizontal plane with those obtained when the pursuit path was circular and in a plane perpendicular to the line of sight. The 120 observers in Miller's study were divided into two equal groups. One group was tested at a horizontal angular velocity of 1919.5 milliradians/sec (110°/sec), and a rotary velocity

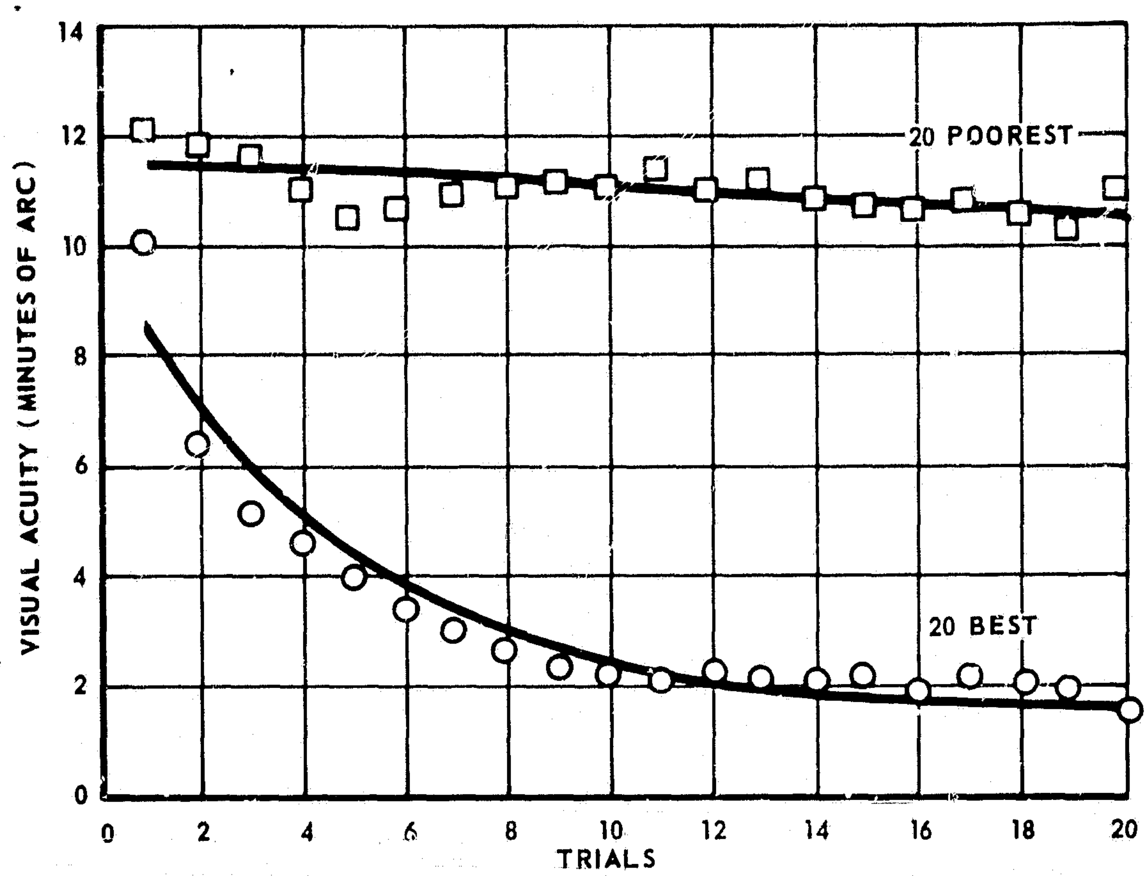

FIGURE 6 – MEAN THRESHOLD VALUES OF THE 20 POOREST AND THE 20 BEST PERFORMERS (FROM LUDVIGH AND MILLER, REF 50)

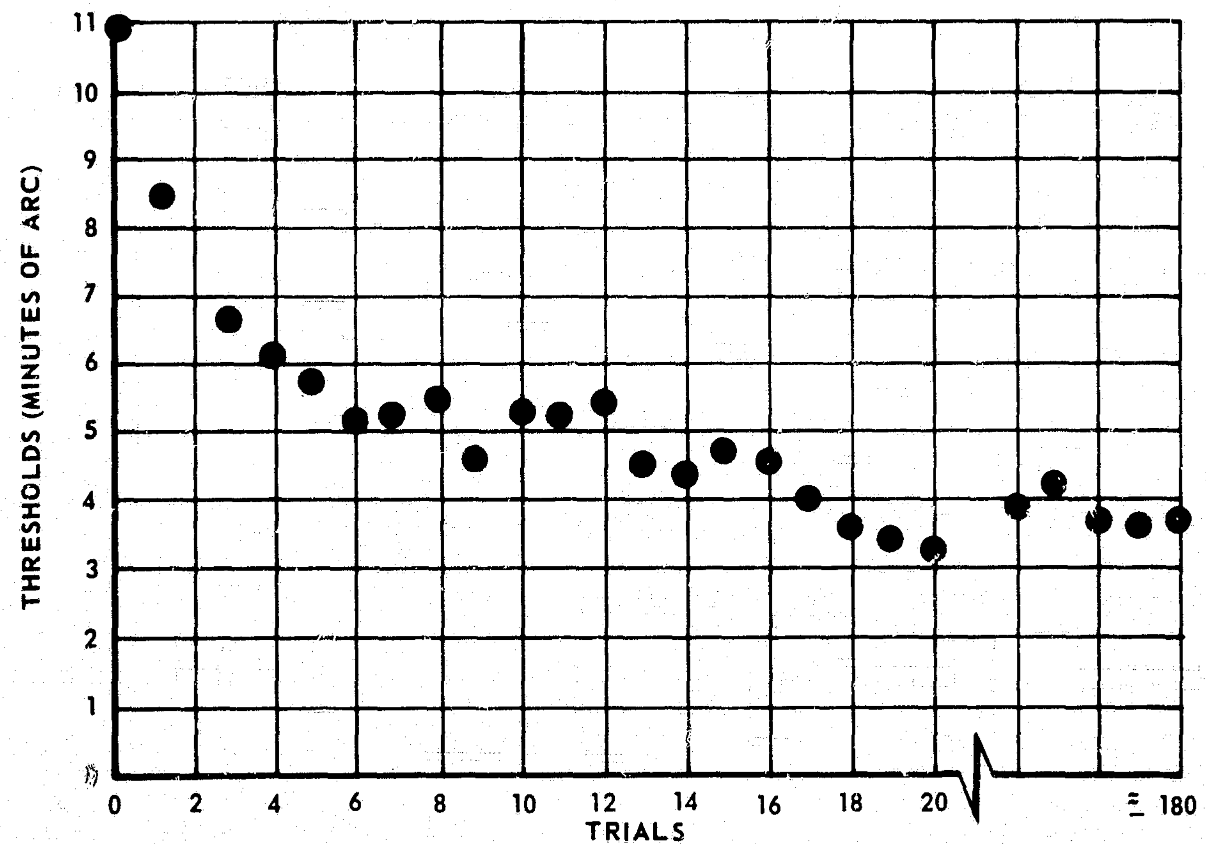

FIGURE 7 – THE EFFECT OF PROLONGED TRAINING ON DYNAMIC VISUAL ACUITY (FROM LUDVIGH AND MILLER, REF 50)

of 872.5 milliradians/sec (50°/sec). The other group was also tested at a horizontal angular velocity of 1919.5 milliradians/sec (110°/sec), but at a rotary velocity of 1343.7 milliradians/sec (77°/sec). The two types of pursuit were significantly correlated. The correlation between the thresholds obtained for 1919.5 milliradians/sec (110°/sec) linear and 872.5 milliradians/sec (50°/sec) circular velocities was 0.61. The correlation between the 1919.5 milliradiradians/sec (110°/sec) linear and 1343.7 milliradians/sec (77°/sec) circular thresholds was 0.60. These results and those of Miller and Ludvigh (ref. 38) and Pollack (ref. 49) suggest that acuity deteriorates most rapidly for circular movement and least rapidly for vertical movement, with horizontal movement falling between.

Smith and Gulick (ref. 54), in a study dealing with form perception, determined the relationship between the perception of a sharp contour and angular velocity. The test object, a black square, was exposed to the observer in a fixed position both before and after movement. The observer was to indicate when the black square was perceived with sharp contours. The existence of sharp contours was investigated as a function of the duration of exposure of the stimulus in various fixed positions. It was found that the contour of the moving stimulus could be maintained as angular velocity was increased by concurrent increases in exposure time, both before and after movement. The results showed that as the angular velocity increased from 244.3 to 436.3 milliradians/sec (14 to 25°/sec), the pre- and post-movement fixation time required for sharp contour perception during movement increased from 0 msec to 300 msec.

Foley (ref. 55) investigated the relationship between digit identification and angular velocity as a function digit separation and direction of movement. The digits were projected onto a screen and moved either vertically or horizontally. The speed of the digits was increased in discrete steps of 34.9 milliradians/sec (2°/sec) until the observer was no longer able to identify any of the digits presented. Observers performed better when digit separation was pronounced, and the movement of the digits was from right to left or upward rather than when the movement was from left to right or downward.

Hulbert, Burg, Knoll, and Mathewson (ref. 56) have investigated DVA in connection with automobile driving. The test objects employed were checkerboard transparencies which were moved by means of a rotating projector similar to that used by Rose. The range of angular velocities utilized was 349.0 to 3140.0 milliradians/sec (20 to 180°/sec). The findings of the four essentially agree with those already reviewed: Visual acuity deteriorates as the angular velocity of the test object increases.

Ludvigh and Miller (ref. 57) also evaluated the effect of variations in test-object angular velocity on DVA. The angular velocities employed were 349.0, 872.5, 1396.0, 1919.5, 2443.0, 2966.5 milliradians/sec (20, 50, 80, 110, 140, 170°/sec). DVA performance deteriorated markedly at angular velocities exceeding 872.5 milliradians/sec (50°/sec).

All of the empirical work discussed thus far concerns the effect on visual acuity of moving the test object relative to a stationary observer. Miller (ref. 58) investigated visual acuity when the observer was moving relative to a fixed test object. The apparatus employed to rotate the observers was a modified Link trainer which could be rotated in the horizontal plane at angular velocities ranging from 0 to 2722.2 milliradians/sec (0 to 156°/sec). The test objects were Landolt rings, the level of illumination was 269.1 lumens/meter^2 (25 ft-candles), and the exposure time was 0.4 sec. Monocular thresholds were obtained at five angular velocities ranging from 349.0 to 2094.0 milliradians/sec (20 to 120°/sec). Figure 8 shows a comparison of DVA scores obtained with the test object moving and scores obtained with the observer moving. The data indicate that the effect of test-object angular velocity chiefly depends on the presence of relative motion between the object and the observer; and, it is relatively unimportant whether the test object or the observer is moved.

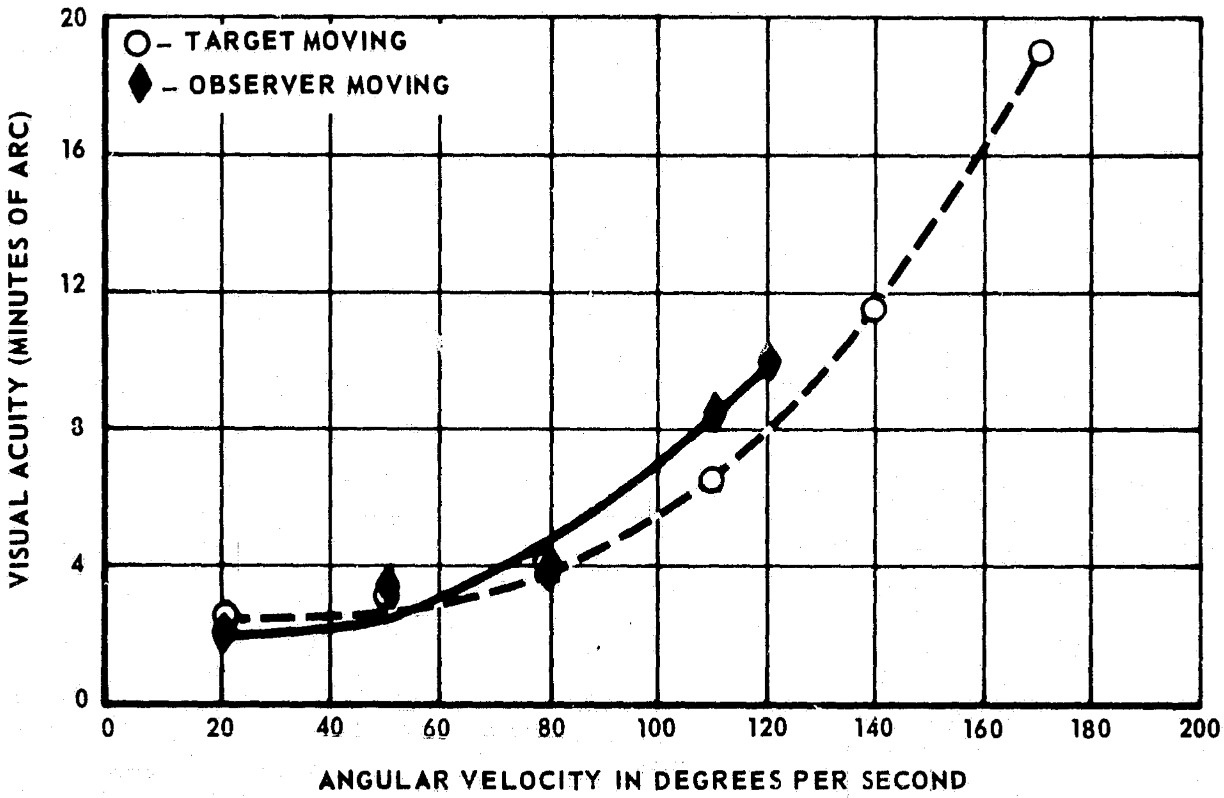

FIGURE 8 – COMPARISON OF VISUAL ACUITY WITH TEST OBJECT MOVING VERSUS OBSERVER MOVING (FROM MILLER, REF. 58)

Van den Brink (ref. 59) evaluated the cumulative effects of angular velocity and exposure time on DVA. The test objects consisted of two luminous bands separated by a dark band. In general, visual acuity deteriorated as the angular velocity of the test object increased. The results also indicated that acuity for moving targets was a function both of exposure time and angular velocity up to a critical point at which the two factors became independent.

Burg and Hulbert (ref. 60) compared binocular DVA scores at target velocities of 1047.0, 1570.5, 2094.0, and 2617.5 milliradians/sec (60, 90, 120, and 150°/sec) with critical flicker frequency (CFF), ACA ratio (derived from near and far phoria measurements), and static acuity measured on the Bausch and Lomb Ortho-Rater. No evidence was found for a statistically significant correlation between DVA score and either CFF or ACA ratio. In addition, the correlations between ACA ratio and either CFF or static acuity, or between CFF and static acuity, were not significant. Low but significant product-moment correlations were found between DVA and static acuity, but these decreased with increasing target velocity.

Goodson and Miller (ref. 61) conducted a study in which the dynamic acuity of 15 observers was measured during actual flight over ground targets of known size at altitudes ranging from 100 to 500 feet. Visual acuity became successively worse at angular velocities of 523.5, 1047.0, 1570.5 milliradians/sec (30, 60, 90°/sec).

Crawford (ref. 62) examined the ability of observers to perceive detail in moving objects as a function of target velocity, exposure time, and training. Acuity markedly deteriorated (measured by ability to identify the orientation of a Landolt ring) as angular velocity increased from 0 to 2191.3 milliradians/sec (0 to 125°/sec), with significant decrements in performance beginning to appear at an angular velocity of 1308.8 milliradians/sec (75°/sec). In the second phase of the experiment, targets were exposed for 400, 500, 600, and 700 msec at angular velocities of 872.5, 1308.8, and 1745.0 milliradians/sec (50, 75, and 100°/sec). Increases in exposure time improved acuity for all observers. Finally, a comparison was made between two observers (the author and his assistant) who had been present at all previous experimental sessions, and two naive observers, both of whom were pilots. The field of view was increased to subtend an arc of 2617.5 milliradians (150°) at the observers' eyes, and the angular velocities were increased in steps of 436.3 milliradians/sec (25°/sec) from 1745.0 to 3926.3 milliradians/sec (100 to 225°/sec). For the experienced observers, the error rate was approximately 50% at 3490 milliradians/sec (200°/sec), and reached 85% at 3926.3 milliradians/sec (225°/sec). The new observers exhibited much poorer performance and substantial failure rates: 50% at 2617.5 milliradians/sec (150°/sec) and almost complete failure at 3490 milliradians/sec (200°/sec).

Burg and Hulbert (ref. 63) examined DVA as it relates to age, sex, and static acuity. The results indicated a low, but significant, correlation between DVA and static acuity that was velocity dependent (a decreasing relationship with increasing velocity). Due to the small number of observers in the higher age brackets, a generalization about the relationship between age and DVA performance was impossible. Finally, the results suggested a consistent and significant difference in performance between male and female observers, the latter performing less adequately.

Elkin (ref. 64) examined the effect of target velocities of 523.5, 1047.0, 1570.5, and 2094.0 milliradians/sec (30, 60, 90, and 120°/sec), two anticipatory tracking times (0.2 and 1.0 sec), and two exposure times (0.2 and 0.5 sec) on DVA performance. The pairing of tracking time with an exposure time was called an exposure-pair. For example, the shortest exposure-pair permitted 0.2 sec for tracking and 0.2 sec for viewing, and the longest permitted 1 sec for tracking and 0.5 sec for viewing. After testing under dynamic viewing conditions, each observer's static acuity was determined under the same conditions that prevailed during DVA testing, except that the target was stationary and the observer had unlimited viewing time. DVA deteriorated as target velocity increased; acuity was improved by lengthening of either the tracking time or the exposure time, or the simultaneous lengthening of both; and good static acuity was necessary, but insufficient, for good dynamic acuity.

Lippert (ref. 65) conducted a study on the ability of observers to identify moving targets consisting of alphanumeric symbols. The targets, randomly assigned, were regularly spaced on an endless belt which was viewed from a constant distance. The targets subtended an angle of 11.3 milliradians (39 min) with the space between targets subtending an angle of 14.8 milliradians (51 min). the target moved vertically from top to bottom in the frontal plane. Six observers were tested on criteria of zero legibility and 100% legibility (one symbol correctly identified and all symbols correctly identified, respectively) when the tareets were viewed through apertures 5.08 cm (2 in.) wide and 5.08, 20.3, or 50.8 cm (2 in., 8 in., or 20 in.) high. As aperture height increased both legibility criteria were met at higher angular velocities of the stimulus materials. The mean angular velocities for the zero legibility criterion were approximately three times as great as for the 100% legibility criterion.

Eriksen (ref. 66) had 16 observers search for an incomplete ring (Landolt C) among a number of solid rings in a square, moving field. Search performance deteriorated as angular velocity or object density increased. Targets close to the center of the field were more easily detected than those with peripheral locations. The correlation between age of the observer and search performance failed to reach significance.

Lippert and Lee (ref. 67) investigated the legibility of moderately spaced alphanumeric symbols. A modified method of limits was employed. The targets were black alphanumeric symbols regularly spaced 130.9 milliradians (7.5°) apart on a brightly illuminated white background. Each target subtended an angle of 11.31 milliradians (39 min). Legibility of the symbols was determined as they moved vertically from top to bottom in a frontal plane. The mean angular velocities for both the zero and 100% legibility performance levels were found to be approximately three times higher for the 130.9 milliradians (7.5°) symbol spacing than for their respective velocities for a previously determined 26.2 milliradian (1.5°) symbol spacing (ref. 65). Performance was approximately twice as good with a 523.5 milliradian (30°) aperture as with a 52.4 milliradian (3°) aperture.

Simon (ref. 68) noted that radar imagery can be presented to an observer for near-real-time interpretation as a continuously moving display or in discrete steps. He studied the effect of presentation mode on the probability and speed of target acquisition. Different observers viewed the imagery on different size displays, 15.24 or 30.48 cm (6-in. or 12-in.) square, for different observation times (10, 20, or 40 sec.), and with differing amounts of ground coverage, 14.48 or 28.96 km (9 or 18 miles). The results indicated that: (1) there were no significant differences in the number of targets acquired as a function of mode of presentation, (2) significantly less time was required to find a target on the moving display, and (3) target recognition increased significantly with increases in exposure time, area of ground coverage, and display size.

Snyder and Greening (ref. 69) related DVA to relative stimulus velocity when the movement of the stimulus contains a vector of motion toward the observer. The specific parameters investigated included: (1) angular velocity of the stimulus perpendicular to the line of sight, and (2) rate of approach or radial velocity of the stimulus directly toward the observer. The primary difference between this study and previous studies of DVA lies in the inclusion of a component of motion toward the observer. In general, the visual acuity threshold increased in direct proportion to increases in angular velocity. More importantly, the visual acuity threshold increased as the rate of motion toward the observer increased from 0 to 1.37 m/sec (0 to 4.5 ft/sec).

Weissman and Freeburne (ref. 70) experimented to determine if there is a relationship between static acuity and DVA at any speed. Thirty female college students were given six speeds, 349.0, 1047.0, 1570.5, 2094.0, 2617.5, and 3140.0 milliradians/sec (20, 60, 90, 120, 150, and 180°/sec.), and one static measure of acuity. Thresholds for the first four speeds exhibited a significant linear relationship with the static acuity thresholds. The relationship disappeared at the two highest speed thresholds.

Burg (ref. 71) measured static visual acuity and DVA for 17,500 observers, (ages 16 - 92). The results show: (a) acuity declines progressively with both increasing speed of target movement and advancing age, (b) males have consistently better acuity (both static and dynamic) than females, and (c) high intercorrelations exist between the static and dynamic tests, decreasing with increasing target speed.

Methling and Wernicke (ref. 72) investigated the effect of variations in target speed and exposure time on DVA. DVA deteriorated markedly at speeds greater than 872.5 milliradians/sec (50°/sec), and as exposure time was shortened. With target velocities equal to or greater than 1047.0 milliradians/sec (60°/sec), recognition in the horizontal plane exceeded that in the vertical.

Implications for This Study

To summarize, the data contained in this section warrant the following conclusions regarding human vision as applied to the present study:

a. Most visual tasks involved in manned space flight can be categorized as target search and acquisition or optical tracking, with navigation being a highly important task grouping involving both categories.

b. Visual task performance is related to the following factors:

   (1) Brightness Contrast - Performance improves as contrast increases.

   (2) Ambient Illumination - Target detection improves as ambient illumination increases up to a point and then tends to level off.

   (3) Atmospheric Transmission - Clouds, glare, haze, and distortion all act to degrade visual performance.

   (4) Figure Ground Differentiation - Both information overload and contrast reduction enter in to degrade visual performance.

(5) Image Magnification - Increased magnification, while providing greater image resolution, causes greater image velocity, and reduces ground cues for target detection.

(6) Method of Viewing the Target - Direct viewing provides the best resolution but can be less convenient than viewing indirectly with a video link.

(7) Eye-Hand Coordination - Optimization of control-display relationships can aid materially in improving visual task performance.

(8) Static Visual Acuity - An object can be most easily resolved when it is stationary with respect to the observer.

