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REMOTE MAN-MACHINE CONTROL SYSTEM EVALUATION

FINAL REPORT

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1.0 INTRODUCTION

This study is based on the premise that improved understanding of the relationship of man with his machine aids can improve his effectiveness in the exploration of space. Because machines and scientific equipment serve to extend man's perceptual and physical capabilities, all space flight experiments eventually involve human participation. To circumvent emotional arguments concerning manned versus unmanned systems, it is important that means for objectively evaluating the integration of human capabilities into each mission be developed.

The determination of which mission tasks are best accomplished by "directly manned," by "automatic systems," or by "remotely controlled" systems involve complex interactions of physical laws with economic and sociological factors. It is the intent of this report to identify some of the factors involved and to provide a basis for further advances in the objective utilization of "remotely controlled" systems in conjunction with directly manned and automatic systems.

DEFINITIONS

Remotely controlled systems, as used in this study, can be illustrated by the following definitions:

1. Directly manned systems - carry human crews.
2. Fully automatic machines - are programmed to gather and transmit preselected information to man. They cannot be reprogrammed.
3. Remotely controlled systems - can transmit information to man over some distance and are capable of being controlled and reprogrammed by man.

2.0 SUMMARY

This study presents the remotely controlled systems role in the exploration of space and the various configurations that such systems might take. An operations analysis on a representative mission was performed, and a system requirements methodology was developed.

2.1 STUDY OUTLINE

2.1.1 The role of remotely controlled systems in space exploration was assessed noting the complexity of the systems and the missions they were to perform.

2.1.2 To assess remotely controled systems in a specific application, the Mars Exploration Mission was selected.

2.1.3 The objective selected for study was the detailed reconnaissance of the Martian surface and its environment in support of subsequent manned Mars landing missions.

2.1.4 Information requirements were determined to satisfy the mission objectives. The general environmental parameters were determined and related to the information requirements to fix the location of sensors for data acquisition.

2.1.5 System approaches, automatic and remotely controlled, were compared with respect to reliability, weight, and cost.

2.1.6 The location of man and the role he has in the loop was compared.

2.1.7 A mission description was presented for a typical remotely controlled system in a representative manned capture orbit profile.

2.1.8 A study of eccentric, circular, and synchronous Martian orbits and multiple surface sites was made and the implications of the various orbits compared.

2.1.9 A systems requirements methodology was developed to assess the role of man in the loop. The philosophy that was followed considered man in the role of an information manager.

2.1.10 A man/machine loop analysis summary format was developed as a means of defining system requirements. Examples for the tasks of observation and locomotion are presented by Tables 11, 12, and 13.

2.2 STUDY RESULTS

The results of this study indicate:

1. A growing requirement for advanced remotely controlled systems in future space exploration as man pushes further into the unknown.

2. Remotely controlled systems will increase in complexity with time due to increasing information requirements. The desirability of increasing the quantity and quality of information obtained from future space missions results from long trip times, 400-600 days for early Mars missions, and the limited availability of interplanetary launch windows.

3. The Mars mission is a timely candidate for a more detailed study of remotely controlled systems applications.

4. To satisfy the mission objective of reconnoitering the environment of Mars to define system requirements for subsequent Mars manned landing systems, many parameters must be measured quantitatively, which results in the following:

- The sensor module should be located on the surface of Mars and be able to sense an area large enough to encompass the initial landing and exploration zone to obtain the required levels of information.

- To achieve a high probability of successfully performing the tasks necessary to obtain the required information of a relatively unknown environment, the system should possess the capability of being reprogrammed and repaired as unanticipated events occur.
- The degree of mission success is enhanced for both the automatic and remotely controlled systems by having man located in Mars' orbit rather than on earth.
- Remotely controlled systems offer greater probability of mission success than automatic systems, regardless of the location of man in the system.
- A major problem area in remotely controlled systems is the time distance considerations in command and control.

5. The methodology developed by this study to establish the requirements of man and machine provides a basis for evaluation of candidate system concepts.