(9) Dynamic Visual Acuity - A target becomes less distinct as its velocity increases with respect to the observer.

c. Whether in terms of the resolution of a minimum line separation or the smallest target that can be detected, static visual acuity is strongly influenced by target brightness and by the contrast between the target and its background. The following generalizations can be made about static visual acuity:

(1) If the target brightness is less than .0032 candela/meter^2 (0.001 foot lamberts), the contrast ratio must approach 100% before a target can be detected or the separation of two lines can be resolved.

(2) Acuity improves steadily as target brightness is increased, irrespective of the target contrast. Acuity tends to level off at about 32 candela/meter^2 (ten foot lamberts), and little improvement is obtained between 32 and 32,000 candela/meter^2 (10 and 10,000 foot lamberts).

(3) Acuity improves as the contrast ratio increases from 1% to 100%. The greatest increase is between 1% and 10%. At contrast ratios above 10%, the rate of acuity improvement lessens, with only a slight improvement between 75% and 100%.

d. The following can be concluded about dynamic visual acuity (DVA):

(1) Dynamic visual acuity is inversely related to the angular velocity of the test object, with marked performance decrements evident at angular velocities equal to or greater than 0.8725 radians/second (50°/sec.). Increases in illumination, object size, and target exposure time can counteract increments in angular velocity to a certain extent, but the reciprocity relationship breaks down at target velocities exceeding 2.443 radians/sec (140°/sec.)

(2) The effect of test-object angular velocity on visual acuity depends on the relative motion between the object and the observer, with focus of movement (either the observer or the target) having a negligible effect.

(3) DVA performance is direction-specific, with acuity deteriorating most rapidly for circular movement and least rapidly for vertical movement, and with movement in the horizontal plane falling between the two extremes.

(4) Any improvement in DVA performance as a result of practice occurs quite rapidly. Practice at higher angular velocities, i.e. greater than 1.920 radians/sec (110°/sec), results in substantially more improvement than practice at lower velocities, and is more beneficial for "good" performers than "poor" ones (selected on the basis of prepractice thresholds). Extended training (overlearning) does not enahnce DVA skill.

(5) There is an improvement in DVA as a function of earlier experience. Once learned, the skill does not deteriorate with the passage of time.

(6) Good static acuity is a necessary, but not a sufficient, condition for good dynamic acuity. In addition, males show consistently better performance on DVA tasks, with both sexes experiencing a decline in dynamic acuity as a function of increasing age.

ELECTRONIC AND PHOTOGRAPHIC SENSOR CHARACTERISTICS

The lower limit of dynamic visual acuity is the smear threshold for human vision. The smear thresholds for the electronic and photographic sensors considered in the present study also depend on the relative velocity of a target with respect to the sensor's line of sight. We have assumed that each sensor will be collimated with the center of the optical telescope so that the observer and the sensors will be looking at the same thing. Thus, by manually nulling the movement that he detects visually, the observer will simultaneously be nulling the movement of the target with respect to the electronic and photographic sensors.

The smear thresholds shown in Table 6 were determined from available literature (refs. 3, 73, 74, 75 and 76). The values selected represent conservative estimates of the angular rates which will result in degraded data acquisition.

TABLE 6

SMEAR THRESHOLDS FOR SENSORS CONSIDERED IN THIS STUDY

Sensor	Smear Threshold
A. High Resolution Color Film	80 Microradians/Sec (16.5 arc sec/sec)
B. SO-132 Aerial Film	100 Microradians/Sec (20.6 arc sec/sec)
C. Infrared Scanner	500 Microradians/Sec (1.72 arc min/sec)
D. Radar Imager Microwave Radiometer	872.5 Microradians/Sec (0.05°/sec)
E. IR Radiometer	3.49 Milliradians/Sec (0.2°/sec)
F. SO-130 Aerial Film	15 Milliradians/Sec (0.86°/sec)
G. SO-102 Aerial Film	55 Milliradians/Sec (3.15°/sec)
H. TRI-X Aerial Film	200 Milliradians/Sec (12.61°/sec)
I. Slight Deterioration of Visual Acuity	349 Milliradians/Sec (20°/sec)
J. Marked Deterioration of Visual Acuity	872 Milliradians/Sec (50°/sec)

MISSION ANALYSIS

Mission Selection

A large number of manned space missions were considered as possible candidates for a detailed visual task analysis. Table 7 (refs. 29, 77, 78, 79, 80, 81, 82, 83, 84, 85, and 86) contains only a sample of potential missions that were considered. A careful review of these missions revealed that, except for differences in mission duration and maneuver methods, there was a high degree of overlap between the basic mission phases and therefore probably a high degree of overlap between the visual tasks. In the interest of economy, it was decided to restrict the analysis to as few missions as possible, each of which was fairly unique, and all of which involved at least the following conditions:

a. Orbit about the Earth.

b. Interplanetary travel.

c. A broad range of navigational tasks.

d. Direct viewing of visual targets.

e. Photographing objects on the ground using conventional, high resolution films.

f. Precision aiming of multi-spectral sensors at objects on the ground.

g. Performance of visual tasks through a range of atmospheric compositions ranging from no atmosphere to that of Earth.

h. A broad range of illumination conditions on the surface being viewed.

i. Indirect viewing of surface targets through a video link system.

Based upon the above considerations, the following three missions were selected for detailed analysis of visual tasks:

a. Mars landing.

b. Lunar landing.

c. Earth resources (agricultural, cartographic, geological, oceanographic, and metrological).

Earth resources objectives.- Earth Resources Missions are aimed at collecting data about the surface of the earth so that these data can be related to social and economic requirements. The advantage of collecting data from an orbiting spacecraft is that a very large surface area can be evaluated during a single time period. With present techniques, data are collected about relatively small surface areas at different time periods and then pieced together in an attempt to determine the nature of the observed phenomena. The economic

TABLE 7. POTENTIAL MANNED MISSIONS

MISSION	DURATION	DATE
LUNAR AND PLANETARY MISSION		
a. Mars Landing (Venus Swingby)	680 Days	1978
b. Mars Landing (Conjunction)	900 Days	1979
c. Venus Orbit (Short Mission)	460 Days	1980
d. Mars Landing (Retrobraker 4 Men)	700 Days (30 Days on Surface)	1982
e. Mercury Orbit	311 Days (63 Days in Orbit)	1988
f. Vesta Orbit	745 Days (60 Day Orbit)	1991
g. Ceres Orbit	785 Days (60 Day Orbit)	1991
h. Jupiter Orbit	1416 Days (60 Day Orbit)	1990
i. Ganymede Orbit	1416 Days	1990
j. Lunar Orbit	6 Days	1969-197?
k. Lunar Landing	8 Days (2 Days on Surface)	197?
AAP EXPERIMENTS	30 Days +	197?
RESCUE MISSIONS	Unknown	Unknown
SATELLITE INSPECTION MISSIONS	Unknown	Unknown
MAINTENANCE & LOGISTIC MISSIONS	Unknown	Unknown
EARTH RESOURCES MISSIONS	2 Days +	197?
a. Geography		
b. Agriculture		
c. Forest Resources		
d. Water Resources		
e. Wildlife Management		
f. Oceanography		
g. Geology		
h. Air Pollution		
i. Archeology		

and scientific impracticality of the present approach has given the Earth Resources Missions great importance(refs. 29, 87, 88, and 89). For this reason we emphasized these missions in our study. Table 7 contains the types of potential earth resource missions that were analyzed in the present study.

Lunar landing objectives.- The objectives of this mission will be similar to those of the Mars Landing Mission. The basic difference between the two is that the lack of a lunar atmosphere will provide greater light transmission, different spectral characteristics, and sharper figure-ground differentiation due to the high brightness contrast between shadowed and unshadowed areas on the lunar surface (refs. 90, and 91).

Mars landing objectives.- The objectives of this mission will be to navigate to Mars, orbit about the planet collecting photographic and multi-spectral sensor data, find a suitable landing site, and land the spacecraft.

Analysis of Mission Functions

The missions selected for analysis were broken down into an integrated family of functional flow diagrams which presented the sequence of visual functions and tasks, indexed by a numerical taxonomy. A single flow diagram was developed for each mission. Each diagram was divided into mission segments which described the major aspects of each mission.

Earth resources survey mission.- This mission was included in the study because it involves all of the basic visual tasks that will be performed in NASA manned missions in the near future, namely navigation, surface surveillance, and rendezvous. Of these tasks, rendezvous has not been emphasized here because it was felt that the navigation and surveillance tasks placed greater emphasis on IMS requirements. It was also felt that the Earth Resources Mission typified the type of NASA mission that will predominate following the Apollo Lunar Mission. Thus, the Earth Resources visual tasks in this report may well encompass the majority of visual tasks requiring IMS under dynamic viewing conditions.

The functions requiring dynamic vision performed in the Earth Resources survey mission are shown in Figure 9. In general, the mission consists of placing a combination of active and passive sensors above the earth to record various features of interest. Some sensors require exact pointing and attitude control while others are less dependent on precise settings. The criteria for effective employment of these sensors were defined in Table 6. Man's stabilization of the multi-spectral sensing system used in earth orbit depends on the characteristics of the ground object, the degradation from the atmospheric media, and the image stability required by the individual sensors. These factors have been discussed in detail in previous reports (ref. 29, and 87). The visual tasks for this mission are described in the Task Analysis Section

Lunar landing mission.- The moon has no atmosphere; it has less mass and a smaller diameter than earth; and the surface features of the moon are visually unlike those of the earth. These differences will have a significant effect on

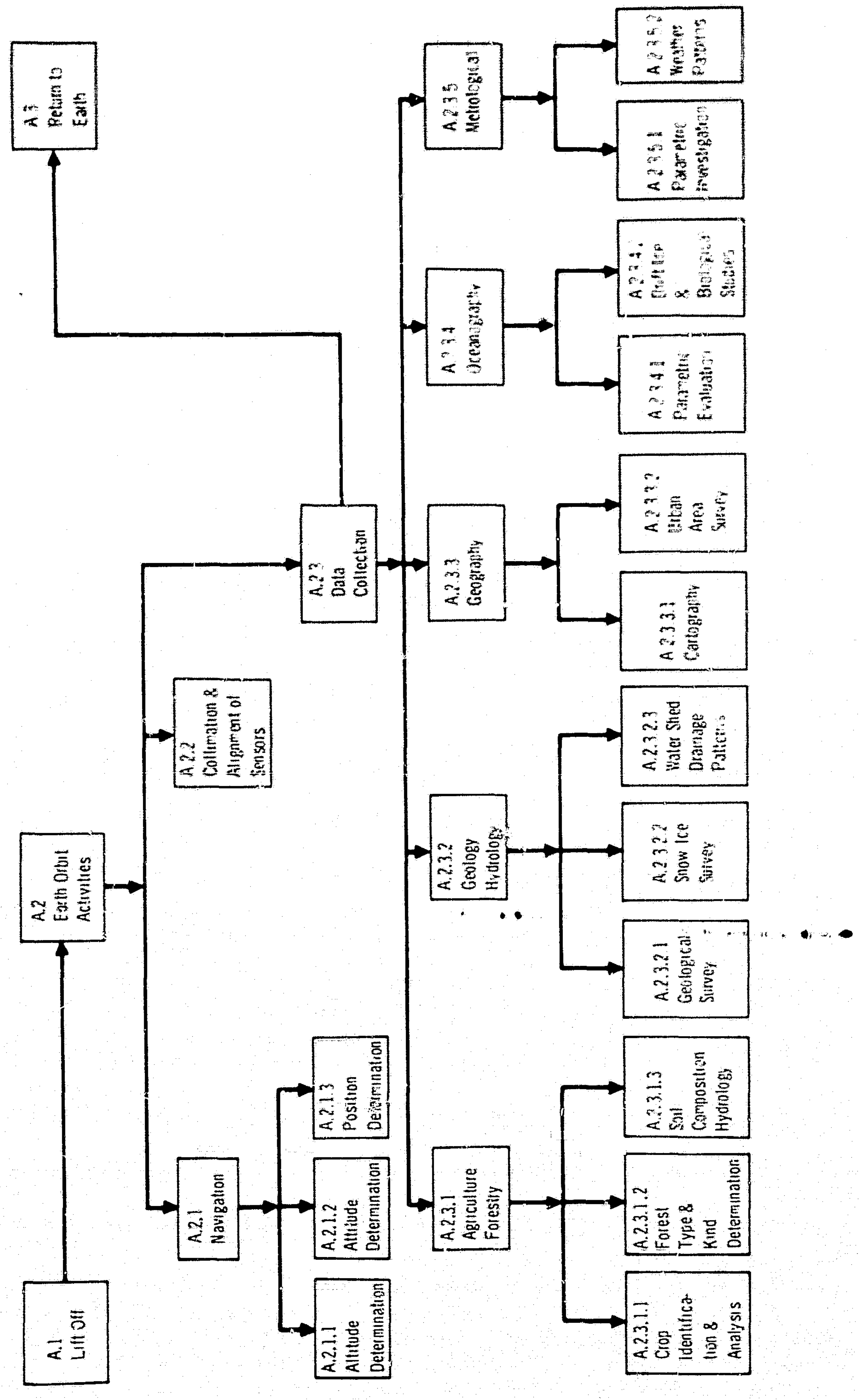

FIGURE 9
MISSION FUNCTIONS REQUIRING DYNAMIC VISION
EARTH RESOURCES SURVEY MISSION

the visual tasks to be performed aboard a lunar orbiting spacecraft for the following reasons:

a. The spacecraft will have a lower orbital velocity.

b. The orbital altitude of the spacecraft will be lower.

c. Due to lack of light gradations due to vegetation, the moon will have a higher brightness contrast between shadowed and unshadowed areas.

d. Vision will not be subject to atmospheric degradation.

e. There will probably be a lack of easily identifiable surface features, e.g., while craters may be easily discerned, it may be difficult to identify which crater is being viewed due to the lack of an exact topographic reference system such as would be found on earth using United States Coast and Geodetic Survey contour section maps.

In addition to the above, the astronauts will probably have a poorly anchored visual frame of reference with which to judge size and distance on the lunar surface.

For these reasons the visual tasks of the Lunar mission differ from the Earth Resources mission with respect to the following:

a. Mid-course navigation.

b. Target characteristics.

c. Orbital altitude.

d. Orbital velocity.

e. Target illumination and contrast.

f. Atmospheric characteristics.

The functions requiring dynamic vision performed in the Lunar Landing mission are shown in Figure 10. Along with the considerations of near lunar observations, particular emphasis was placed on the tasks of navigation and guidance in interplanetary flight. In general, by navigation and guidance, we mean the process of computing the space vehicle trajectory at various time periods and then exercising control so as to arrive at the terminal body within acceptable end-of-flight conditions. Many studies have been conducted to confirm the fact that man can effectively navigate over interplanetary distances (refs. 5, 6, 7, 8, 9, and 10).

<u>Mars landing mission</u>.- The mission to Mars will involve problems similar to those of the Lunar mission. Since Mars has different physical characteristics

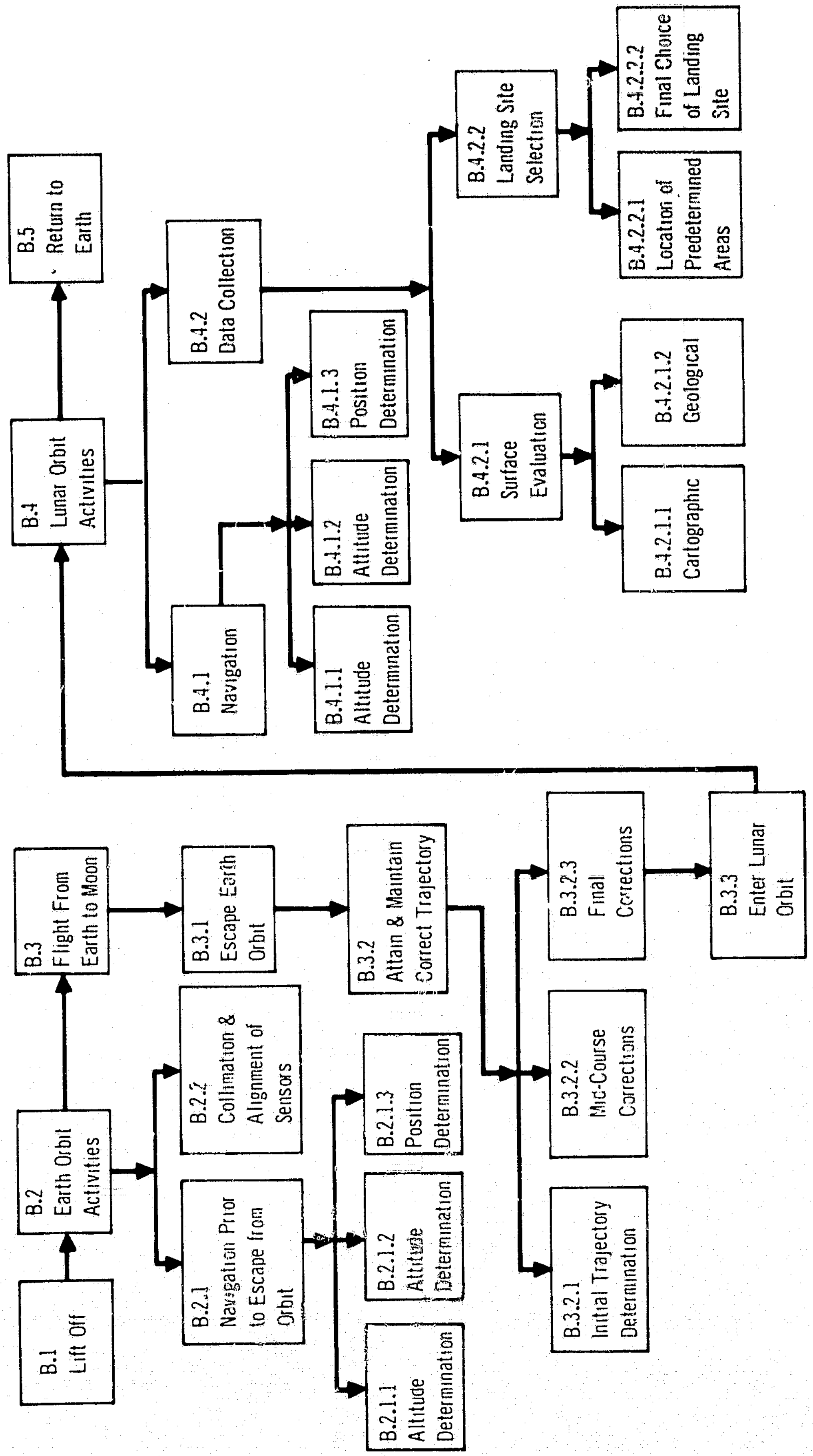

FIGURE 10
MISSION FUNCTIONS REQUIRING DYNAMIC VISION
LUNAR LANDING MISSION

than the Earth or the Moon, the visual requirements will be different. The major differences and their effects are:

a. Mar's small mass and diameter will mean that the spacecraft will attain a lower orbit with a slower orbital velocity.

b. The atmosphere of Mars differs greatly from the Earth's. It is predicted that the visible spectrum (3800Å to 7200 Å) will be restricted by Martian atmosphere which is probably opaque to human vision below 4500 Å.

c. The Martian surface is subject to what appear to be sand or dust storms. These storms will attenuate existing illumination as well as degrade figure-ground contours.

Scaling problems due to unfamiliarity with size of terrain features will exist, but not to the extent of those of the Lunar mission. Contrast between various features of the Martian landscape is expected to the lower than Lunar or Earth contrasts.

The functions requiring dynamic vision performed in the Mars Landing mission are shown in Figure 11. The visual tasks peculiar to the Mars mission are described in the Task Analysis Section.

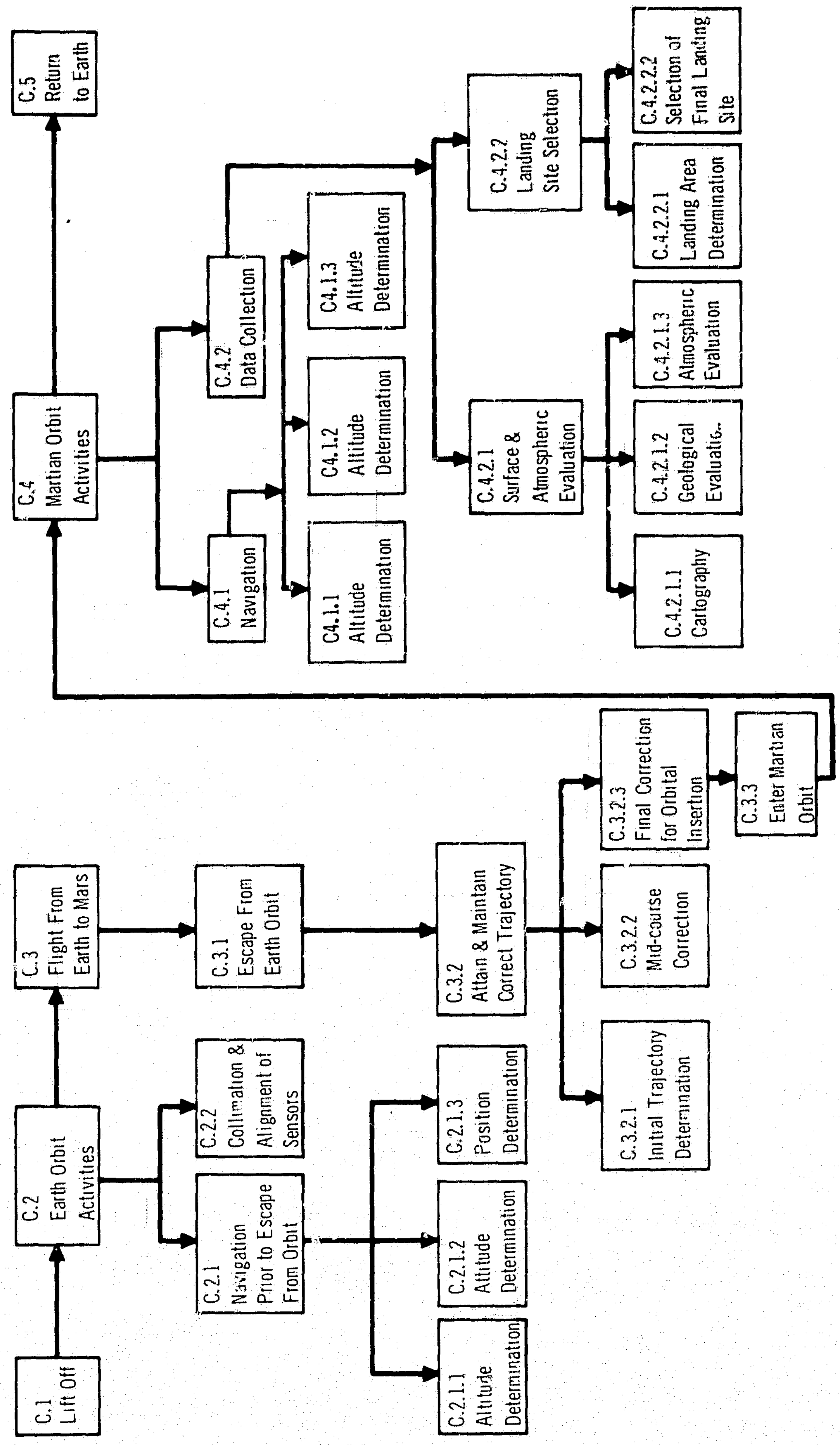

FIGURE 11
MISSION FUNCTIONS REQUIRING DYNAMIC VISION MARS LANDING MISSION

TASK ANALYSIS

Each of the missions was broken down into appropriate visual tasks which were analyzed to aid in the determination of mission and sensor constraints on the performance of the tasks. The same taxonomy applied to mission analysis was continued for the task analysis. The mission analysis determined the altitude and velocity of the vehicle, while the task analysis determined which visual tasks and sensors were appropriate. If mission and sensor constraints are known, then magnification required, image velocity and the amount of time the image will remain in the FOV can be determined. These data are developed in the next section under Physical and Environmental Conditions.

Each mission was sub-divided into major segments. The visual tasks which comprise each mission segment were then identified. Each visual task was then evaluated in terms of desired performance criteria, potential task failures and the effects of task failure. Performance criteria were determined by examination of the literature regarding the resolution required in each mission segment and the present or predicted state-of-the-art of the sensors (refs. 3, 12, 29, 87, 88, 89, and 95). The information from all sources was integrated into tables 8 through 70. Each visual task has been provided with a separate table.

Another set of tables was constructed for each sensor-mission combination. Expected or desired ground resolved distance for each sensor was extracted from the task analyses. This information was then collated for each sensor so that probable ground resolution required for each visual task could be compared. The ground resolved distances established for each task are representative of values used in the references cited (refs. 3, 12, 29, 87, 88, 89, and 95).

Earth Resources Survey Mission

Analysis of the Earth Resources Survey Mission into visual tasks is found in Tables 8 through 23. The visual tasks presented in the tables represent the most probable and productive missions of the near future. Probable targets and the estimated ground resolution required for each sensor are presented in Tables 24 through 29.

Lunar Landing Mission

Major visual tasks for the Lunar Landing Mission are shown in Tables 30 through 43. Probable targets, and the estimated ground resolution required for each sensor are presented in Tables 44 through 49.

Mars Landing Mission

Major visual tasks for the Mars Landing Mission are shown in Tables 50 through 64. Probable targets, and the estimated ground resolution required for each sensor are presented in Tables 65 through 70.

TABLE 8. VISUAL TASK ANALYSIS FOR: ALTITUDE DETERMINATION (A.2.1.1)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Navigation (A.2.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Identify checkpoint on earth's surface.	Should be identifiable with naked eye (i.e. distance across major axis): 100 N.M.Alt = 1800 Feet 150 N.M.Alt = 2700 Feet 200 N.M.Alt = 3600 Feet Must discriminate true checkpoint from other possible targets by means of shape, size and perhaps, color cues.	Failure to detect.	Incorrect altitude determination could have serious effects on validity of data collected from orbit.
		Acquisition of incorrect point.	Detection of alternate target could result in expenditure of mission time that could more profitably be used to collect surface data.
2. Activate altitude determination sensor. 2.1 Radar Altimeter. 2.2 Laser Altimeter.			
3. Center checkpoint in optical system and maintain optical line of sight tracking.	Tracking criterion = .05°/second (ref. 3).	Failure to maintain track on surface area of uniform elevation.	Unreliable altitude data could result in degraded sensor data.

TABLE 9. VISUAL TASK ANALYSIS FOR: ATTITUDE DETERMINATION (A.2.1.2)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Navigation (A.2.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Identify two known stars	The stars selected will largely depend on availability. The stars should be about the third magnitude of brightness and should be discriminable. Search for a specific location within a known and unique pattern would greatly aid in acquisition.	Failure to acquire stars. Acquisition of incorrect stars.	Incorrect attitude determination could result in degraded sensor data.
2. Using inertial measurement unit optical system acquire the first star.			
3. Acquire the second star.	This will provide the attitude of the spacecraft with respect to inertial space.		
4. Hold spacecraft attitude while reading out the present attitude.	Maximum rotation rate = 1.22 milliradians/sec (.07°/sec) (ref. 92).		
5. If present attitude differs from sensor requirement, insert the desired attitude.			

TABLE 10. VISUAL TASK ANALYSIS FOR: POSITION DETERMINATION (A.2.1.3)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Navigation (A.2.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Identify checkpoint on Earth's surface.	See A.2.1.1.1	See A.2.1.1.1	Incorrect position determination could result in: Degraded sensor data Excessive fuel expenditure.
2. Acquire checkpoint in primary line-of-sight field of sextant.	The sextant should have a field of view of about 122.15 milliradians (7°) and a magnification factor of 8 (ref. 9). A resolution of 48 microradians (10 arc seconds) is desirable for the sextant. Information on star sightings during night time Gemini flights indicates that stars of the sixth magnitude can be used as navigational aids (ref. 14, 18). Simulator studies (ref. 8, 10, 13) have been concerned with the simulated precision by which they can be measured		
3. Identify known star.			

TABLE 10. VISUAL TASK ANALYSIS FOR: POSITION DETERMINATION (A.2.1.3) - CONTINUED

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Navigation (A.2.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
4. Acquire known star in secondary line of sight field.			
5. Superimpose the star over the center of the landmark by rotating the sextant indexing arm.			
6. Read the resultant angle directly from the vernier scale and the indexed arc.	Spacecraft movement = 26.2 milliradians/sec (1.5°/sec) in each axis (roll most critical for navigation) resulting in relative motion of up to 1.44 milliradians/sec (300 arc sec/sec) with respect to target. Error is minimized at 96 microradians/sec (20 arc sec/sec) (ref. 11). Desirable to consider IMS to achieve desired 48 microradian (10 arc second) accuracy.		

TABLE 11. VISUAL TASK ANALYSIS FOR: COLLIMATION AND ALIGNMENT OF SENSORS (A.2.2)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Collimation and Alignment of Sensors (A.2.2)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Acquire a prominent target for purpose of sensor alignment. Would have to provide for alternate targets in case of cloud cover in target area.	All sensors held on target which gives known signal for each sensor for purposes of alignment and calibration. Must be able to discriminate correct target on basis of pattern and prelaunch briefing. Alternate targets must also have same degree of discriminability.	Acquisition of a different target.	Calibration tests useless, requires another data pass if sensors are to be checked out.
	Pointing Criteria (see Table 6).	Misalignment of target and/or failure to accurately track target.	Calibration data inaccurate. Could also result in lack of any calibration data being acquired.

TABLE 12. VISUAL TASK ANALYSIS FOR: CROP IDENTIFICATION & ANALYSIS (A.2.3.1.1)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Agricultural/Forestry (A.2.3.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Location of crop areas as differentiated from rangeland or forests.	Need to discriminate cultivated from uncultivated land. Terrain features and brightness contrast can assist in making discriminations. Must detect land areas which have a high probability of being crop land. Need to detect particular areas of interest from highly similar terrain features.	Tracking incorrect target.	Lost data pass. If wrong target is sensed, the resulting data could approximate expected data. Acceptance or rejection of data on a statistical basis could lead to acceptance of spurious data as valid. Statistical acceptance model will probably be modified by data feedback.
		Partial tracking of target.	Confusion of valid and invalid data compounded by uncertainty of which portion of target area the valid data come from.
2. Differentiation of crops within cultivated area.	Need to discriminate one type of crop from another.		

TABLE 13. VISUAL TASK ANALYSIS FOR: FOREST TYPE & KIND DETERMINATION (A.2.3.1.2)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Agricultural/Forestry (A.2.3.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Differentiation of forest areas from crop land or range land.	Discrimination of forested from unforested areas means of: a) brightness contrast b) topographical features c) color d) patterns.	Tracking incorrect targets.	Lost data pass. No firm knowledge of what acquired target signatures represent.
2. Determination of types (hardwood vs conifers) within the forest area.		Partial tracking of target.	Confusion of valid and invalid data.
3. Possible determination of which stands have reached the maturity for harvesting.			

TABLE 13. VISUAL TASK ANALYSIS FOR: FOREST TYPE & KIND DETERMINATION (A.2.3.1.2)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Agricultural/Forestry (A.2.3.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Differentiation of forest areas from crop land or range land.	Discrimination of forested from unforested areas means of: a) brightness contrast b) topographical features c) color d) patterns.	Tracking incorrect targets.	Lost data pass. No firm knowledge of what acquired target signatures represent.
2. Determination of types (hardwood vs conifers) within the forest area.		Partial tracking of target.	Confusion of valid and invalid data.
3. Possible determination of which stands have reached the maturity for harvesting.			

TABLE 14. VISUAL TASK ANALYSIS FOR: SOIL COMPOSITION/HYDROLOGICAL DETERMINATION (A.2.3.1.3)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Agricultural/Forestry (A.2.3.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Broad sweep of an area from a known start point to a known stop point.	Identification of target is the limiting task as long as sensors are held steady along the desired line of track.	Misidentification of initial target.	Duplication of data with gaps in coverage. Possibility of mis-identification of data.
	Identification of the starting point & stopping point will require ability to recognize prominent landmarks.	Lack of target stabilization.	Useless data because of inconsistency or uncertainty of what target was.

TABLE 15. VISUAL TASK ANALYSIS FOR: GEOLOGICAL SURVEY (A.2.3.2.1)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Geology/Hydrology (A.2.3.2)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Investigation of major geologic features such as crust structure, faults, or domes. Resultant data useful for determination of those crust structures associated with various minerals or oil deposits.	Specific areas that would possibly yield various minerals. Identification of landmarks for recognition, or those land mass structures which are associated with mineral or oil deposits.	Misidentification of target.	Data of wrong area used as basis of decision. Perhaps solved by placing at least one prominent known landmark in FOV.
		Failure to track target.	Decisions made on basis of incorrect data. Smear rates too high to give useable data.
		Non-recognition of targets due to lack of pre-briefing of what possible targets exist.	Data loss requiring duplication of effort.

TABLE 16. VISUAL TASK ANALYSIS FOR: SNOW/ICE SURVEY (A.2.3.2.2)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Geology/Hydrology (A.2.3.2)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Water management & control. Possible use as flood and/or recreational prediction.	Targets will range from polar caps to mountains, snow depths or large area coverage of snow patterns. Need to identify specific watershed patterns, i.e. distinctive river basins, that will either be predetermined targets or targets of opportunity.	Misidentification of target areas.	Data from unknown source possibly used as basis for prediction.

TABLE 17. VISUAL TASK ANALYSIS FOR: WATERSHED DRAINAGE PATTERNS (A.2.3.2.3)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Geology/Hydrology (A.2.3.2)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Watershed drainage patterns for major river systems. Seasonal changes, weather & flood control, agricultural prediction.	Location & identification of specific areas. Reference landmarks need to have high probability of identification so that successive data may be taken.	Misidentification of assigned target. Sensors not always on target.	Failure to get data or data acquired from another area. Confusion of desired & spurious data.
2. Targets range from small streams & ponds to large river basins, i.e. Missouri-Mississippi drainage complex.		Misalignment of sensors on landmarks on successive passes.	Lack of consistent data for comparison purposes.

TABLE 18. VISUAL TASK ANALYSIS FOR: CARTOGRAPHY (A.2.3.3.1)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Geography (A.2.3.3)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Cartographic updating, correction or initial mapping.	Acquisition of landmarks for initiation & termination of sensors. Need to have landmarks which will give consistent start points on successive orbital paths.	Misidentification or no identification of starting point.	Lost data pass or gaps in data with extra coverage of other areas.
2. Various scales required & desirable - worst case presented.			

TABLE 19. VISUAL TASK ANALYSIS FOR: URBAN AREA SURVEY (A.2.3.3.2)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Geography (A.2.3.3)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Definition of land use, types & location of structures & transportation networks within urban areas.	Location of assigned urban areas. Must have precise identification cues so that one urban area can be discriminated from another and to provide firm benchmarks for re-acquisition.	Misidentification or not locating target. Failure to maintain sensor focus on data area.	Lost data pass. Lost data or confusion of desired and undesired data.

TABLE 20. VISUAL TASK ANALYSIS FOR: OCEANOGRAPHIC PARAMETRIC INVESTIGATION (A.2.3.4.1)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Oceanography (A.2.3.4)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Measurement of ocean parameters such as currents, temperature, sea state, coastal & shoal mapping.	Definite targets near coasts, reefs or relatively defined areas (Gulf of Mexico). Large ocean expanses need definite benchmarks for reference.	Mislocating or missing the target completely in reef & shoal mapping.	Lost data pass.
		Lack of benchmarks when sampling ocean parameters.	Uncertainty as to where data came from.

TABLE 21. VISUAL TASK ANALYSIS FOR: DRIFT ICE & BIOLOGICAL STUDIES (A.2.3.4.2)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Oceanography (A.2.3.4)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Location of drift ice within shipping lanes or that could possibly drift into shipping lanes. Targets of opportunity would also include large schools of fish.	Need to identify shipping lanes. Drift ice which is within or drifting into shipping lanes must be identified. Need to establish permanent benchmarks with respect to each lane and location of drifting ice within the lane. This will require accurate location of position of drift ice using few landmarks. Successive passes will require re-acquisition in order to calculate drift rate & new position.	Failure to recognize targets (ice or fish). Failure to provide benchmarks for data.	Implicit assumption that sea lanes are clear when in fact they aren't. Useable data but no identification of location of data.

TABLE 22. VISUAL TASK ANALYSIS FOR: ATMOSPHERIC PARAMETERS STUDY (A.2.3.5.1)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Metrological (A.2.3.5)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Measurement of various parameters of large weather systems, probably on a recurring basis.	Recognition of major weather systems for purposes of periodic measurement. Need to establish firm benchmarks for return passes.	Failure to provide for benchmarks so that periodic samplings are not of same area.	Lack of correlation of data so that periodic samples do not give a history of the system.

TABLE 23. VISUAL TASK ANALYSIS FOR: LOCATION & DOCUMENTATION OF WEATHER PATTERNS (A.2.3.5.2)

Mission: Earth Resources Survey (A)
Mission Segment: Earth Orbit Activities (A.2)
Function: Data Collection (A.2.3)
Task Type: Metrological (A.2.3.5)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Location of targets such as hurricanes, tornadoes, or other potentially destructive weather systems.	Detection, recognition & localization of cloud cover which is indicative of a particular weather system.	Failure to locate & identify potentially destructive weather systems.	Missed data pass. Information may be unavailable until fully developed system exists.

TABLE 24. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: CONVENTIONAL PHOTOGRAPHY

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.1.1	Crop identification and analysis.	Cultivated land boundaries.	100 ft	50 ft	5 ft
A.2.3.1.2	Forest type determination.	Forest stands.	100 ft	20 ft	10 ft
A.2.3.1.3	Watershed areas.	Land areas either used as crop land or with potential use as crop land.	200 ft	100 ft	10 ft
A.2.3.2.1	Geological survey to determine Earth's surface structure.	Specific or general land areas that will show faults, domes, etc. in Earth's structure.	100 ft	50 ft	10 ft
A.2.3.2.2	Snow and ice depth survey to determine depth and yield.	Polar areas, mountainous areas of earth which are generally snow covered (Western plains or Rocky Mountains).	500 ft	200 ft	100 ft
A.2.3.2.3	Watershed drainage area.	Lakes, ponds, marshes, rivers, river deltas either in small sections or as continental patterns.	500 ft	100 ft	10 ft

TABLE 24. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: CONVENTIONAL PHOTOGRAPHY - CONTINUED

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.3.1	Cartography.	Small scale maps of continental land masses and detailed maps of chosen areas.	100 ft	50 ft	10 ft
A.2.3.3.2	Urban use.	Urban planning area identification, transportation system.	10 ft	5 ft	2 ft
A.2.3.4.1	Oceanographic parametric investigation.	Sea state, currents, pollution, wave action or tide action.	1000 ft	200 ft	100 ft
A.2.3.4.2	Sea ice and/or schools of fish.	Location of ice in shipping lanes or coming off the polar caps. Location of schools of fish for commercial purposes.	200 ft	100 ft	50 ft
A.2.3.5.1	Cloud formation and weather system patterns.	Formation, location and movement of gross or fine weather systems.	500 ft	200 ft	100 ft
A.2.3.5.2	Storm location.	Targets of opportunity consisting of extremely damaging weather phenomena.	500 ft	200 ft	50 ft

TABLE 25. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: MULTISPECTRAL SCANNER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.1.1	Analysis of crop type and health.	Cultivated land.	100 ft	50 ft	5 ft
A.2.3.1.2	Analysis of type of trees within forested areas.	Forested areas.	100 ft	20 ft	10 ft
A.2.3.1.3	Soil composition and moisture content.	Soil comparisons from various portions of the watershed and supporting various crops.	200 ft	100 ft	10 ft
A.2.3.2.1	Geological survey of the types of surface rock formations.	Areas which would most likely show mineral or oil deposits.	100 ft	50 ft	10 ft
A.2.3.2.2	Snow and ice survey to determine characteristics of snow or ice.	Areas in which knowledge of snow or ice cover state can yield data for transportation, recreational and agricultural purposes.	500 ft	200 ft	100 ft
A.2.3.2.3	Analysis of moisture content within a watershed area.	Comparison of amount of water within the various areas of the drainage pattern.	500 ft	100 ft	10 ft

TABLE 25. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: MULTISPECTRAL SCANNER - CONTINUED

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.3.2	Urban use.	Urban areas for determination of transportation, power sources, population-manufacturing distribution.	10 ft	5 ft	2 ft
A.2.3.4.1	Parametric investigation of oceans.	Sea state, current flow, tide patterns and coastal mapping.	1000 ft	200 ft	100 ft
A.2.3.4.2	Sea ice and/or biological phenomena.	Shipping lanes and targets of opportunity.	500 ft	200 ft	100 ft
A.2.3.5.1	Atmospheric parametric investigation.	Large cloud formations.	500 ft	200 ft	50 ft
A.2.3.5.2	Storm centers.	Tornado, cyclone, hurricane; formation investigation.	500 ft	200 ft	50 ft

TABLE 26. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: COHERENT RADAR

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.1.1	Analysis of crop type and health.	Location and identification of cultivated field boundaries.	100 ft	50 ft	20 ft
A.2.3.1.2	Determination of forested areas with possible tree type analysis.	Range lands with interspersed forest tracts.	100 ft	50 ft	25 ft
A.2.3.1.3	Soil composition and moisture content.	Cultivated areas and watershed data.	200 ft	100 ft	20 ft
A.2.3.2.1	Geological survey of surface structure.	Selected areas for identification of lines, faults, etc.	500 ft	200 ft	100 ft
A.2.3.2.2	Snow and ice field survey.	Those areas covered by snow and ice which make major contribution to a watershed area.	500 ft	200 ft	100 ft
A.2.3.2.3	Watershed drainage patterns.	Mapping of watershed areas in gross form with finer mapping of selected areas.	500 ft	200 ft	25 ft
A.2.3.3.1	Mapping.	Mapping as supplement to photo and as primary collection system.	500 ft	100 ft	25 ft

TABLE 26. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: COHERENT RADAR - CONTINUED

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.3.2	Urban use.	Urban area mapping.	100 ft	50 ft	10 ft
A.2.3.4.1	Parametric investigation.	Sea state, shoal and coastal mapping.	300 ft	100 ft	25 ft
A.2.3.4.2	Sea ice and/or biological phenomena.	Shipping lanes with high probability of containing sea ice.	500 ft	200 ft	100 ft
A.2.3.5.1	Atmospheric parameters.	Cloud and atmospheric patterns.	500 ft	200 ft	100 ft
A.2.3.5.2	Storm centers.	Major storm systems.	500 ft	200 ft	100 ft

TABLE 27. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: INFRARED SCANNER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.1.1	Analysis of crop type and health.	Cultivated land.	500 ft	200 ft	100 ft
A.2.3.1.2	Analysis of type of trees within forested areas.	Forested areas.	500 ft	200 ft	100 ft
A.2.3.1.3	Analysis of soil composition and moisture content.	Cultivated areas and watershed data.	500 ft	200 ft	100 ft
A.2.3.2.1	Geological survey of surface structure.	Selected areas to obtain information about surface features and composition.	500 ft	200 ft	100 ft
A.2.3.2.2	Survey of snow and ice fields.	Areas covered by snow or ice to determine hydrologic data.	500 ft	200 ft	100 ft
A.2.3.2.3	Watershed drainage patterns.	Water content within a watershed area examined.	500 ft	200 ft	100 ft
A.2.3.3.1	Cartography.	Mapping can occur on passes in dark side of orbit.	500 ft	200 ft	100 ft
A.2.3.3.2	Urban use.	Urban areas with respect to transportation, industry and power use.	100 ft	50 ft	10 ft

TABLE 27. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: INFRARED SCANNER - CONTINUED

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.4.1	Parametric investigation.	Sea state and current mapping.	1000 ft	500 ft	100 ft
A.2.3.4.2	Sea ice and/or biological phenomena.	Shipping lanes and areas of ocean suspected to have biological interest.	1000 ft	500 ft	100 ft
A.2.3.5.1	Atmospheric parameters.	Large weather systems.	500 ft	200 ft	100 ft
A.2.3.5.2	Storm centers.	Tornados, hurricanes, etc.	500 ft	200 ft	100 ft

TABLE 28. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: MICROWAVE RADIOMETER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.1.3	Analysis of soil composition and moisture content.	Cultivated and watershed areas.	200 ft	100 ft	20 ft
A.2.3.2.1	Geological survey of surface structure.	Selected areas for identification of lines, faults, etc.	500 ft	200 ft	100 ft
A.2.3.2.2	Snow and ice field survey.	Snow and ice fields for depth and consistency.	500 ft	200 ft	100 ft
A.2.3.2.3	Watershed drainage area.	Determination of depth of moisture content.	500 ft	200 ft	100 ft
A.2.3.4.1	Parametric investigation.	Sea surface states and coastal mapping.	500 ft	200 ft	100 ft
A.2.3.4.2	Sea ice and/or biological phenomena.	Shipping lanes.	500 ft	200 ft	100 ft

TABLE 29. SUMMARY OF TARGET CHARACTERISTICS FOR EARTH RESOURCES SURVEY MISSION
SENSOR: LASER ALTIMETER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
A.2.3.2.2	Determine depth of snow or ice field.	Polar areas, upper portion of watershed area.	ADEQUATE INFORMATION NOT AVAILABLE		
A.2.3.3.1	Mapping.	Ground slope mapping.			
A.2.3.4.1	Parametric investigation.	Sea state and coastal mapping.			
A.2.3.5.1	Atmospheric parameters.	Turbulence, wind shear.			
A.2.3.5.2	Storm center.	Turbulence, wind shear.			

TABLE 30. VISUAL TASK ANALYSIS FOR: ALTITUDE DETERMINATION (B.2.1.1)

Mission: Lunar Landing (B)
Mission Segment: Earth Orbit Activities (B.2)
Function: Navigation Prior to Escape from Orbit (B.2.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is Identical to A.2.1.1 (Earth Resources Survey).			

TABLE 31. VISUAL TASK ANALYSIS FOR: ATTITUDE DETERMINATION (B.2.1.2)

Mission: Lunar Landing (B)

Mission Segment: Earth Orbit Activities (B.2)

Function: Navigation Prior to Escape from Orbit (B.2.1)

Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is Identical to A.2.1.2 (Earth Resources Survey).			