3.0 TECHNICAL DISCUSSION

3.1 ROLES OF RMMS IN SPACE EXPLORATION

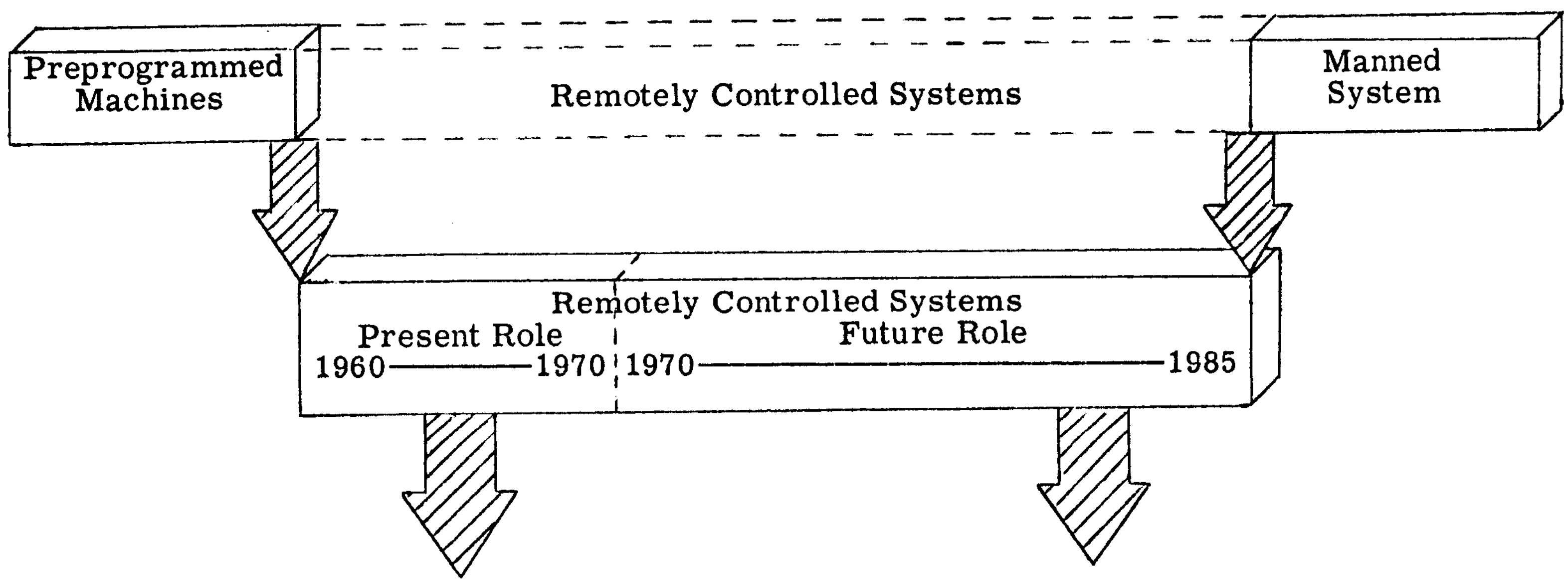
Remotely controlled systems have an important place in the spectrum of space exploration, Figure 1. The broad expanse between a simple preprogrammed machine, such as a space probe with one-way communication, and the manned system in contact with the environment contains all sizes, types, and complexities of remotely controlled systems. This study is primarily concerned with the more complex systems of the future where man's sensory and control capabilities are more fully extended.

The growth of remotely controlled systems in increasing order of complexity is illustrated as follows:

1. Simple ON-OFF control
2. Mode selection for equipment
3. Repair by selection of redundant elements
4. Simple course correction (orientation and thrust)
5. Repetitive attitude and course correction (thrust or aerodynamic forces)
6. Simple reprogramming of experimental procedure
7. Simple sample acquisition
8. Simple locomotion
9. Complex locomotion and complex manipulation
10. Simple adaptation to environmental hazards
11. Full extension of man's sensory and control capability including repair

The status of complexity can be determined by examination of the present role of remotely controlled systems.

SPECTRUM OF SPACE EXPLORATION



- First-Generation RMMS
- Multitude of special vehicles
- Simple mission objectives

- Approaching true extension of man's sensory and control functions
- Integration of sensors yielding complex systems and providing more information
- Complex mission objectives

Figure 1

3.1.1 Present Role

At present, many programs are being funded to conduct unmanned space exploration missions to determine the environment to which man will be subjected in space. Many of the mission experiments are of a purely scientific nature and supply data to increase man's knowledge. Most of the spacecraft being utilized now, and planned for the near future, are such that man plays an important role in remotely conducting and monitoring the acquisition of data. Major areas of present effort include:

Meteorological Satellites — Presently operational are a series of Tiros earth satellites being utilized for weather research. The satellite is remotely controlled in that stored data (meteorological pictures) are transmitted to a ground station on command. In addition, gross orientation of the Tiros is achieved by remotely controlling the magnetic field in a field coil.

Scientific Satellites — An example of scientific satellites is the Orbiting Solar Observatory (OSO). This satellite obtains data on such things as solar X-rays, solar flares, and ultraviolet effects. The satellite is remotely controlled in that a selection of sensors to be used at a particular time could be made from earth.

Communications Satellites — The Telstar satellites are prime examples of space-oriented communication relays that have remotely controlled features. These are (1) simple on-off control, (2) channel selection, (3) repair using circuit selection, and (4) transmitting data on request.

Lunar Exploration — Remotely controlled systems will be used extensively to determine the lunar environment prior to a manned landing. A primary example is the planned Surveyor Lunar Lander. Guidance and control maneuvers will be controlled from earth through final descent to the lunar surface. This includes pitch, yaw, and roll, as well as mid-course corrections. The TV cameras will be actuated from earth as well as the control of focusing and scanning. The orientation of solar panels and antennae will be controlled from earth as well as the actions of a mechanical extendable arm.

Planetary Exploration — The exploration of interplanetary space and the planets themselves was furthered by the launching of a Mariner space probe to the vicinity of Venus. The remotely controlled features incorporated into Mariner are that the power and TV cameras are turned on and off and mid-course corrections and spacecraft orientation are controlled from earth.