TABLE 32. VISUAL TASK ANALYSIS FOR: POSITION DETERMINATION (B.2.1.3)

Mission: Lunar Landing (B)
Mission Segment: Earth Orbit Activities (B.2)
Function: Navigation Prior to Escape from Orbit (B.2.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is Identical to A.2.1.3 (Earth Resources Survey).			

TABLE 33. VISUAL TASK ANALYSIS FOR: COLLIMATION AND ALIGNMENT OF SENSORS (B.2.2)

Mission: Lunar Landing (B)
Mission Segment: Earth Orbit Activities (B.2)
Function: Collimation and Alignment of Sensors (B.2.2)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
See A.2.2 (Earth Resources Survey).			

TABLE 34. VISUAL TASK ANALYSIS FOR: INITIAL TRAJECTORY DETERMINATION (B.3.2.1)

Mission: Lunar Landing (B)

Mission Segment: Flight From Earth to Moon (B.3)

Function: Attainment and Maintenance of Correct Trajectory (B.3.2)

Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Acquire Earth in scanning telescope (ref. 93).	See A.2.1.3 for Performance Requirements and Task Failure Data.		
2. Identify known star.			
3. Using sextant, measure the angle between the two bodies. This will provide position data.			
4. Determine spacecraft attitude.	See A.2.1.2 for Performance Requirements and Task Failure Data.		
5. Determine radar range to moon.	Antenna pointing within .05°/sec (ref. 93).	Failure to hold spacecraft within pointing limits while measuring range.	May result in faulty range estimation but would be updated during midcourse corrections.

TABLE 35. VISUAL TASK ANALYSIS FOR: MID-COURSE CORRECTIONS (B.3.2.2)

Mission: Lunar Landing (B)

Mission Segment: Flight from Earth to Moon (B.3)

Function: Attainment and Maintenance of Correct Trajectory (B.3.2)

Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Determine present trajectory (See B.3.2.1 for task details).			
2. Apply correction if present trajectory differs from desired trajectory.			
3. Re-check trajectory to insure that it is now correct.	(See B.3.2.1 for details)		

TABLE 36. VISUAL TASK ANALYSIS FOR: FINAL CORRECTIONS FOR ORBITAL INSERTION (B.3.2.3)

Mission: Lunar Landing (B)
Mission Segment: Flight from Earth to Moon (B.3)
Function: Attainment and Maintenance of Correct Trajectory (B.3.2)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Same as B.3.2.2.			Precise determination of interplanetary trajectory and attitude crucial for correct retro braking time and impulse.

TABLE 37. VISUAL TASK ANALYSIS FOR: ALTITUDE DETERMINATION (B.4.1.1)

Mission: Lunar Landing (B)
Mission Segment: Lunar Orbit Activities (B.4)
Function: Navigation (B.4.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Identify checkpoint on Lunar surface.	Should be identifiable with naked eye (i.e. approximately 1330 feet across major axis)(ref. 93).	See A.2.1.1.1.	See A.2.1.1.1.
2. Remainder of task identical to A.2.1.1 (Earth Resources Survey).			

TABLE 38. VISUAL TASK ANALYSIS FOR: ATTITUDE DETERMINATION (B.4.1.2)

Mission: Lunar Landing (B)
Mission Segment: Lunar Orbit Activities (B.4)
Function: Navigation (B.4.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is Identical to A.2.1.2 (Earth Resources Survey).			

TABLE 39. VISUAL TASK ANALYSIS FOR: POSITION DETERMINATION (B.4.1.3)

Mission: Lunar Landing (B)
Mission Segment: Lunar Orbit Activities (B.4)
Function: Navigation (B.4.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Identify checkpoint on lunar surface.	See B.4.1.1.1.	See A.2.1.1.1.	See A.2.1.1.1.
2. Remainder of Task Identical to A.2.1.1.			

TABLE 40. VISUAL TASK ANALYSIS FOR: CARTOGRAPHIC (B.4.2.1.1)

Mission: Lunar (B)
Mission Segment: Lunar Orbit Activities (B.4)
Function: Data Collection (B.4.2)
Task Type: Surface Evaluation (B.4.2.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Large area mapping of surface and fine scale mapping of selected areas.	Area mapping of major areas of moon with large ground resolution. Detailed mapping of craters and other geological formations.	Failure to maintain sensors within limits of field of view or motion rate.	Data lost or garbled.

TABLE 41. VISUAL TASK ANALYSIS FOR: GEOLOGICAL PARAMETERS (B.4.2.1.2)

Mission: Lunar (B)

Mission Segment: Lunar Orbit Activities (B.4)

Function: Data Collection (B.4.2)

Task Type: Surface Evaluation (B.4.2.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Investigation of the major geological structural features and soil composition. Determination of area made first while subsequent data passes are used to acquire target information.	Selected geographical structures and areas of distinct soil type.	Failure to acquire target.	Lost data pass.
	Requires determination of precise location of selected area for future reference.	Failure to maintain target within field of view or to maintain motion within required limits.	Lost data or data not within acceptable limits of processor.

TABLE 42. VISUAL TASK ANALYSIS FOR: LOCATION OF PREDETERMINED LANDING AREAS (B.4.2.2.1)

Mission: Lunar (B)
Mission Segment: Lunar Orbit Activities (B.4)
Function: Data Collection (B.4.2)
Task Type: Landing Site Selection (B.4.2.2)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Location of predetermined landing areas.	Identification of those areas which meet requirements as landing sites. Some identified from previous missions. Others on basis of terrain features.	Misidentification of potentially hazardous landing areas as safe landing areas.	Potentially hazardous landing.

TABLE 43. VISUAL TASK ANALYSIS FOR: FINAL SELECTION OF LANDING SITE (B.4.2.2.2)

Mission: Lunar (B)
Mission Segment: Lunar Orbit Activities (B.4)
Function: Data Collection (B.4.2)
Task Type: Landing Site Selection (B.4.2.2)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Final selection of landing site within the landing areas.	Need to ascertain if final site is level enough and if the soil will bear landing loads.	Landing on hazardous site.	Catastrophic.

TABLE 44. SUMMARY OF TARGET CHARACTERISTICS FOR LUNAR LANDING MISSION

SENSOR: CONVENTIONAL PHOTOGRAPHY

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
B.4.2.1.1	Large area mapping of lunar surface with detailed mapping of some areas.	Fine detail mapping of future landing sites.	500 ft	100 ft	10 ft
B.4.2.1.2	Photography of major areas of geological interest.	Craters, faults, impact lines.	500 ft	250 ft	100 ft

TABLE 45. SUMMARY OF TARGET CHARACTERISTICS FOR LUNAR LANDING MISSION

SENSOR: MULTISPECTRAL SCANNER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
B.4.2.1.2	Signature data on various geological structures.	Craters, plateaus, characteristic soils.	250 ft	100 ft	25 ft

TABLE 46. SUMMARY OF TARGET CHARACTERISTICS FOR LUNAR LANDING MISSION

SENSOR: INFARARED SCANNER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
B.4.2.1.1	Temperature and contour maps of terrain.	Selected surface features & areas.	500 ft	250 ft	100 ft
B.4.2.1.2	Terrain structures and "typical" soil areas.	Craters, prominent geological structures & formations.	500 ft	250 ft	100 ft
B.4.2.2.2	Load bearing ability of surface & slope mapping.	Final landing sites.	250 ft	100 ft	10 ft

TABLE 47. SUMMARY OF TARGET CHARACTERISTICS FOR LUNAR LANDING MISSION

SENSOR: COHERENT RADAR

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
B.4.2.1.1	Radar mapping of surface. Slope and altitude determination.	Characteristic terrain areas and geological formations of interest.	500 ft	250 ft	100 ft
B.4.2.1.1	Delineation of faults, domes, fractures of the lunar surface.	Geological formations indicative of the formation of craters and subsequent action of meteorites on lunar surface.	500 ft	250 ft	100 ft
B.4.2.2.2	Final determination of surface slope and terrain features of landing site.	Final landing site.	100 ft	50 ft	10 ft

TABLE 48. SUMMARY OF TARGET CHARACTERISTICS FOR LUNAR LANDING MISSION

SENSOR: MICROWAVE RADIOMETER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
B.4.2.1.2	Determination of soil and rock structure on lunar surface.	Representative samples of terrain.	500 ft	250 ft	100 ft
B.4.2.2.2	Determination of constitution and load bearing strength of landing site surface.	Final landing sites selected.	200 ft	100 ft	50 ft

TABLE 49. SUMMARY OF TARGET CHARACTERISTICS FOR LUNAR LANDING MISSION

SENSOR: LASER ALTIMETER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
B.4.2.1.1	Altitude determination of various terrain features.	Prominent terrain features which are being mapped.		ADEQUATE DATA NOT AVAILABLE	
B.4.2.1.2	Slope determination for geological features.	Craters, faults.			
B.4.2.2.2	Slope and altitude determination of final landing site.	Landing sites.			

TABLE 50. VISUAL TASK ANALYSIS FOR: ALTITUDE DETERMINATION (C.2.1.1)

Mission: Mars Landing (C)
Mission Segment: Earth Orbit Activities (C.2)
Function: Navigation Prior to Escape from Orbit (C.2.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is Identical to A.2.1.1 (Earth Resources Survey).			

TABLE 51. VISUAL TASK ANALYSIS FOR: ATTITUDE DETERMINATION (C.2.1.2)

Mission: Mars Landing (C)
Mission Segment: Earth Orbit Activities (C.2)
Function: Navigation Prior to Escape from Orbit (C.2.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is Identical to A.2.1.2 (Earth Resources Survey).			

TABLE 52. VISUAL TASK ANALYSIS FOR: POSITION DETERMINATION (C.2.1.3)

Mission: Mars Landing (C)

Mission Segment: Earth Orbit Activities (C.2)

Function: Navigation Prior to Escape from Orbit (C.2.1)

Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is Identical to A.2.1.3 (Earth Resources Survey).			

TABLE 53. VISUAL TASK ANALYSIS FOR: CALIBRATION AND ALIGNMENT OF SENSORS (C.2.2)

Mission: Mars Landing (C)
Mission Segment: Earth Orbit Activities (C.2)
Function: Calibration and Alignment of Sensors (C.2.2)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
See A.2.2 (Earth Resources Survey).			

TABLE 54. VISUAL TASK ANALYSIS FOR: INITIAL TRAJECTORY DETERMINATION (C.3.2.1)

Mission: Mars Landing (C)
Mission Segment: Flight from Earth to Mars (C.3)
Function: Attainment and Maintenance of Correct Trajectory (C.3.2)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
C.3.2.1.1 thru C.3.2.1.4	Identical to B.3.2.1.1 thru B.3.2.1.4		
Determine Radar Range to Mars.	Antenna pointing within .05°/sec.	Failure to hold spacecraft within pointing limits while measuring range. Failure to acquire Mars due to distance.	May result in faulty range estimation but would be updated during subsequent corrections.

NOTE: The earth will be used as a navigational aid for about the first 130 days after the launch onto an Earth to Mars trajectory. Sighting errors will be reduced by using Mars as a reference after this point of the trip (ref. 94). The ground based radio-navigational information will be a strong source of data until the craft nears Mars where the preciseness of ground based data is effectively negated by transmission delays. (Delays up to 12 minutes one way may be encountered). This would be especially crucial in a situation where very small arrival corridors are demanded as in the case of aerodynamic braking at Mars.

TABLE 55. VISUAL TASK ANALYSIS FOR: MID-COURSE CORRECTIONS (C.3.2.2)

Mission: Mars Landing (C)
Mission Segment: Flight from Earth to Mars (C.3)
Function: Attainment and Maintenance of Correct Trajectory (C.3.2)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is essentially the same as B.3.2.1.			

TABLE 56. VISUAL TASK ANALYSIS FOR: FINAL CORRECTIONS FOR ORBITAL INSERTION (C.3.2.3)

Mission: Mars Landing (C)

Mission Segment: Flight from Earth to Mars (C.3)

Function: Attainment and Maintenance of Correct Trajectory (C.3.2)

Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is similar to C.3.2.2.	This is a crucial task for attainment of desired Mars orbital positioning. Braking by use of the Mars atmosphere (aerodynamic braking) will be efficient in regards to fuel consumption and allowable arrival velocities.		

TABLE 57. VISUAL TASK ANALYSIS FOR: ALTITUDE DETERMINATION (C.4.1.1)

Mission: Mars Landing (C)
Mission Segment: Martian Orbit Activities (C.4)
Function: Navigation (C.4.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Identify checkpoint on Martian surface.	Should be identifiable with naked eye; i.e. distance across major axis: 300 km alt = 883.92 meters (2900 feet) 500 km alt = 1463.04 meters (4800 feet).	See A.2.1.1.1.	See A.2.1.1.1.
2. Remainder of task identical to A.2.1.1.			

TABLE 58. VISUAL TASK ANALYSIS FOR: ATTITUDE DETERMINATION (C.4.1.2)

Mission: Mars Landing (C)
Mission Segment: Martian Orbit Activities (C.4)
Function: Navigation (C.4.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
This Task is similar to A.2.1.2 (Earth Resources Survey).			

TABLE 59. VISUAL TASK ANALYSIS FOR: POSITION DETERMINATION (C.4.1.3)

Mission: Mars Landing (C)
Mission Segment: Martian Orbit Activities (C.4)
Function: Navigation (C.4.1)
Task Type: Not Applicable

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
1. Identify checkpoint on Martian surface.	See C.2.1.1.1.	See A.2.1.1.1.	See A.2.1.1.1.
2. Remainder of Task is identical to A.2.1.1 (Earth Resources Survey).			

TABLE 60. VISUAL TASK ANALYSIS FOR: CARTOGRAPHY (C.4.2.1.1)

Mission: Mars (C)
Mission Segment: Martian Orbit Activities (C.4)
Function: Data Collection (C.4.2)
Task Type: Surface and Atmospheric Evaluation (C.4.2.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Systematic mapping of large areas of Martian surface.	Gross mapping tasks with finer detailed mapping of some areas. Must determine and identify areas of interest from prelaunch briefings and examination of terrain features.	Failure to hold sensors within motion constraint requirements.	Lost data or data which are unusable.

TABLE 61. VISUAL TASK ANALYSIS FOR: GEOLOGICAL EVALUATION (C.4.2.1.2)

Mission: Mars (C)

Mission Segment: Martian Orbit Activities (C.4)

Function: Data Collection (C.4.2)

Task Type: Surface and Atmospheric Evaluation (C.4.2.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Evaluation of major geological features and surface composition.	Major surface structures must be held within sensor's field of view. Selected areas of terrain will be investigated. Requires ability to discriminate geologically important terrain features.	Failure to hold area of interest within sensor field of view. Failure to acquire desired targets.	Lost data or extraneous data mixed with desired data. Lost data pass.

TABLE 62. VISUAL TASK ANALYSIS FOR: ATMOSPHERIC EVALUATION (C.4.2.1.3)

Mission: Mars (C)
Mission Segment: Martian Orbit Activities (C.4)
Function: Data Collection (C.4.2)
Task Type: Atmospheric Evaluation (C.4.2.1)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Parametric evaluation of the Martian atmosphere.	Evaluation of surface and altitude temperatures, wind speed and shear.	Failure to maintain sensor within motion constraints.	Lost data.

TABLE 63. VISUAL TASK ANALYSIS FOR: LANDING AREA DETERMINATION (C.4.2.2.1)

Mission: Mars (C)
Mission Segment: Martian Orbit Activities (C.4)
Function: Data Collection (C.4.2)
Task Type: Landing Site Selection (C.4.2.2)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Identify predetermined landing areas and those other areas which meet landing requirements.	Must identify preselected areas and determine possible landing sites within them.	Failure to identify predetermined landing areas.	Landing in less than optimum areas.
		Identification of wrong landing area as a possible landing site.	Possible hazardous landing or landing in area with less pertinent information.

TABLE 64. VISUAL TASK ANALYSIS FOR: FINAL LANDING SITE SELECTION (C.4.2.2.2)

Mission: Mars (C)
Mission Segment: Martian Orbit Activities (C.4)
Function: Data Collection (C.4.2)
Task Type: Landing Site Selection (C.4.2.2)

Task Description	Performance Criteria	Potential Task Failure	Failure Effect
Selection of final landing site among landing areas.	Must determine the safety of final landing site and its relative data value.	Selection of hazardous landing site.	Catastrophic.
		Failure to establish benchmarks of landing site.	Lack of complete identification of landing site conditions.

TABLE 65. SUMMARY OF TARGET CHARACTERISTICS FOR MARS LANDING MISSION

SENSOR: CONVENTIONAL PHOTOGRAPHY

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
C.4.2.1.1	Cartographic.	Large areas as well as selected targets for fine detail.	500 ft	100 ft	10 ft
C.4.2.1.2	Geological evaluation.	Selected surface features at both large and small scale.	500 ft	250 ft	10 ft

TABLE 66. SUMMARY OF TARGET CHARACTERISTICS FOR MARS LANDING MISSION

SENSOR: MULTISPECTRAL SCANNER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
C.4.2.1.2	Determination of soil composition and geological features.	Selected areas of representative terrain and prominent surface formations.	250 ft	100 ft	25 ft
C.4.2.1.3	Atmospheric phenomena.	Investigation of the "Blue Haze" and white cloud cover.	500 ft	250 ft	100 ft
C.4.2.2.2	Determination of soil composition and load bearing strength.	Final landing sites.	250 ft	100 ft	10 ft

TABLE 67. SUMMARY OF TARGET CHARACTERISTICS FOR MARS LANDING MISSION

SENSOR: INFRARED SCANNER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
C.4.2.1.1	Map temperature gradients of surface.	Large area coverage and selected surface features.	500 ft	250 ft	100 ft
C.4.2.1.2	Surface features and soil investigation.	Representative terrains and prominent geological structures.	500 ft	250 ft	100 ft
C.4.2.1.3	Temperature gradients in atmosphere and wind currents.	Cloud formations.	500 ft	250 ft	100 ft
C.4.2.2.2	Determine soil composition and load bearing capacity of landing site.	Selected landing sites.	200 ft	100 ft	25 ft

TABLE 68. SUMMARY OF TARGET CHARACTERISTICS FOR MARS LANDING MISSION

SENSOR: COHERENT RADAR

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
C.4.2.1.1	Cartography.	Prominent surface features.	500 ft	250 ft	100 ft
C.4.2.1.2	Geological Evaluation.	Geological structures.	500 ft	250 ft	100 ft
C.4.2.1.3	Atmospheric Evaluation.	Cloud and weather formations.	500 ft	200 ft	100 ft
C.4.2.2.2	Determination of landing site characteristics.	Landing sites.	250 ft	100 ft	25 ft

TABLE 69. SUMMARY OF TARGET CHARACTERISTICS FOR MARS LANDING MISSION

SENSOR: MICROWAVE SCANNER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
C.4.2.1.2	Evaluation of representative soils by composition and structure.	Selected terrain areas.	200 ft	100 ft	25 ft
C.4.2.1.3	Atmosphere in clouds and wind formations.	Clouds and weather formations.	500 ft	250 ft	100 ft
C.4.2.2.2	Evaluation of surface structure and soil composition of landing sites.	Selected landing sites.	250 ft	100 ft	25 ft

TABLE 70. SUMMARY OF TARGET CHARACTERISTICS FOR MARS LANDING MISSION

SENSOR: LASER ALTIMETER

Task Number	Task Description	Probable Targets	Probable Resolution Required		
			Large	Intermediate	Small
C.4.2.1.1	Determine ground slopes and relative altitudes.	Selected portions of terrain - craters, rock types.		ADEQUATE INFORMATION NOT AVAILABLE	
C.4.2.1.3	Determine wind shear and turbulence.	Areas of known or suspected wind shear and turbulence.			

DETERMINATION OF IMS REQUIREMENTS

The analytical efforts that have been documented so far describe (1) man's visual tasks in representative space missions and (2) the constraints that define the limits of his performance of these tasks.

The characteristics of the visual environment that functionally depend on spacecraft velocity and altitude, image magnification, and sensor smear thresholds have been analyzed to determine which visual tasks require image motion stabilization. The criticality of these tasks was then determined empirically.

Physical and Environmental Considerations

Space missions were analyzed to establish visual requirements and the physical parameters that determine expected target size and apparent angular rate.

Determination of orbital velocity and altitude.- From the analysis, characteristic mission altitudes were determined. The following simplifying assumptions were made:

a. A circular, equatorial, direct orbit was used for all cases.

b. The surface beneath the satellite was considered to be flat and nonrotational.

Since orbital velocity is a function of the altitude of the spacecraft and the gravitational constant of the planet, the following formula (ref. 79) was used to determine the orbital velocity for each mission:

$$\text{Velocity} = \frac{g\ (\text{Radius})^2}{(\text{orbital altitude} + \text{radius})} \qquad (1)$$

The apparent angular velocity of a point within the field of view can be determined once the spacecraft's altitude and velocity are known. If a ground point is assumed, a line of sight (LOS) can be established to the spacecraft. If the spacecraft's orbit is assumed to be parallel to the planet's surface, the distance that the spacecraft travels in one second forms a base of a triangle with the other legs equal to the LOS distance from the groundpoint to the spacecraft at the initial and terminal points. Thus, if the velocity of the spacecraft is known, the length of the base is known. The angle opposite the base, θ, can then be calculated by the following expression (refs. 2 and 37):

$$\tan\frac{\theta}{2} = \frac{\text{base length}}{2\ (\text{altitude})} \qquad (2)$$

The above expression is the same as that used to derive the visual angle subtended by an object of a known length. Therefore, a point traversing the distance of the base length is equivalent to the angle generated expressed as a function of time, i.e. radians per second. In this manner, the altitude, linear velocity, and apparent angular rate for a nominal orbit can be established.

Determination of Magnification Requirements.- Magnification will be required from all nominal orbits, if desired ground resolution objectives are to be met. Magnification alters the apparent altitude of the spacecraft although velocity and base length remain the same (Figure 12). Inspection of equation (2) indicates that as the apparent altitude decreases (higher magnification), higher apparent angular rates result (Figures 13, 14, and 15). Magnifications to achieve various ground resolutions for the nominal missions are given in Table 71 and Figures 16, 17, and 18. Figures 13, 14, and 15 show the extreme angular rates of motion which will be encountered at the higher magnifications.

In addition to the increase of apparent angular rate, magnification also decreases the field of view (FOV) of the observer (Figure 19). The combination of increase in apparent angular rate of an object and decrease in field of view reduces the time an object remains available for acquisition (Figures 20, 21, and 22).

Determination of target detection probabilities.- Target acquisition and tracking are the two basic classifications of visual tasks considered in this study. The technique that was used to determine target detection probabilities is described here.

The optical system being considered has sufficient resolving power to allow the observer to discriminate an object subtending a visual angle of 8.89 microradians (1.83 seconds of arc) under ideal conditions. We have conservatively assumed, however, that 2.9 milliradians (10 minutes of arc) represents the typical resolution of the human visual system under the environmental conditions described in the Task Analysis. The magnification required to see a target of a given size is a function of the distance of the observer from the target and the visual angle subtended by the target. Table 71 shows the magnification required to enlarge various size targets so that they subtend 2.9 milliradians (10 minutes of arc) and thus become visible to the observer under widely adverse viewing conditions. As magnification is increased, target exposure time is decreased, since field of view is inversely proportional to magnification. The relationship between target exposure time and the probability of detection is positive and, according to Boynton and Bush (ref. 95, page 25) can be expressed as follows:

$$P = 93.67 + (\log_2 N - 2.75)(t - 19.7) \quad (3)$$

Where: P = Probability of detection (expressed as per cent).

N = The number of similarly configured targets in the field of view.

t = The exposure time in seconds.

Using the above equation, and assuming that the target to be detected is embedded in a complex of 95 similarly configured targets (i.e. we conservatively

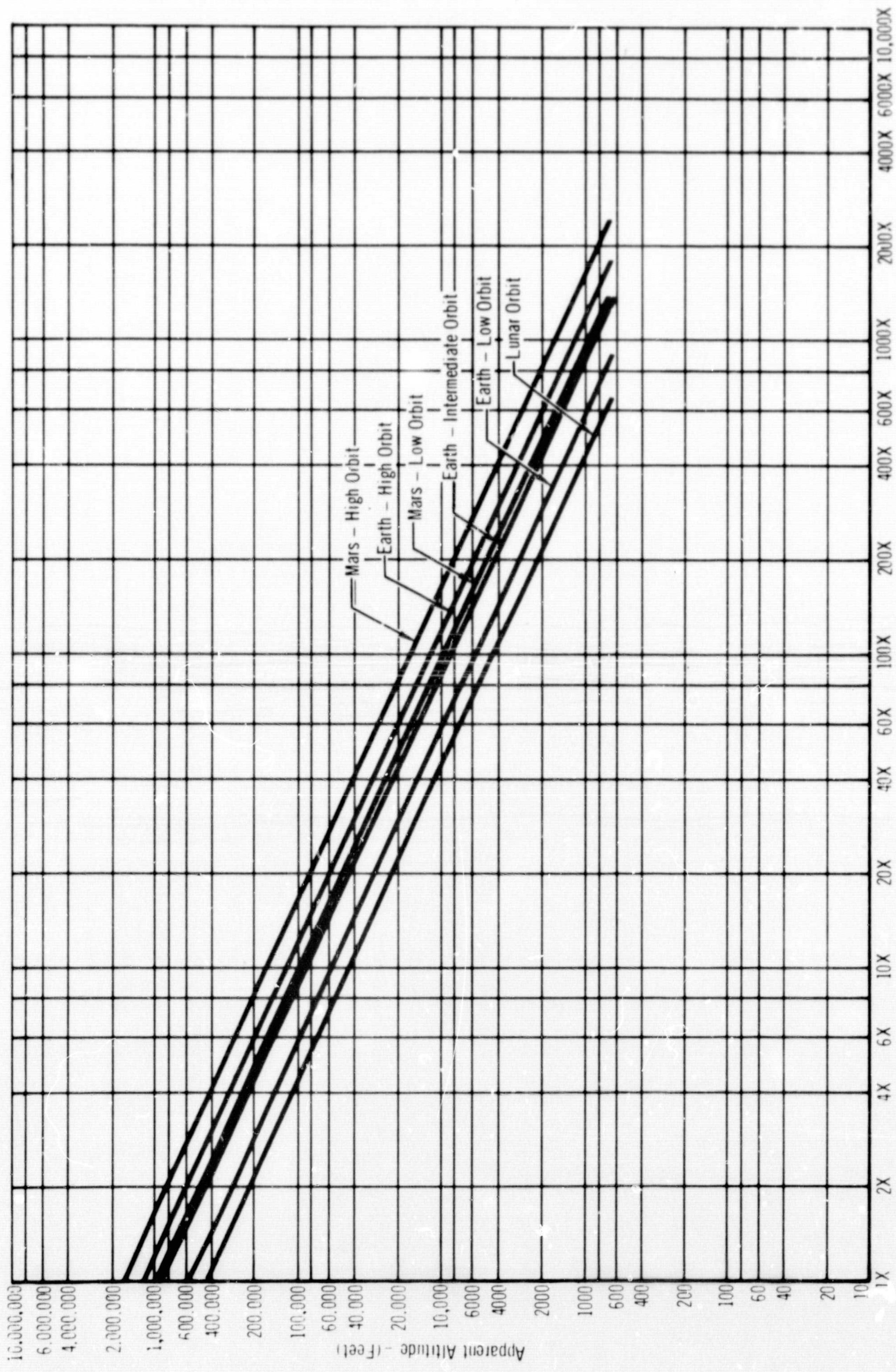

FIGURE 12
APPARENT ALTITUDE AS A FUNCTION OF MAGNIFICATION

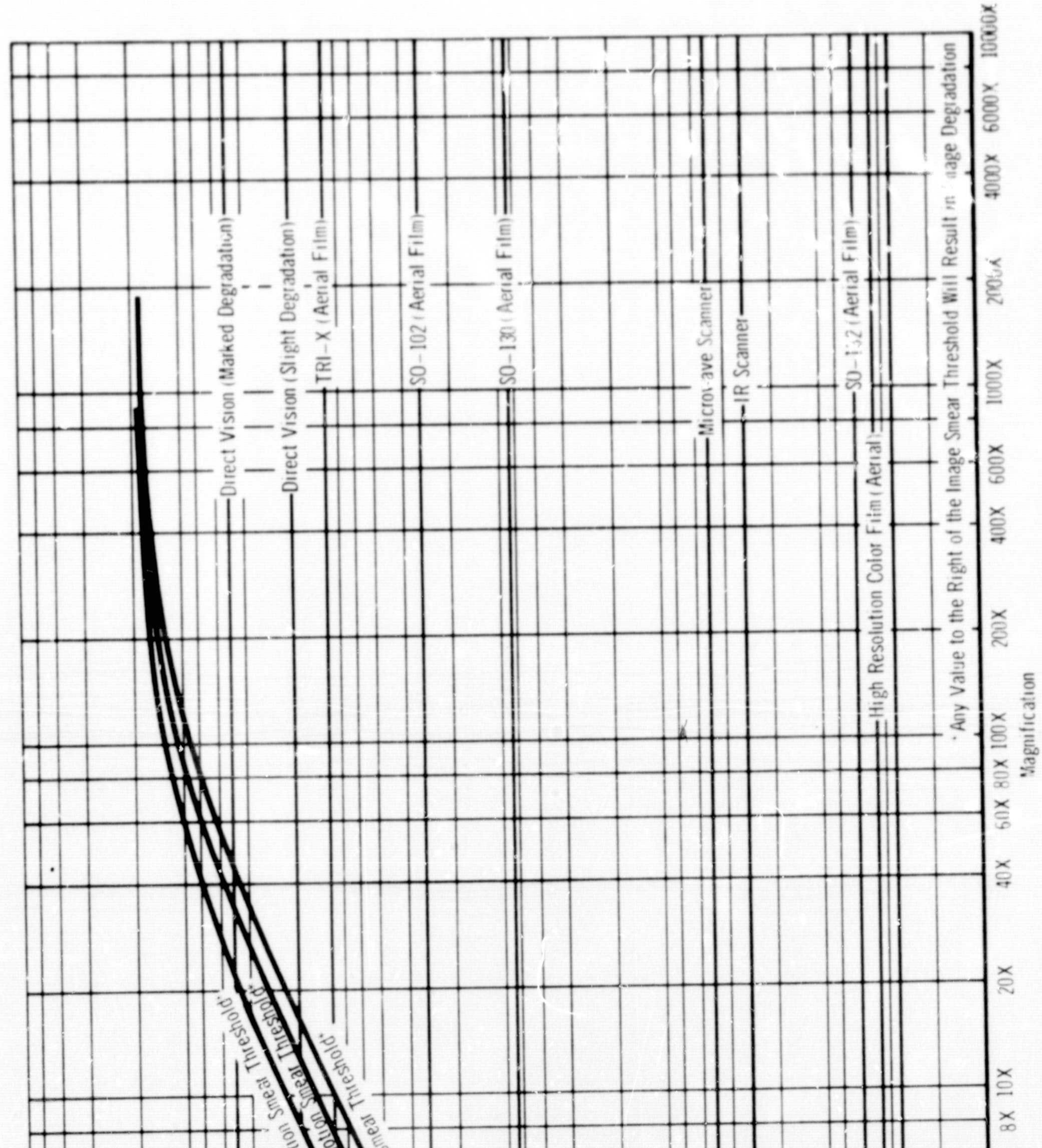

FIGURE 13
EFFECT OF MAGNIFICATION ON IMAGE RESOLUTION FOR VARIOUS SENSORS – EARTH ORBITS

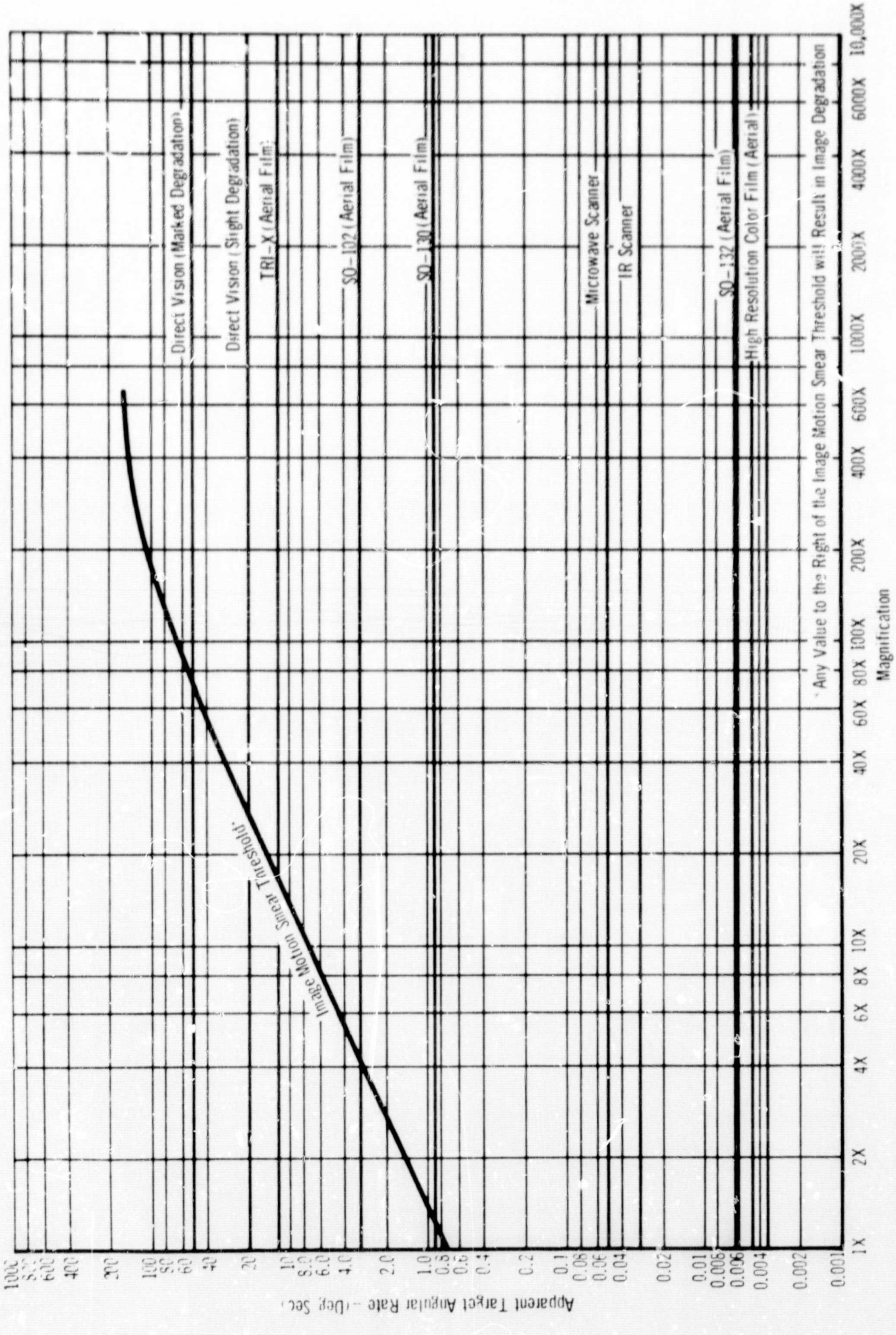

FIGURE 14
EFFECT OF MAGNIFICATION ON IMAGE RESOLUTION FOR VARIOUS SENSORS – LUNAR ORBIT

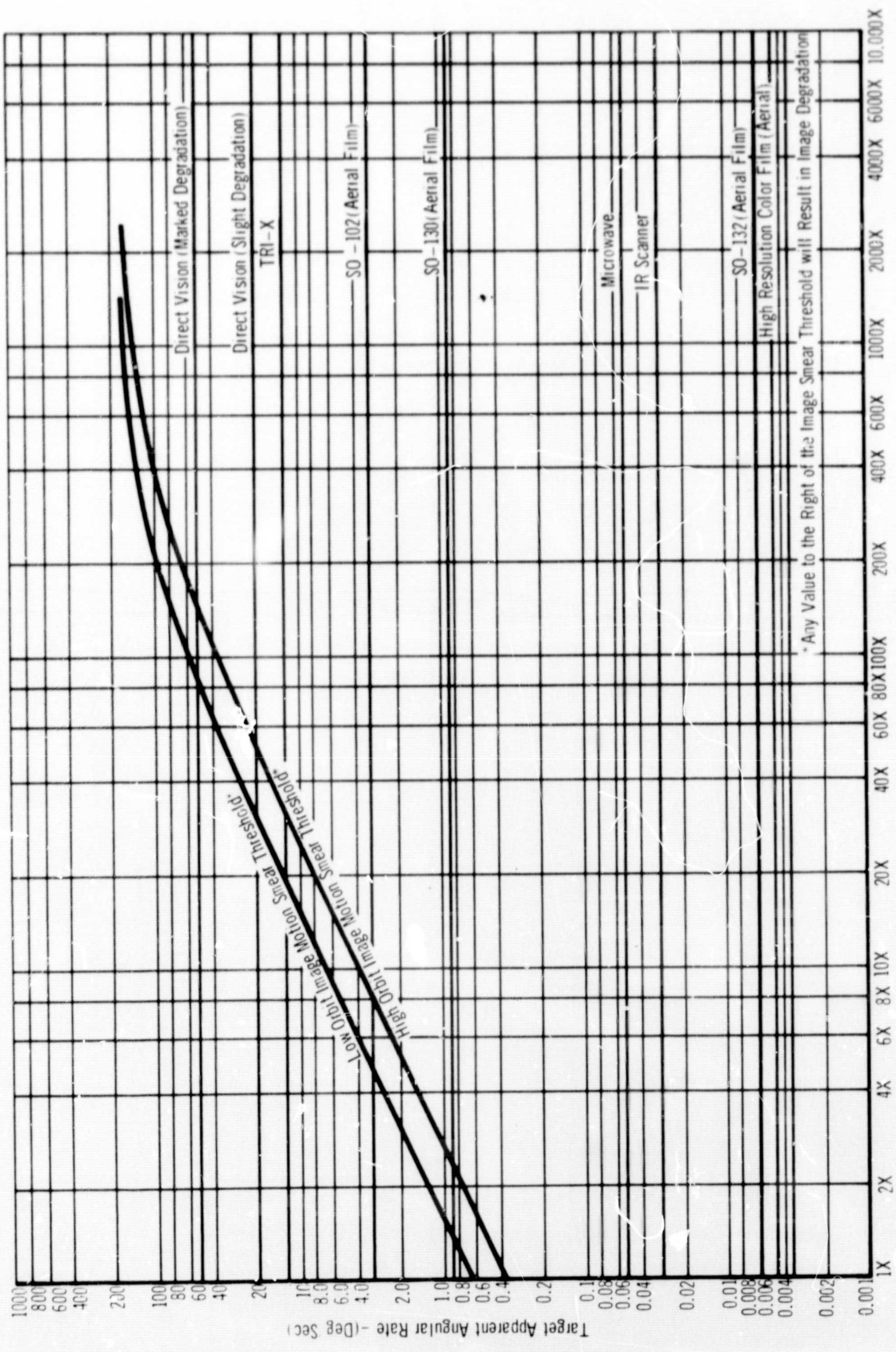

FIGURE 15
EFFECT OF MAGNIFICATION ON IMAGE RESOLUTION FOR VARIOUS SENSORS – MARS ORBIT

TABLE 71

MAGNIFICATION REQUIRED TO OBTAIN A DESIRED GROUND RESOLUTION DISTANCE (GRD)

Mission	Orbital Velocity In Meters/Sec (Ft/Sec)	Altitude In Kilometers (Nautical Miles)	Size Object That Can Be Seen With Naked Eye In Meters[1] (Feet)	Magnification Required[2]								
				Desired GRD								
				0.61M (2 Ft)	1.52M (5 Ft)	3.05M (10 Ft)	6.10M (20 Ft)	15.24M (50 Ft)	30.48M (100 Ft)	60.96M (200 Ft)	152.40M (500 Ft)	304.80M (1000 Ft)
Earth Resources	7,694 (25,243)	370 (200)	1,080 (3,542)	1,771X	708X	354X	177X	71X	35X	18X	7X	4X
	7,748 (25,419)	278 (150)	810 (2,657)	1,329X	531X	265X	133X	53X	27X	13X	5X	3X
	7,802 (25,598)	185 (100)	540 (1,771)	866X	354X	177X	89X	35X	18X	9X	4X	2X
Lunar Landing	1,813 (5,947)	139 (75)	405 (1,328)	664X	266X	133X	67X	27X	13X	7X	3X	1X
Mars Landing	3,340 (10,958)	500 (270)	1,458 (4,782)	2,391X	956X	478X	239X	96X	48X	24X	10X	5X
	3,432 (11,259)	296 (160)	864 (2,834)	1,417X	567X	283X	142X	57X	28X	14X	6X	3X

Notes: 1 It has been assumed that under worst case conditions, the smallest visible object will subtend an angle of 2.9 milliradians (10 minutes of arc).

2 Magnification values have been rounded to the nearest whole number.

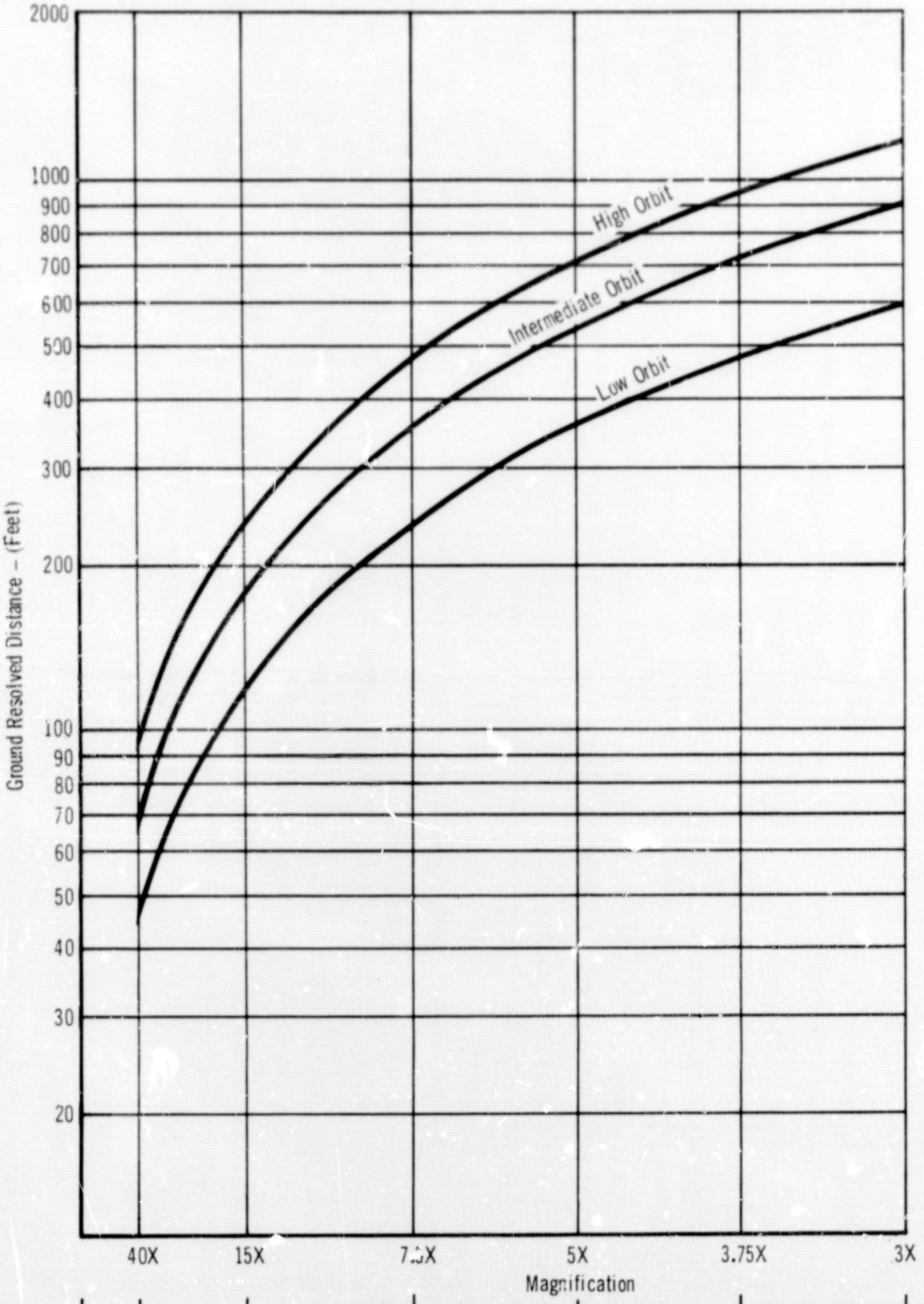

FIGURE 16

GROUND RESOLVED DISTANCE AS A FUNCTION OF FIELD OF VIEW AND MAGNIFICATION – EARTH ORBITS

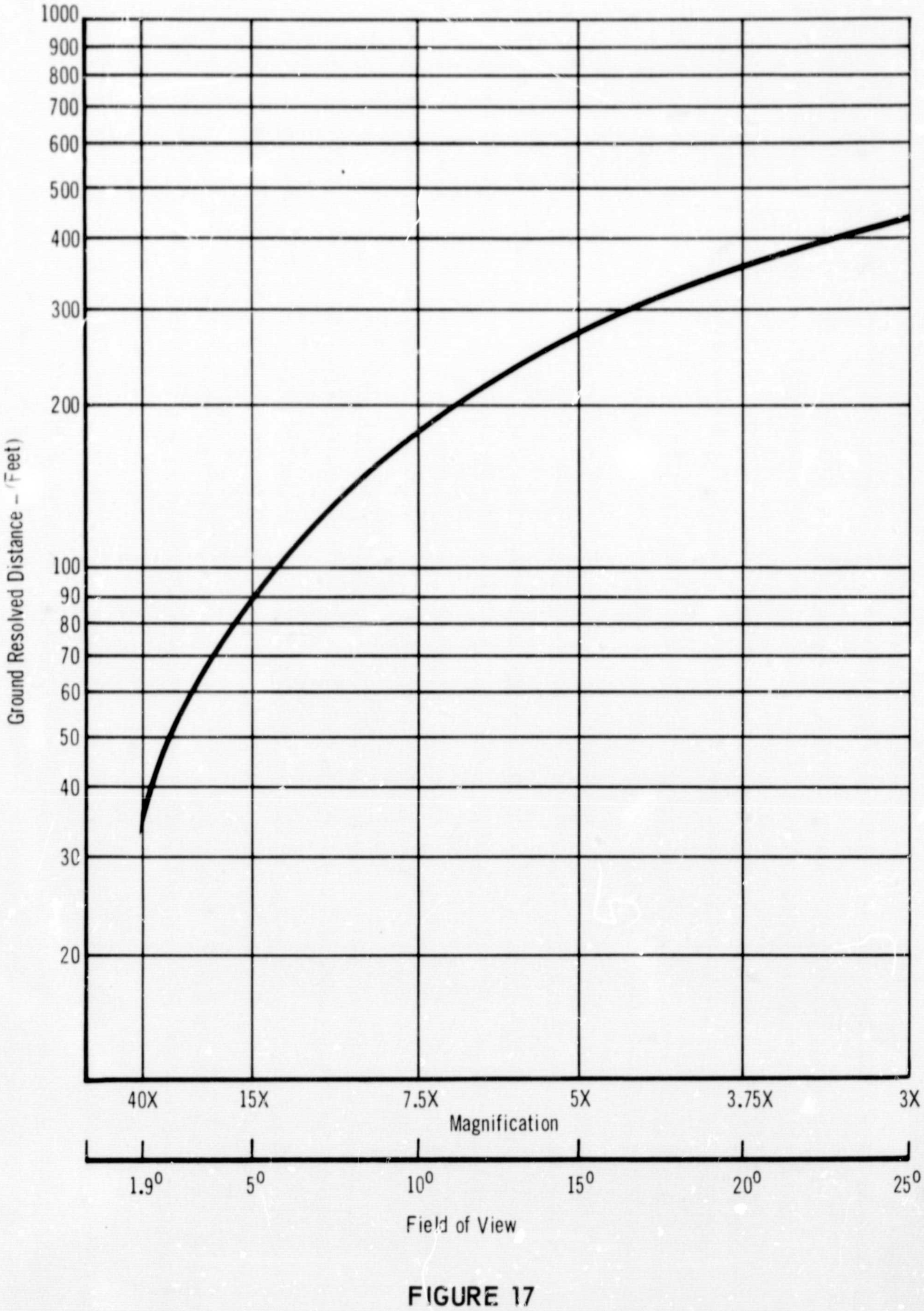

FIGURE 17
GROUND RESOLVED DISTANCE AS A FUNCTION OF FIELD OF VIEW AND MAGNIFICATION – LUNAR ORBIT

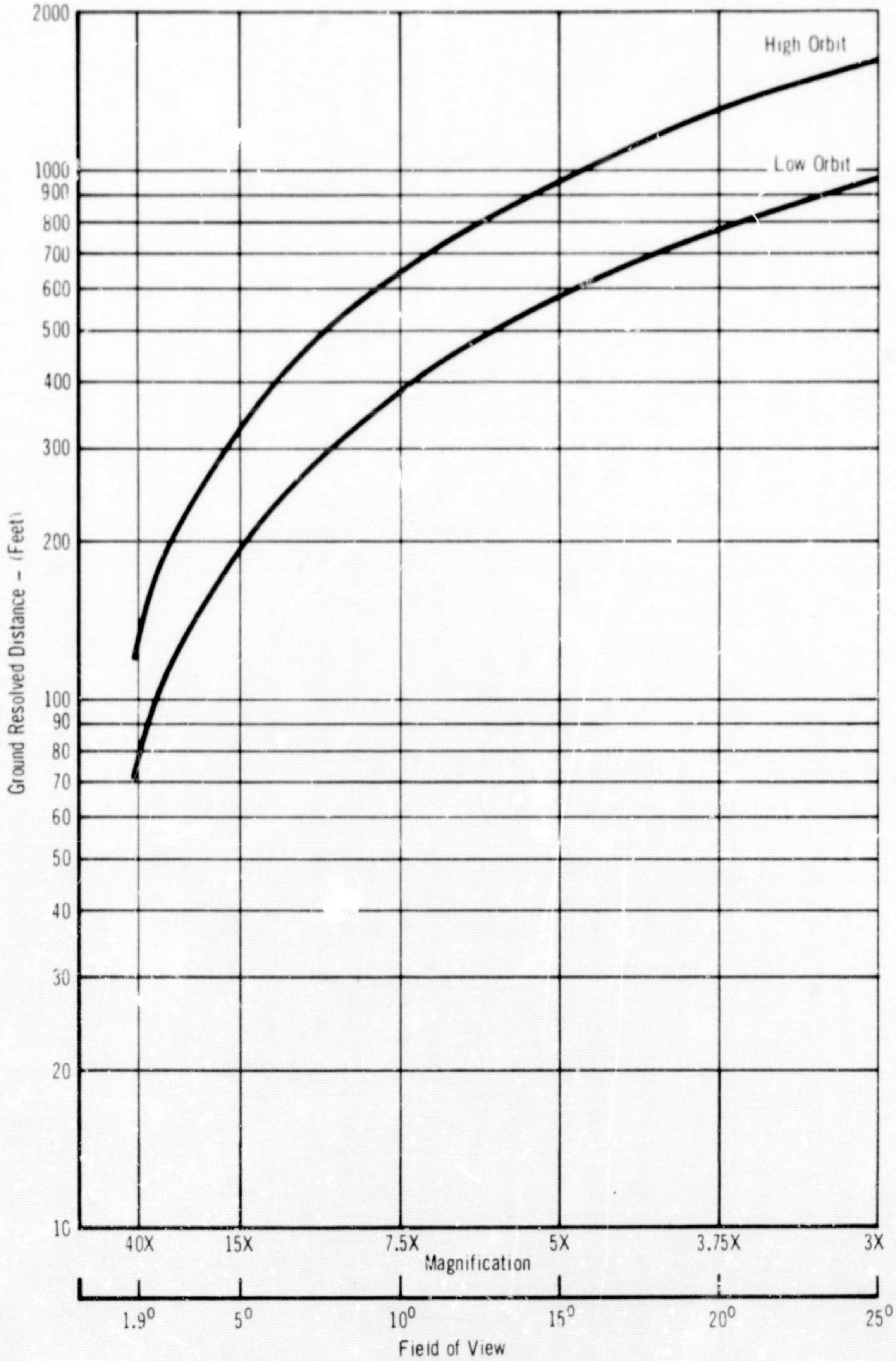

FIGURE 18
GROUND RESOLVED DISTANCE AS A FUNCTION OF FIELD OF VIEW AND MAGNIFICATION – MARS ORBIT

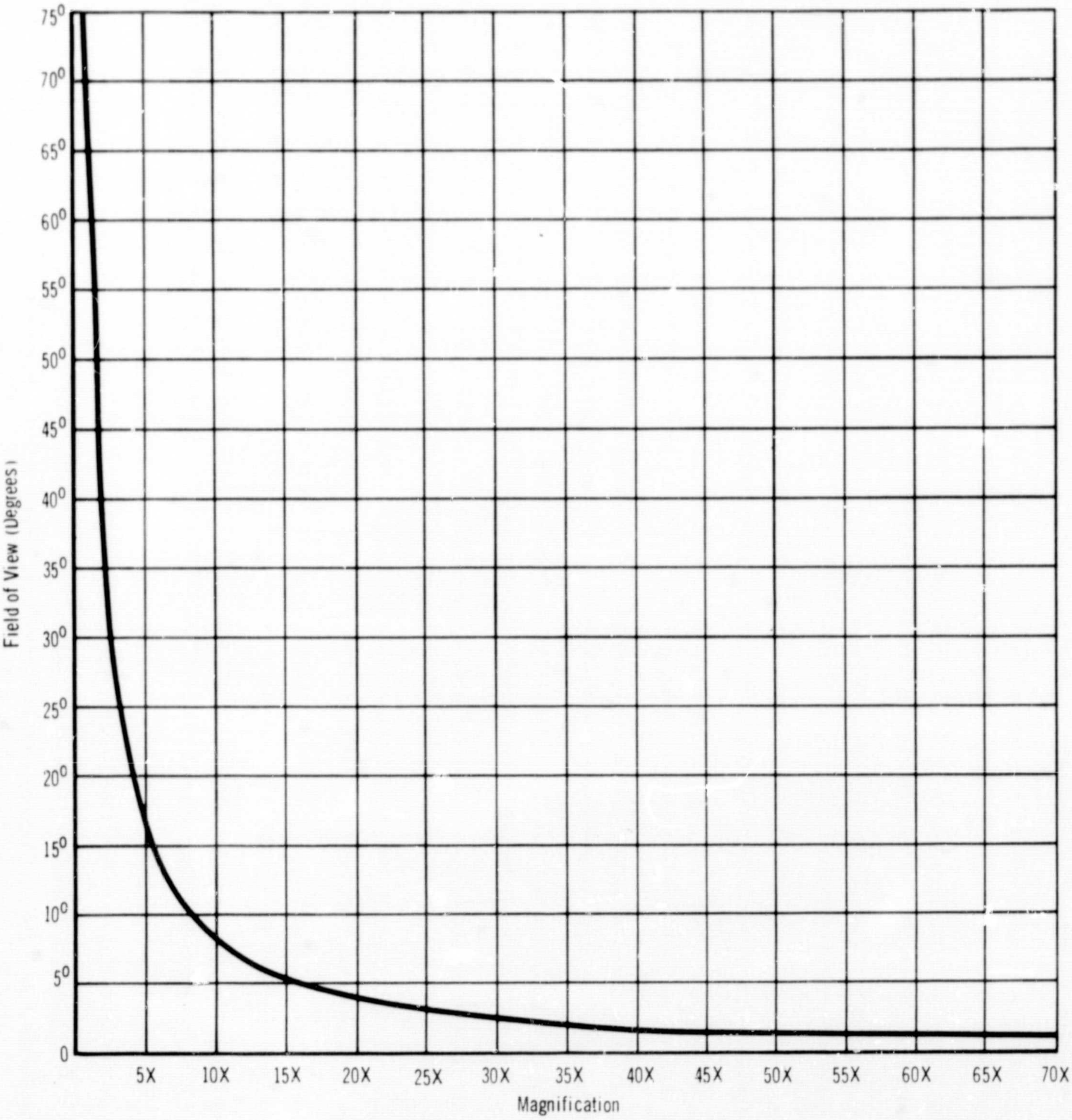

FIGURE 19
FIELD OF VIEW AS A FUNCTION OF MAGNIFICATION

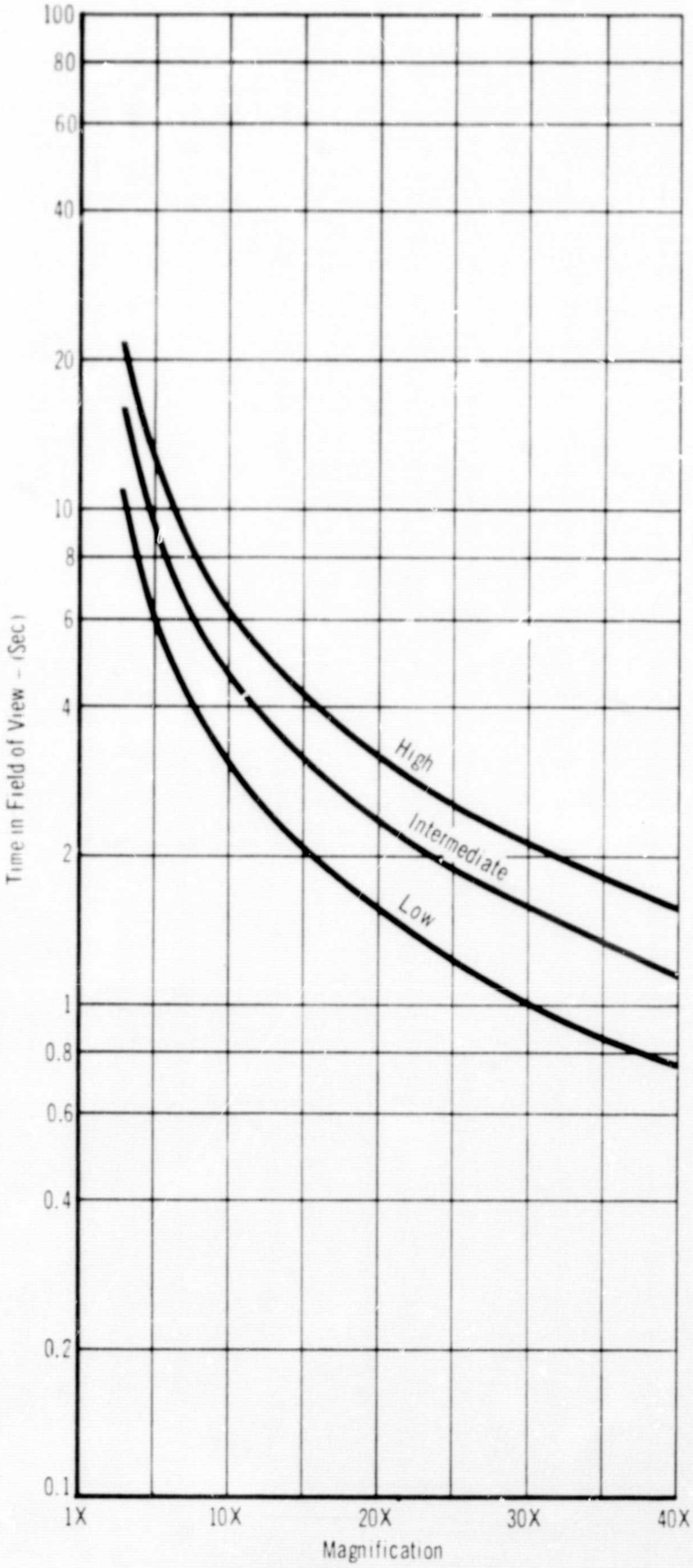

FIGURE 20

TIME IN FIELD OF VIEW AS A FUNCTION OF MAGNIFICATION – EARTH ORBITS

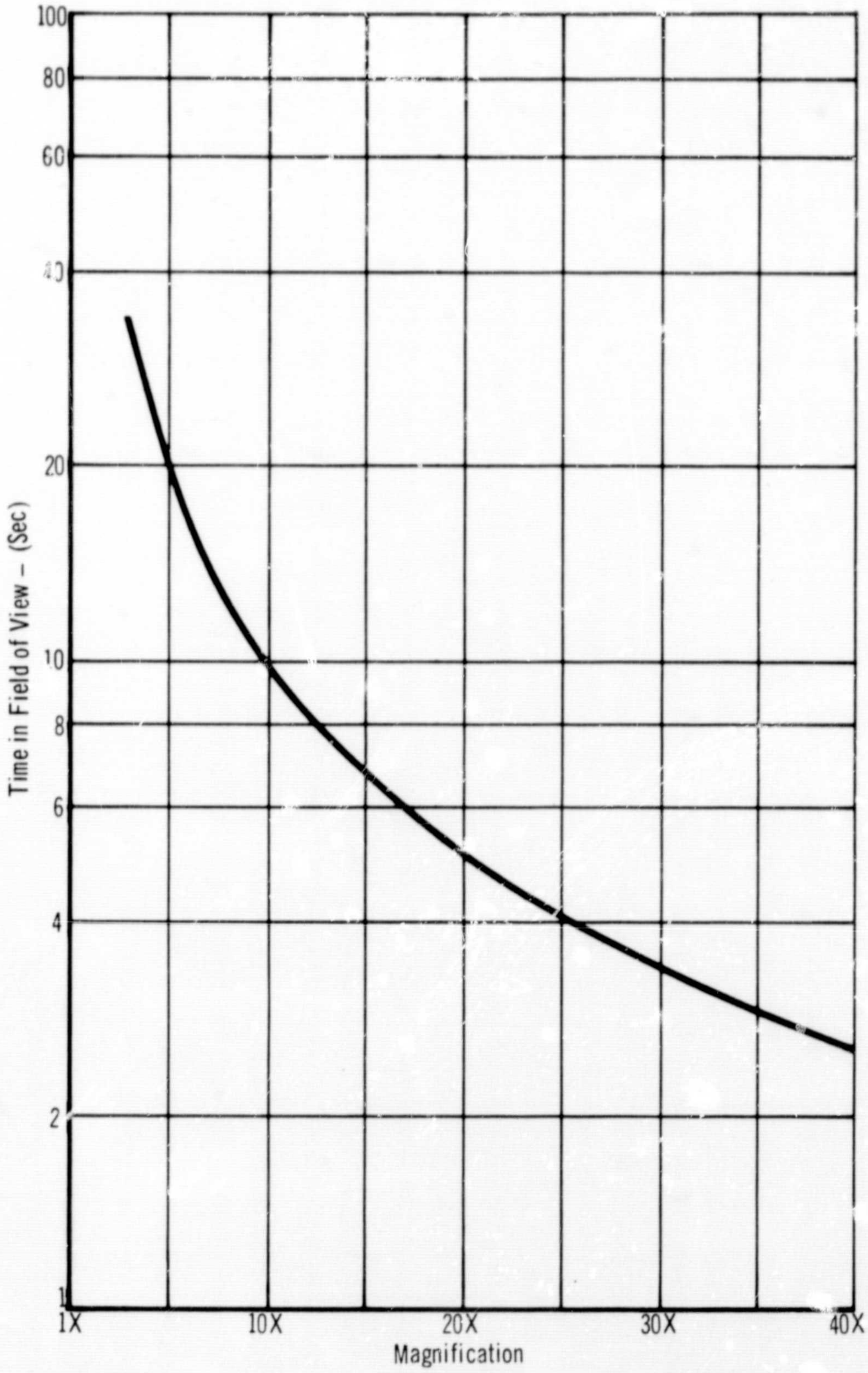

FIGURE 21

TIME IN FIELD OF VIEW AS A FUNCTION OF MAGNIFICATION – LUNAR ORBIT

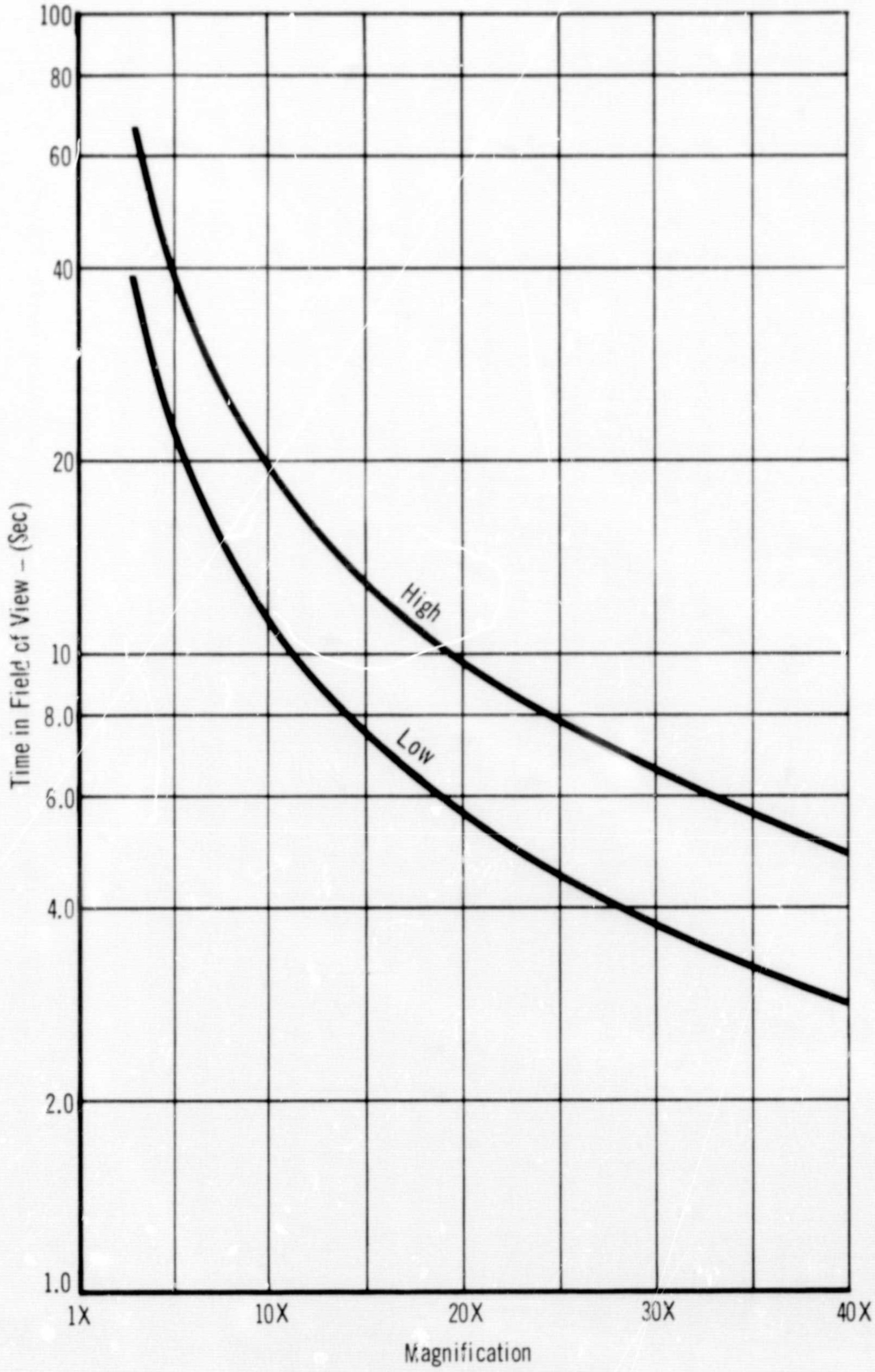

FIGURE 22

TIME IN FIELD OF VIEW AS A FUNCTION OF MAGNIFICATION – MARS ORBITS

assume that the probability of detecting the correct target by chance alone = $1 - \frac{95}{96} = 0.01$), we find that:

$$P = 93.67 + (\log_2 95 - 2.75)(t - 19.7), \text{ which reduces to:} \quad (4)$$

$$P = 3.82t + 18.42$$

Thus, if the time that the target would be expected to remain in the field of view was 10 seconds, the probability of finding it would be (3.82)(10) + 18.42 = 56.62%. To find the amount of IMS required to insure a 95% probability of detection, equation (4) is used to solve for "t" as follows:

$$t = \frac{95 - 18.42}{3.82} = 20.05 \text{ seconds}$$

Since the optical system would only permit a 10 second search time, IMS would be required for 20.05 - 10 or 10.05 seconds. Figure 25 shows the relationship between target exposure time and the probability of target detection as derived from Boynton and Bush (ref. 6, page 39).

Equation (4) was used for all exposure times between two and 12 seconds. For values outside of these limits, Figure 23 was interpolated to determine the detection probability because values obtained with equation (4) depart drastically from empirical data (ref. 96) between zero and two seconds exposure time.

The effects of differential target illumination and size on the probability of detection were initially considered, because of the reciprocity relationship between stimulus area and luminance (Ricco's law) and between exposure duration and luminance (Block's law). This time-intensity relationship has been summarized by Graham (ref. 37, page 339), who stated that "when exposure time is short, and the area of the test object is small, there is reciprocity among the factors of time, intensity, and area." The reciprocity relationship breaks down, however, as exposure time exceeds 0.1 seconds. Approximately 45 seconds exposure time is required to obtain a 95% probability of detection. Thus, we assumed that target illumination and size contributed minimally to detection, and that exposure time was the primary variable.

The relationship between exposure time and the amount of magnification required to resolve a 10 arc minute target is shown, by mission in Figures 20 through 22. The probabilities of target detection for each mission are shown as a function of magnification in Figure 24. The detection probabilities for each of the major target acquisition tasks are listed in the Summary Table.

Determination of relative target velocities.- A set of angular rate boundaries was generated as a function of altitude and velocity, and is shown in Figures 13, 14, and 15. This information was used to establish the relative target velocities for missions shown on these figures.

Some of the contours in Figures 13, 14, and 15 above are the equivalent angular motion rates which define the smear thresholds of the sensors. If these rates are exceeded, then degraded data acquisition, e.g., film smear, will result. Sensitivity levels were determined from available literature (ref. 3).

FIGURE 23

EMPIRICALLY DERIVED CURVE FOR DETERMINING THE PROBABILITY OF TARGET DETECTION WHEN THE EXPOSURE TIME IS KNOWN (DERIVED FROM BOYNTON AND BUSH, REF 97)

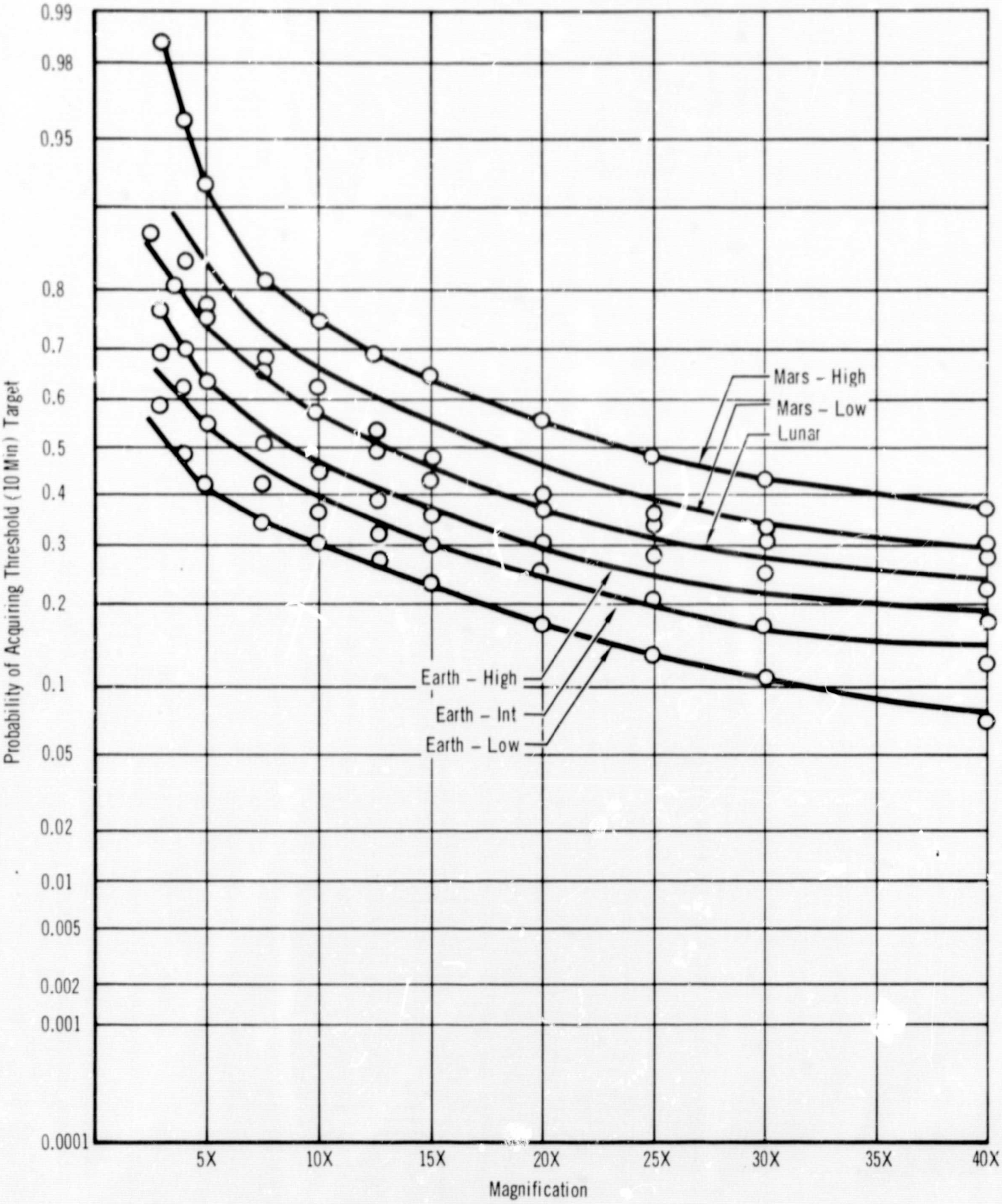

FIGURE 24

THRESHOLD TARGET DETECTION AS A FUNCTION OF MAGNIFICATION

Sensitivity to apparent angular motion rates varies but is generally greatest for film and least for the human eye.

Criticality Analysis

The visual tasks were subjected to a criticality analysis to aid NASA in determining priorities for future mission planning.

Criticality was determined for each task based upon two factors:

a. Rank order judgements by persons familiar with NASA mission goals.

b. The physical and environmental conditions that make some visual tasks more difficult to perform than others.

For the latter, combining orbital velocity and altitude peculiar to each mission had a different effect on the criticality of detection and tracking tasks. For example, a task that was critical in terms of detection because of target size might be less critical in terms of image tracking. Therefore, detection and tracking criticality were considered separately for each visual task.

Twenty-five experienced scientists and engineers from the McDonnell Douglas Astronautics Company rated the tasks in terms of criticality to mission success. The judges were selected for their overall knowledge of the characteristics of the three missions analyzed. They rated the tasks according to the rules of the Thurstone Method of Equal Appearing Intervals (ref. 97) which provided both the judged criticality of each task and the degree of inter-judge agreement about the relative criticality. A task judged critical with high inter-judge agreement was counted as more critical than a task with the same median rated criticality but with low inter-judge agreement. The ratings were made after each judge had been given the following instructions:

> "In a NASA funded study, McDonnell Douglas has been examining man's role in space programs contemplated in the next decade.
> "The three major missions which have been considered are Earth Resources Missions, a Lunar Landing Mission, and a Mars Landing Mission. During the course of the study the major visual tasks for each mission have been determined. In order to determine the relative criticality of each of these visual tasks, a number of aerospace engineers who are familiar with aerospace hardware and the general goals of NASA has been selected to rate each visual task for criticality.
> "To determine task criticality you should consider the visual task in terms of its contribution to mission objectives, safety, economy, efficiency and reliability. The criticality of a visual task should be judged "5" if it is an important consideration for the above factors. Those visual tasks judged to be less critical should be given ratings of "4", "3", or "2", while those tasks judged least critical should be given a "1" rating."

This procedure produced an ordinal ranking of the tasks in terms of criticality. Each statement was judged against five categories of criticality, but equal intervals between the categories were not assumed.

The number of times that a task was assigned to each category was compiled, and the median (50th percentile) judgment and inter-quartile scores (75th percentile minus the 25th percentile) were obtained for each task. The tasks were then ranked from least critical to most critical on the basis of the medians. If two tasks had the same median value, the task with the smaller inter-quartile range (greater consistency in subject agreement) was considered to be more critical. The ranked value (C_J) of each task was then used to determine criticality of detection and tracking.

Total task criticality for target detection was determined by the following expression:

$$C_D = C_J \left(1 - \frac{P_{D(est)}}{P_{D(.95)}}\right) \tag{5}$$

Where: C_D = Total task criticality for target detection.

C_J = Judged task criticality.

$P_{D(est.)}$ = Probability of target detection associated with the number of seconds a target remains in FOV when magnification required to resolve 30.48 meters (100 feet) is used.

$P_{D(.95)}$ = Desired detection probability = 0.95

To ensure compatibility between missions, a ground resolved distance (GRD) of 30.46 meters (100 feet) was used in obtaining $P_{D(est)}$ for all missions. The magnification required to obtain a GRD of 30.48 meters (100 feet) was determined for the Low Orbit Earth Resources Mission, the Lunar Landing Mission, and the Low Orbit Mars Landing Mission. Then target time in FOV was determined for each orbit so that the probability of detection could be found. The more critical the task, the lower the ratio between $P_{D(est)}$ to $P_{D(.95)}$ and the closer the expression $\left(1 - \left(\frac{P_{D(est)}}{P_{D(.95)}}\right)\right)$ approaches 1.0. Therefore, a highly critical task will equal a higher C_D score since the expression representing criticality imposed by physical constraints approaches 1.0.

The tasks involving star sighting data were evaluated differently. It was assumed that the probability ratio could be validly estimated by the ratio formed when estimated image motion due to spacecraft motion was divided by desired image motion. These values are found in Table 10. This expression assumes that probability of detecting the target is least when image movement is greatest, and that when image motion is nulled, the greatest probability of detection exists.

Task criticality for target tracking is essentially composed of judged task criticality and the amount of image motion which must be nulled. The following expression was developed to estimate the tracking task criticality:

$$C_T = \left(C_J\right)\left(V_I\right) \tag{6}$$

Where: C_T = The total task criticality in tracking.

C_J = Judged task criticality.

V_I = The amount of image velocity at the magnification required for 30.48 meters (100 feet) GRD.

The above formula will differentially weigh tracking criticality so that highly critical tasks (C_J) with large image motion will have a large C_T. In those instances of star tracking, the apparent motion imparted to the image by perturbations of the spacecraft was used.

Ranks for C_J, C_D, and C_T were transformed into a set of standard scores based on a normal distribution with a mean = 50 and standard deviation = 10 (ref. 98, Appendix Table XX). This procedure permits direct comparison of each ranking, since highest rank equals the highest standard score and intervals between the standard score are equal. With this type of transformation, values of 71 and 29 are assigned to the most and least critical tasks, respectively. Table 72 lists the visual tasks in order of judged criticality (C_J) and provides the associated values of C_D and C_T.

Summary of IMS Requirements

The major visual tasks are summarized in Table 73 in terms of ground resolved distance, magnification, field of view, time in field of view, probability of detection, image velocity, and task criticality.

TABLE 72. VISUAL TASK CRITICALITY

	Task Criticality		
Task Number and Title	C_J*	C_D*	C_T*
B.3.2 and C.3.2 Maintain desired interplanetary trajectory.	71	**	38
B.3.2.2 and C.3.2.2 Make trajectory corrections during interplanetary transit.	66	**	36
C.4.2.2.2 Final selection of landing site on Mars.	64	54	59
B.4.2.2.2 Final selection of landing site on Moon.	62	63	50
A.2.1.1 Determine spacecraft altitude after orbital insertion.	60	71	71
C.4.1.2 Determine position with respect to Martian surface.	59	59	57
A.2.1.3 Determine position after Earth orbital insertion.	58	66	66
A.2.1.2 Determine attitude after Earth orbital insertion.	57	**	34
C.4.1.1 Determine spacecraft attitude with respect to Lunar or Martian surface.	55	**	29
C.4.2.1.3 Evaluate Martian atmosphere.	55	56	54
B.4.1.3 Determine position with respect to Lunar surface.	54	50	48
A.2.2 Collimate and align sensors.	53	61	64
A.2.3.5.2 Locate and track potentially destructive weather systems.	52	58	62

TABLE 72. VISUAL TASK CRITICALITY - CONTINUED

	Task Criticality		
Task Number and Title	C_J*	C_D*	C_T*
A.2.3.2.1 Geological survey of Earth.	51	57	60
C.4.2.1.1 Cartographic investigation of Martian surface.	50	52	51
B.4.2.1.1 Cartographic investigation of Lunar surface.	50	46	46
C.4.2.2.1 Examine preselected landing areas on Mars for best site.	49	50	49
B.4.2.2.1 Examine preselected landing areas on Moon for best site.	48	47	45
A.2.3.3.1 Cartographic measurement of Earth surface.	47	53	58
A.2.3.3.2 Urban survey.	46	51	55
A.2.3.4.2 Examine shipping lanes for drift ice.	45	49	55
A.2.3.5.1 Investigate large scale weather patterns.	45	48	53
A.2.3.4.1 Parametric investigation of ocean states.	43	44	52
A.2.3.1.3 Soil composition and hydrological investigation.	42	43	50
C.4.2.1.2 Geological evaluation of Martian surface.	41	42	43
B.4.2.1.2 Geological evaluation of Lunar surface.	40	37	41
A.2.3.1.1 Crop identification and analysis.	38	41	47
A.2.3.1.2 Forest type and kind of determination.	36	39	45

TABLE 72. VISUAL TASK CRITICALITY - CONTINUED

Task Number and Title	Task Criticality		
	C_J*	C_D*	C_T*
A.2.3.2.3 Investigate watershed patterns.	34	34	42
A.2.3.2.2 Survey snow and ice cover.	29	29	40

* Standard scores.

** Not ranked since probability of detection is so high that it approaches 1.0.

TABLE 73
SUMMARY OF IMS REQUIREMENTS FOR MAJOR VISUAL TASKS

Task Number and Title	Ground Resolved Distance In Meters (Feet)	Magnification Required	Field of View in Milliradians (Degrees)	Target Time In Field Of View In Seconds	Detection Probability	Detection Criticality C_D	Image Velocity In Milliradians/Sec (Degrees/Sec)	Tracking Criticality C_T
A.2.1.1 – Altitude determination while in 277.8 Km (150 n.m.) nominal earth orbit	822.96 (2700)	1X (Naked Eye)	1.31 Radians $(75^0)^1$	47.7	0.95+	71	27.92 (1.6)	71
A.2.1.2 – Attitude determination while in 277.8 Km (150 n.m.) nominal earth orbit	Not Applicable (Targets = Point Source)	8X	164.03 (9.4^0)	113.1	0.99+	Not Applicable, Since $C_D \approx 1.0$	1.45 (.083)	34
A.2.1.3 – Position determination while in 277.8 Km (150 n.m.) nominal earth orbit	822.96 (2700)	1X	1.31 Radians (75^0)	47.7	0.95+	66	27.92 (1.6)	66
A.2.2 – Collimation and alignment of sensors while in 277.8 Km (150 n.m.) nominal earth orbit.	30.48 (100)	27X	48.48 (2.778)	1.739	0.19	61	698 (40)	64
A.2.3.1.1–Crop Identification and Analysis	15.24 (50)	53X	24.69 (1.415)	0.87	< 0.01	41	1.31 Radians (75)	47
A.2.3.1.2–Forest Type Determination Survey	6.1 (20)	133X	9.84 (.564)	0.35	< 0.01	39	2.09 Radians (120)	45
A.2.3.1.3–Soil Composition/Hydrology Survey	30.48 (100)	27X	48.48 (2.778)	1.739	0.19	43	698 (30)	50
A.2.3.2.1–Geological Survey for Mineral and Oil Deposits	15.24 (50)	53X	24.69 (1.415)	0.87	< 0.01	57	1.31 Radians (75)	60
A.2.3.3.2–Snow/Ice Cover Survey	6.96 (200)	13X	100.67 5.769	3.614	0.32	29	349 (20)	40
A.2.3.2.3–Water Shed Drainage Pattern Survey	30.48 (100)	27X	48.48 (2.778)	1.739	0.19	34	698 (40)	42

[1] The focal field of view approximately 1.31 radians (75^0) assuming maximum freedom of lateral eye movement (Ref 99, pg 91).

TABLE 73
SUMMARY OF IMS REQUIREMENTS FOR MAJOR VISUAL TASKS (Continued)

Task Number and Title	Ground Resolved Distance In Meters (Feet)	Magnification Required	Field of View In Milliradians (Degrees)	Target Time In Field Of View In Seconds	Detection Probability	Detection Criticality C_D	Image Velocity In Milliradians/Sec (Degrees/Sec)	Tracking Criticality C_T
A.2.3.3.1–Cartography Survey of Earth	15.24 (50)	54X	24.69 (1.415)	0.87	< 0.01	53	1.31 Radians (75)	58
A.2.3.3.2–Urban Area Survey	1.52 (5)	531X	2.44 0.14	0.088	< 0.01	51	2.79 Radians (160)	55
A.2.3.4.1–Parametric Evaluation of Ocean States	30.48 (100)	27X	48.48 (2.778)	1.739	0.19	44	698 (40)	52
A.2.3.4.2–Drift Ice Survey of Shipping Lanes	30.48 (100)	27X	48.48 (2.778)	1.739	0.19	49	698 (40)	55
A.2.3.5.1–Meteorological Parametric Investigation	60.96 (200)	13X	100.67 (5.769)	3.614	0.32	48	349 (20)	53
A.2.3.5.2–Survey of Potentially Destructive Storm Patterns	60.96 (200)	13X	100.67 (5.769)	3.614	0.32	58	349 (20)	62
B.4.2.1.1–Cartographic Survey of Lunar Surface	30.48 (100)	13X	100.67 (5.769)	7.723	0.48	46	174.5 (10)	46
B.4.2.1.2–Geological Survey of Lunar Surface	30.48 (100)	13X	100.67 (5.769)	7.723	0.48	37	174.5 (10)	41
B.4.2.2.2–Final Choice of Landing Site on Lunar Surface	15.24 (50)	27X	48.48 (2.778)	3.716	0.326	63	349 (20)	50
C.4.2.1.1–Cartography Survey of Martian Surface	30.48 (100)	29X	45.13 (2.586)	3.898	0.333	52	349 (20)	51
C.4.2.1.2–Geological Evaluation of Martian Surface	30.48 (100)	29X	45.13 (2.586)	3.898	0.333	42	349 (20)	43
C.4.2.1.3–Atmospheric Evaluation of Mars	60.96 (100)	14X	93.48 (5.357)	8.081	0.493	56	157.05 (9)	54

FUNCTIONAL DESCRIPTION OF AN IMAGE MOTION STABILIZATION SYSTEM

Many of the visual tasks identified here were shown to require image motion stabilization. This section describes the functional characteristics of an IMS system. The system should consist of a telescope which will stabilize the observer's line of sight by utilizing manually generated rate commands. The optical system should also be capable of being connected and collimated with various electronic and photographic sensors. In this mode, the optical line of sight that is maintained on a given visual target simultaneously should cause the sensors to maintain the same line of sight. The system should incorporate a zoom lens. Although this system is adequate, it is limited. For example, an astronomical telescope, using various magnifying lenses housed in a turret, would have much greater resolving power, magnification, and compatibility with a stabilizing platform. Although, such a system would have greater complexity and weight than the specified system, and would inherently involve focusing problems, such limitations should not discourage the ultimate use of a turret-mounted optical system.

Field of View

Functional requirement.- The field of view should be adequate to allow the maximum probability of detection of a threshold size target. The longer the target remains within the field of view, the greater the probability of its being detected (see Figure 23).

Source of functional requirement.-

a. Target Search and Acquisition subsection.

b. Task Number A.2.1.1 (Table 8) and similar search and acquisition tasks.

c. The subsection of this report dealing with Determination of Target Detection Probabilities.

Solution of functional requirement.- The maximum real field of view should be at least 436 milliradians (25°).

Justification of functional requirement.- The probability of detecting a target that is within the field of view for approximately 45 seconds is 0.95. In at least one of the missions considered (the Mars high orbit), a detection probability of 0.95 will be feasible with a 436 milliradian (25°) field of view. In the worst case (the Earth low orbit) an object would be within this field of view for approximately 12 seconds, yielding an above-chance detection probability of 0.60.

Magnification Range

Functional Requirement.- The maximum magnification should allow the observer to resolve at least 30.48 meters (100 feet) from the expected orbital altitudes.

Source of functional requirement.-

a. Summaries of target characteristics (Tables 24 through 29, Tables 44 through 49, and Tables 65 through 70).

b. Magnification requirements (Table 71).

c. Ground resolved distance as a function of magnification (Figures 16, 17, and 18).

Solution of functional requirement.- The maximum magnification should be at least 40 power although higher magnification should be considered if a larger, heavier system can be tolerated. The minimum magnification should be 3 power.

Justification of functional requirement.- The apparent field of view is 1308 milliradians (75°). The magnification multiplied by the real field of view always equals the apparent field of view. The 436 (25°) milliradian real field of view at minimum magnification defines this minimum magnification as 1308 milliradians ÷ 436 milliradians or 3 power. Therefore, the range of magnification should be from 3 power to 40 power. The real field of view consistent with this magnification range is from 436 milliradians (25°) to 33 milliradians (1.9°).

Focal Length

Functional requirement.- The overall size of the telescope should be similar to existing small portable telescopes for maximum handling ease, and for minimum weight and volume. The focal length should be compatible with the maximum magnification.

Source of functional requirement.-

a. Assumptions about size and weight stated in the Introduction.

b. Justification of Magnification Range.

Solution of functional requirement.- The focal length of the objective should be approximately 228.6 mm (9 inches).

Justification of functional requirement - A 228.6 mm (9 inch) focal length telescope will weight approximately 3 pounds and will be compatible with a 40 power maximum magnification.

Diameter of the Objective

Functional requirement.- The objective lens should have sufficient light gathering power to allow the resolution of a 2.9 milliradian (10 arc minutes) object under 0.0032 candela/meter^2 (0.001 foot Lamberts) luminance. The diameter of the objective lens should be compatible with the size and weight of existing small portable telescopes.

Source of functional requirement.-

a. Assumptions about target luminance stated in the Introduction.

b. Assumptions about size and weight stated in the Introduction.

c. Functional Requirement for Focal Length.

Solution of functional requirement.- The diameter of the objective lens should be approximately 76.2 mm (3 inches).

Justification of functional requirement.- A 76.2 mm (3 inch) diameter objective lens will exhibit the necessary light gathering characteristics and will be compatible with size and weight of the telescope.

F-Ratio

Functional requirement.- The f-number of the system should be compatible with the diameter of the objective lens and with the focal length of the telescope.

Source of functional requirement.-

a. Focal length recommendation.

b. Objective diameter recommendation.

Solution of functional requirement.- The f-number of the system should be f/3.

Justification of functional requirement.- The f-number is used to express the ratio of the focal length to the diameter of the objective. In this case, the ratio is 228.6 mm/76.2 mm yielding an f-number of f/3.

Optical Quality

Functional requirement.- The optical quality of the telescope should allow the observer to resolve, under nearly ideal viewing conditions, a target of threshold size, i.e. 14.4 milliradians (30 arc seconds).

Source of functional requirement.-

a. Minimum separable acuity as a function of contrast (Table 3).

b. Task number A.2.1.1 (Table 8) and similar search and acquisition tasks.

Solution of functional requirement.- The system should be capable of a diffraction - limited resolution of 8.89 microradians (1.83 arc seconds).

Justification of functional requirement.- The maximum resolution of a high quality optical system is ultimately limited by diffraction effects. The Rayleigh limit for the resolution of two points is determined using the equation:

$$\alpha_s = \frac{1.22\lambda}{d_o} \quad \text{(From Graham, ref. 37, page 32)} \qquad (7)$$

where α_s = the angular separation of two just-resolvable points, λ = the wavelength of the light entering the eye (we have assumed that λ = 555 millimicrons which is the maximum value of the photopic luminosity function), and d_o is the diameter of the objective lens. Thus:

$$\alpha_s = \frac{(1.22)(555)}{76.2} = 8.89 \text{ microradians (1.83 arc seconds)}$$

Stabilization Subsystem

Functional requirement.- The optical system should incorporate a stabilization subsystem capable of reducing the apparent image velocities to the lowest dynamic line of sight rates that are compatible with the estimated smear thresholds for human vision and for the electronic and photographic sensors that have been considered.

Source of functional requirement.-

a. Smear thresholds for sensors (Table 6).

b. Effects of magnification on image resolution of various sensors (Figures 13, 14, and 15).

Solution of functional requirement.- The stabilization subsystem should be capable of producing image motion stabilization as low as 80 microradians/sec (16.5 arc sec/sec) regardless of whether the image motion involves rotation or vibration of the observer's line of sight.

Justification of functional requirement.- The degree of image motion stabilization for each sensor system was found to be a function of the parameters dictating a particular system configuration. Because of these constraints, a set of stabilization rates was chosen which was conservative and maintained the relative order indicated in the data reviewed. For the classes of sensors considered here, the values for smear threshold are shown in Table 6.

Summary of Desired Equipment Characteristics

In summary, the IMS system should possess the following equipment characteristics:

a. 1308 milliradian (75°) apparent field of view with a real field of view ranging from 33 milliradians (1.9°) to 436 milliradians (25°).

b. A zoom lens to vary the magnification from 3 power to 40 power with minimum refocusing following a magnification change.

c. 228.6 mm (9 inch) focal length.

d. 76.2 mm (3 inch) objective lens diameter.

e. f/3 f-ratio.

f. Minimum separable resolution = 8.89 microradians (1.83 arc seconds).

g. Gyro stabilization rates compatible with visual, electronic, and photographic smear thresholds.

TEST PLAN

Test Objectives

This test plan provides a method for evaluating the effectiveness of an image motion stabilization (IMS) device such as the one described in the previous section.

The plan covers two types of testing, laboratory, and airborne. The primary objective for both types is to evaluate the effectiveness of the IMS device with representative targets and dynamic viewing conditions. A secondary objective is to develop an experimental protocol for the test of the device in future manned space missions.

Laboratory Testing

The laboratory testing of the IMS device should be accomplished with stationary observers and moving targets.

Test equipment.- A convenient way of imparting image motion would be to use a gimballed mirror whose rotation about two axes provides the desired direction and magnitude of image motion. This motion would be stabilized through appropriate attitude commands to the mirror from the observer. For the test plan, such a rotating mirror device has been considered as an integral part of the IMS system. An existing IMS simulation device (ref. 4) is schematically shown in Figure 25. A device of this kind provides a highly effective means of testing the IMS system. This simulator consists of the following six major components whose functions are described below.

a. A photomosaic of an area of the earth's surface.

b. A gimballed mirror.

c. A refracting telescope.

d. A two-axis hand controller.

e. Control electronics.

f. A performance measurement system.

The photomosaic is rotated relative to the line of sight of the optical system to simulate an orbital pass over an area of the earth's surface. A gimballed mirror, positioned between the telescope and the photomosaic can be rotated around two axes with step inputs to simulate spacecraft pitch and roll disturbances. The observer uses the hand controller to null any image motion. IMS performance is measured in terms of the amount of time that image motion is held below a given angular velocity during a simulated 40 second orbital pass.

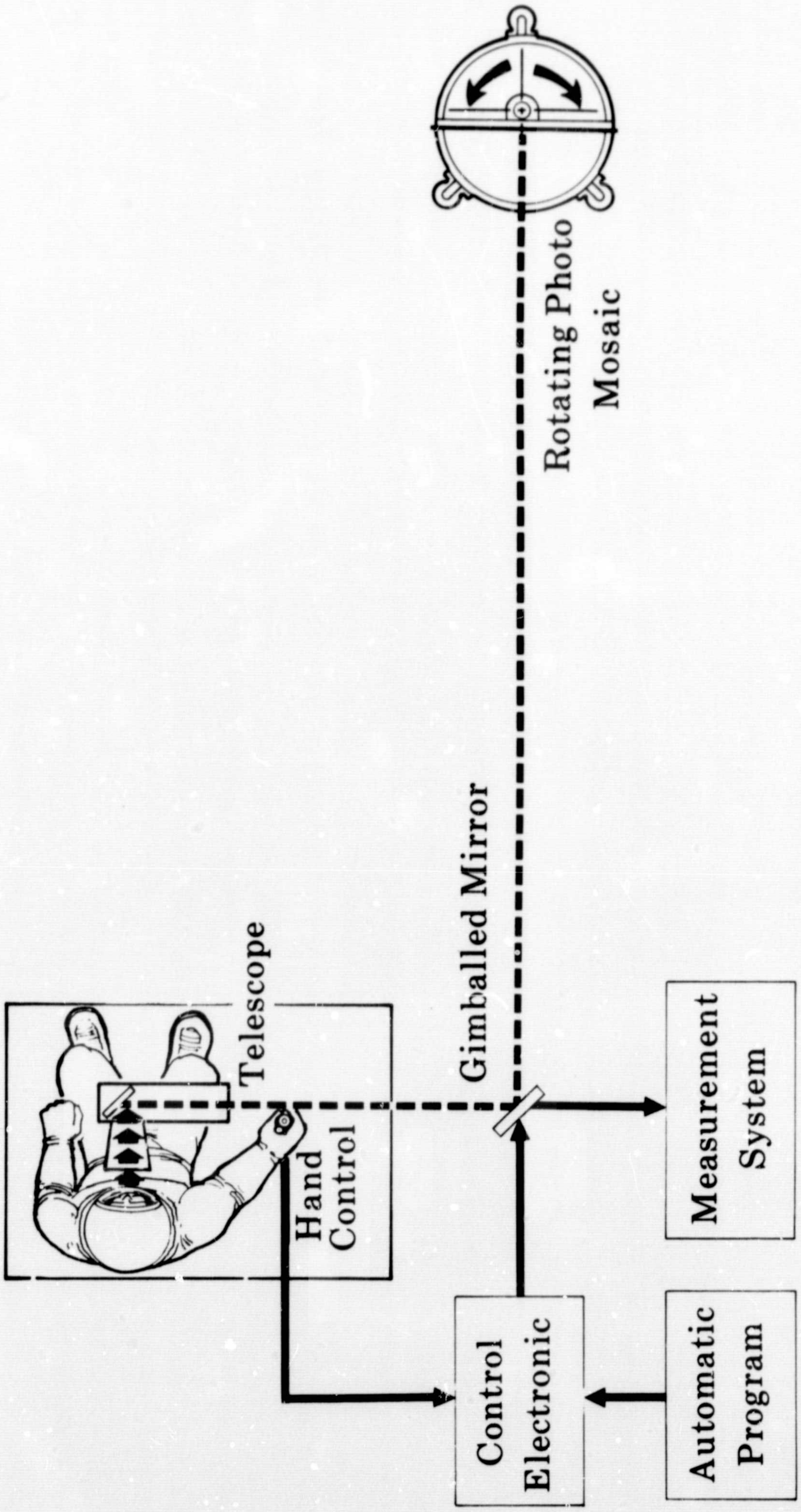

FIGURE 25
SCHEMATIC OF EXISTING IMS SIMULATOR

All signals representing spacecraft motion relative to the earth are delivered to the servo of the appropriate mirror gimbal as either a positive or negative potential difference. The control stick is in parallel with the spacecraft motion signals. By moving the control stick toward the apparent target motion, the observer generates a voltage opposite in polarity to that representing spacecraft motion. The difference between these two voltages at any point is the rate error and is relayed to rate level detectors for evaluation. A block diagram of the control electronics and the performance measurement system is shown in Figure 26. The system is composed of three subsystems: stimulus delivery, mirror gimbal drive, and error rate measurement.

Section A - Stimulus delivery subsystem: When a trial starts, a voltage signal moves the roll gimbal at a rate of 500 microradians (1.72 minutes) per second and the pitch gimbal at a rate of 300 microradians (1.03 minutes) per second. These movements represent the residual effects of an automatic attitude stabilization system, which would theoretically account for 98.5 percent of the spacecraft attitude correction. During a 40 second trial, random signals are inserted at a rate of 300 microradians (1.03 minutes) per second in pitch and 500 microradians (1.72 minutes) per second in roll. These movements simulate corrective firings from the automatic attitude control system. The time of onset and the polarity of these inputs is randomly varied by the experimenter. In addition, throughout each trial a constant sinusoidal voltage change presented to the pitch gimbal moves it at a rate of zero to ± 200 microradians (41.26 arc seconds) per second. This error source simulates a random vibration of the space platform.

Section B - Mirror gimbal drive subsystem: The mirror is moved in response to the stimulus delivery by a very precise servo system. The performance characteristics of the servo loop are as follows:

a. Line of Sight Measurement Accuracy - The measurement accuracy of the gimbal pick-off potentiometer is 6.4 microradians (1.32 seconds) due to backlash in the micrometer/tangent-arm drive between the pick-off potentiometer and the mirror.

b. Vibration - There is no perceivable line-of-sight vibration when the peak to peak oscillation amplitude on the target is measured.

c. Servo Null Sensitivity -

° The measured breakout rate is 5 microradians (1.03 arc seconds) per second.

° The slowest smooth rate is 16 microradians (3.3 arc seconds) per second.

° Control stick sensitivity is a direct function of servo loop gain. One milliradian (206.28 arc seconds) per second was commanded with maximum stick deflection.

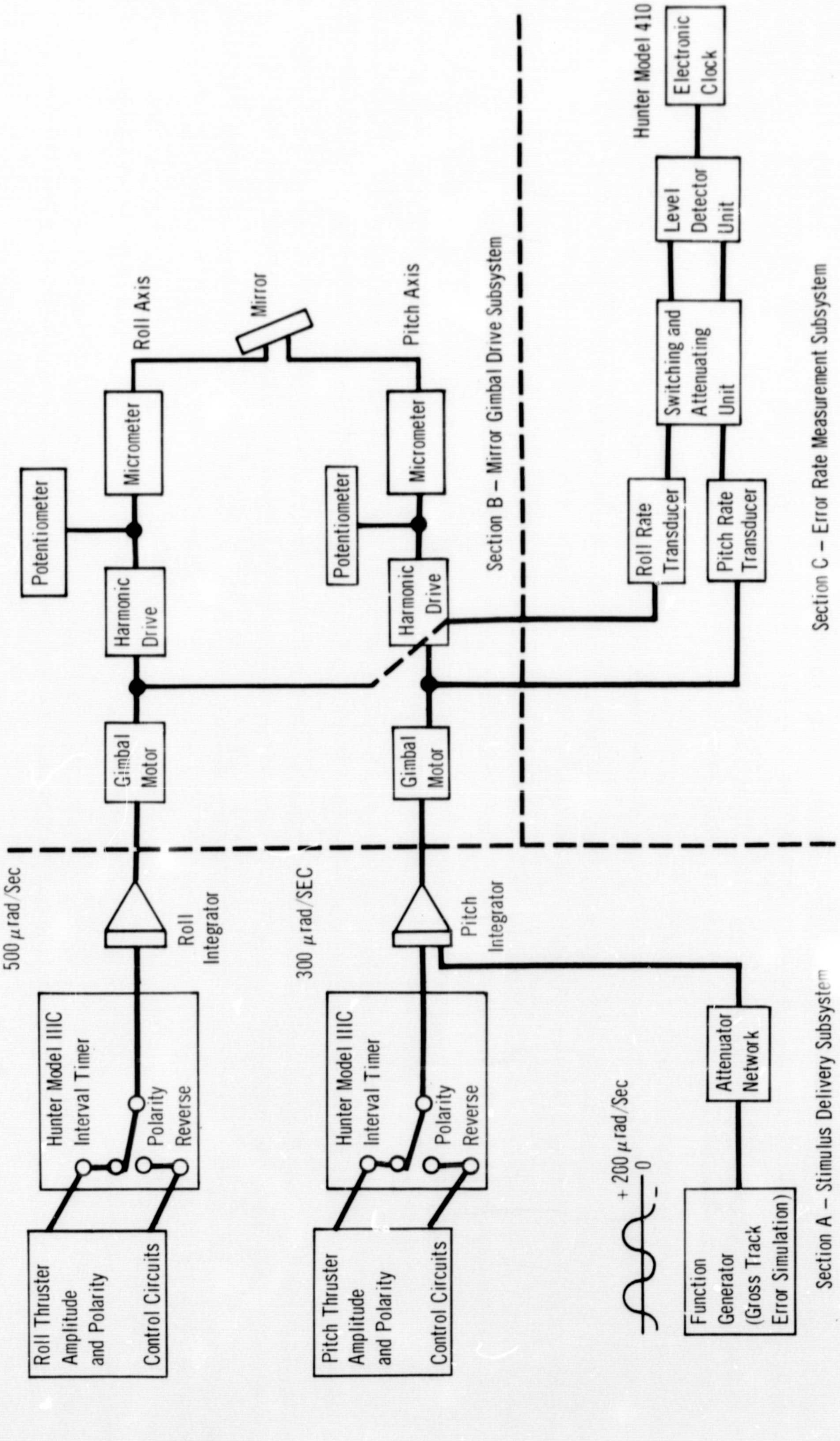

FIGURE 26
BLOCK DIAGRAM OF CONTROL ELECTRONICS AND MEASUREMENT SYSTEMS

° System backlash due to micrometer/tangent-arm drive is 6.4 microradians (1.32 arc seconds). Backlash due to harmonic gear drive is 4.6 microradians (0.95 arc seconds) for a total system backlash of 11 microradians (2.27 arc seconds).

° Integrator drift over a two minute period is 0.23 microradians (0.05 arc seconds) per second.

Section C - Error rate measurement subsystem: The error measurement subsystem directly indicates the time that the mirror gimbals exceed a certain rate of angular displacement. Tachometers attached to the pitch and roll gimbals sense any mirror movement by producing a voltage proportional to the movement. The voltages are integrated and compared in a level detector network. If they exceed a predetermined amplitude, a pulse to one of four Hunter Model 410 clocks gives a direct reading of the time the mirror movement exceeds an established rate.

The system just described, or one similar to it, would provide a convenient way of laboratory testing the IMS device. If used, the center of the mirror should be 15.24 meters (50 feet) from the targets. The zoom telescope should be adjustable within its magnification range, in 1 power increments. The target images should be moved at apparent constant velocities ranging from at least 0.347 meters/second (1.14 ft/sec) to 4.627 meters/second (15.18 ft/sec) with an accuracy of ± 3.05 mm/sec (.01 ft/sec). The experimenter should have the capability of adjusting the target velocities in increments of 3.05 mm/sec (.01 ft/sec).

<u>Targets</u>.- The following classes of targets, the first two of which subtend 2.9 milliradians (10 min of arc), should be used:

a. Geometric figures.

b. Actual aerial photographs of prominent terrain features.

c. Steady lights with a brightness equivalent to third magnitude stars.

The first two classes of targets should be illuminated by a brightness source providing an overall luminance of approximately 600 candela/meter^2 (500 foot Lamberts). With the first two classes of targets, 50 percent cloud cover should be simulated by placing panes of glass dotted with a cotton-like material in front of the targets at a distance to simulate cumulus clouds at 1524 meters (5000 feet).

<u>Target velocity with respect to the observer</u>.- The observer should use the IMS system to reduce the target angular velocity from 872 milliradians/sec (50°/sec) to the lowest rate possible. To evaluate the IMS system over its magnification range, the following magnification values should be used with the appropriate rate commands to impart an image velocity of 872 milliradians/sec (50°/sec): 3X, 5X, 7X, 10X, 15X, 20X, and 40X.

Performance measurement.- An error rate measurement capability similar to the one that has been described should be utilized to indicate the time that the mirror gimbals exceed each of the 10 critical smear threshold rates that are delineated in Table 6. To accomplish this, tachometers should be attached to the pitch and roll gimbals to sense any mirror movement by producing a voltage proportional to the movement. If the voltages exceed a predetermined amplitude, they should deliver a pulse to one of the 10 clock counters, each of which indicates the amount of time that the mirror movement exceeded the criterion rate assigned to that clock. If possible, a digital printout of clock data should be provided.

Experimental design.- A modified repeated measures design should be utilized to minimize the number of subjects required (10 in this case) and also to minimize the confounding of test conditions and individual differences. In order to avoid confounding subject performance with differential learning rates, the subjects should be trained to perform the basic manual image motion compensation task by having them reduce the rate of movement of a target driven at 500 microradians/second (1.72°/sec) down to 100 microradians/second (0.34°/sec). Training should utilize trials of 40 seconds duration with a single black-and-white striped rectangle as the target. When each subject attains stable state performance (ref. 100) on the training task, he should be tested under the experimental conditions. Stable state performance is defined, in this case, as meeting the criterion of the 100 microradian/second (0.34°/sec) IMS for at least 15 seconds per trial for five successive training trials. Subjects failing to meet the training criterion performance within 60 trials should be replaced. The independent variables for the test should be magnification/target velocity and target type. Target size and illumination are held constant. The independent variables of target type and magnification/target velocity consist of three and seven levels, respectively, for a total of 21 treatment combinations. Each of the 10 subjects should receive all treatment combinations in a random sequence. The experimental array is shown in Table 74.

Regarding the "independent variables," the sources of variance attributable to two of the conditions being systematically varied, i.e., magnification and target velocity, cannot be separated. Difference in target type, the third condition, is only of limited interest. These three variables provide a method to evaluate the dependent variable. In short, the major concern in testing is not whether the IMS device operates differentially for different kinds of targets moving at different velocities, but rather its effectiveness in stabilizing relative target motion at or below the 10 selected smear thresholds. The motion being stabilized represents an extremely high angular velocity which can be considered to be a worst case condition. If this degree of motion can be stabilized down to the required smear thresholds, then lesser magnitudes should be well within capability of the system.

Data analysis.- A randomized block analysis of variance should be utilized to evaluate the data. The dependent variable should be the percentage of trial time that image motion is held below a specified rate of movement. Separate analyses for each of the 10 criterion rates should be performed so that the data can be evaluated in terms of the ability of the IMS device to perform its required function. If the treatment main effects are significant, this can be

TABLE 74 EXPERIMENTAL ARRAY – IMS TESTS

Independent Variable																					
Target Type	Geometric Figures							Terrain Features							Lights						
Magnification / Target Velocity	3X	5X	7X	10X	15X	20X	40X	3X	5X	7X	10X	15X	20X	40X	3X	5X	7X	10X	15X	20X	40X
Subject 1	1	9	16	15	4	17	10	2	18	20	7	8	19	3	6	11	14	21	12	5	13
2	4	15	9	19	21	8	18	1	3	14	7	13	12	10	17	2	20	6	11	5	16
3	3	14	19	1	4	17	9	7	20	2	21	8	16	13	5	12	18	10	11	6	15
4	7	4	12	16	18	20	5	19	21	8	17	11	10	15	1	9	6	3	13	2	14
5	12	5	11	2	14	16	6	6	15	1	13	3	18	4	20	10	8	21	17	19	7
6	15	2	19	14	3	9	4	6	13	16	11	12	1	21	20	8	18	7	5	10	17
7	9	13	18	4	7	15	5	14	8	11	2	20	10	12	19	1	6	3	17	21	16
8	14	21	7	15	10	3	5	17	4	16	11	19	9	2	20	18	1	13	8	6	12
9	5	12	16	13	18	8	14	11	20	10	1	15	6	2	7	4	3	19	21	17	9
10	20	3	14	19	1	6	7	2	13	8	12	5	15	18	9	21	17	10	4	11	16

NOTE: 1. Cell Entries = Order of presentation of test conditions to subject.
2. Different target image velocity is combined with each magnification value shown to provide an apparent velocity of 872 milliradians/sec (50^0/sec) for all conditions.

taken as evidence that the IMS device may not function effectively throughout its operational range. To evaluate such an occurrence more fully, orthogonal comparisons and one-tailed "t" tests should be utilized.

Airborne Testing

Test equipment.- The airborne testing of the IMS device should be accomplished aboard the NASA CV-990 research aircraft over the High Range of the Flight Research Center. The aircraft should be equipped similarly to that described by Acken and Smith (ref. 5) except that a special observation port will be installed to allow the IMS mirror to point toward the nadir. The altitude of the aircraft should vary between 1829 and 7620 meters (6000 and 25,000 ft) with ground speed varying from 110.03 meters/second (361 ft/second) to 213.36 meters/second (700 ft/second). The vernier telescope zoom adjustment used for the ground tests should be retained for the airborne tests. The targets should be stationary. Relative target velocity should be obtained by varying the aircraft ground speed and magnification.

Targets.- The same classes of targets should be used for the airborne test as were used in the laboratory tests, except that actual terrain features subtending 2.9 milliradians (10 minutes of arc) can be employed. All test runs should be made under approximately the same atmospheric and illumination conditions to avoid introducing uncontrolled sources of variance.

Target velocity with respect to the observer.- Because of the limitations set by the flight envelope of the CV-990, it is not possible to obtain relative target velocities of 872 milliradians/sec (50°/sec) over the entire magnification range of the IMS system. Maximum obtainable target angular velocities have been specified where applicable. As in the laboratory tests, the observer should use the IMS system to reduce the target angular velocity from that maximum rate down to the lowest rate possible. In order to evaluate the IMS system over its magnification range, the following combinations of aircraft speed and altitude, and magnification settings should be employed to produce the maximum target angular velocities compatible with the flight envelope of the test aircraft:

Target Angular Velocity	Aircraft Altitude	Aircraft Ground Speed	Mag.
55 mrad/s (3.15°/sec)	7620 meters (25000 ft)	137.2 m/s (450 ft/sec)	3X
110 mrad/s (6.30°/sec)	7620 meters (25000 ft)	182.9 m/s (600 ft/sec)	5X
220 mrad/s (12.61°/sec)	7620 meters (25000 ft)	213.4 m/s (700 ft/sec)	7X
872 mrad/s (50°/sec)	1829 meters (6000 ft)	166.7 m/s (547 ft/sec)	10X
872 mrad/s (50°/sec)	1829 meters (6000 ft)	110.0 m/s (361 ft/sec)	15X
349 mrad/s (20°/sec)	7620 meters (25000 ft)	137.2 m/s (450 ft/sec)	20X
872 mrad/s (50°/sec)	7620 meters (25000 ft)	182.9 m/s (600 ft/sec)	40X

Performance measurement.- If feasible, the airborne tests should utilize the same type of error-rate measurement system that was used for the laboratory tests. If this is not possible a beam splitter should be used in the telescope to allow the optical tracking to be monitored via a ground based video system, or recorded by a video tape recorder or motion picture camera for detailed evaluation subsequent to the tests.

Experimental design.- The same design used for the laboratory tests is applicable to the airborne tests. Training trials beyond those required for basic familiarity with the airborne set-up are not anticipated because the airborne tests should follow the laboratory tests.

Data analysis.- The data should be analyzed and evaluated similar to the laboratory test data. It should be noted in evaluating, however, that the maximum target angular velocity is not constant in all cases due to aircraft flight envelope limitations.

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