3.1.2 Future Role

In the not too distant future, man will have established himself in the space environment on an extended basis; viz, earth-orbiting stations and manned lunar landings. The next logical steps include those of lunar exploration and manned planetary landings. Studies that have been, and are being, conducted in this area (reference 3) indicate that considerable activity will be required in the near-earth space environment to support these missions. Such activities as assembly, propellant transfer, checkout, maintenance, and repair of the mission vehicles will be required. Remotely controlled systems may be used to implement these activities so that man will not be exposed unduly to the hazards of the space environment.

Future planetary missions include the exploration of Mars and Venus. The frequency of launches to the planets will be low because planetary launch windows are far apart in time and early mission duration is of the order of 400-600 days (reference 2). The initial manned missions being considered include flybys and captures with no attempt being made to land a man on the surface. However, while in the vicinity of the planet, effort would be expended to determine the planetary environment for subsequent manned landings. Since these missions will be expensive and infrequent, the most effective method of determining the environment will be used. Remotely controlled systems capable of being reprogrammed by a human operator such that the quantity and quality of data gathered can be significantly increased as opposed to automatic systems will, therefore, provide man with a useful tool for space exploration. The determination of this effectiveness requires a selected mission for study.

3.1.3 Mission Selection

The determination of a specific role for a remotely controlled system necessitates the choice of a mission. The choice for this study is the Mars Exploration Mission. The selection resulted from the consideration of several factors:

1. The future space missions are considered for this study to take place in the 1970-1985 time period.
2. The Mars mission is sufficiently advanced in time that specific concepts are not yet fixed.
3. The Mars mission will probably precede the Venus missions.

4. Mars has an environment more like that of earth and has a higher probability of supporting life.

5. The Mars mission contains features representative of all other missions.

Having selected a mission, we may now proceed with an operations analysis.

3.2 OPERATIONS ANALYSIS

3.2.1 Mission Objective

Before performing a detailed analysis of the Mars Exploration Mission, an objective for a remotely controlled system was selected. The objective chosen was: "Conduct detailed reconnaissance of the Martian surface and its environment in support of subsequent manned Mars landing missions."

Having selected a mission and objective, the next item to be determined is the information requirements.

3.2.2 Information Requirements

3.2.2.1 General Environmental Parameters

A general analysis was conducted to establish major categories or groups of items that, if known, would specify the environment of Mars. The categories established were:

- Radiation
- Fields
- Forces
- Matter
- Physical Information

Each of these major groups were further broken down into fairly specific parameters as summarized in Table 1.

3.2.2.2 Information Required

The information that must be determined prior to a manned landing on Mars is that required for the design of the systems necessary to land on Mars surface, rove about the surface, launch from Mars, and provide a safe environment for man throughout the mission. With the knowledge of the

TABLE 1

GENERAL ENVIRONMENTAL PARAMETERS

	Parameter	Category
1	Gamma	Radiation
2	Hard X-ray	
3	Soft X-ray	
4	Ultraviolet	
5	Visible	
6	Infrared	
7	Radio	
8	Electron (Free)	
9	Particles (Free)	
10	Electron	
11	Neutrons	
12	Protons and Mesons	
13	Electrostatic	Fields
14	Magnetic	
15	Gravitational	
16	Subsurface	Forces
17	Acoustics	
18	Atmospheric	
19	Rare Earths	Matter
20	Inert Gases	
21	Nonmetals	
22	Heavy Metals	
23	Light Metals	
24	Hydrogen	
25	Salts	
26	Bases	
27	Acids	
28	Aromatics	
29	Aliphatics	
30	Microorganisms	
31	Macroorganisms	
32	Surface Hardness	Physical
33	Surface Density	
34	Surface Resistivity and Magnetivity	
35	Topography Contour	
36	Temperature	

general environmental parameters identified in Section 3.2.2.1, it was then possible to identify the information requirements in terms of the design parameters. Table 2 presents the levels of information required of the Martian surface and atmosphere for the design of these systems. The key used to denote the various information levels is:

0 Knowledge not required; no knowledge of the item is required for the design of the system indicated.

1 Measure existence; the sensor must determine only that the item is or is not part of the environment.

2 Measure qualitatively; if the item is part of the environment, the degree that it is present must be determined.

3 Measure quantitative ranges; this is required if the upper and lower limits must be established for the item as well as the average or mean value.

4 Measure specifics; the statistical distribution of the item must be determined whether it be a function of time or location.

The level of information required for the design of each system — landing, launch, roving, or life support — is indicated for each atmospheric or surface parameter. The maximum level of information required for each parameter is shown in the extreme right-hand column which serves as a summary of the information requirements for the support of subsequent manned missions to the surface of Mars.

TABLE 2 INFORMATION REQUIREMENTS

Information Required of	Information Category	Design Parameter	Manned Systems: Landing	Launch	Roving	Life Support	Information Level Required
Mars Atmosphere	Matter (Composition)	Moisture	1	2	2	2	2
		Gases - Elements	3	3	3	3	3
		Dust - Compounds	2	2	3	2	3
		Living Organisms	0	0	0	3	3
	Force	Wind Velocity	4	4	4	3	4
		Pressure versus Altitude	4	4	4	3	4
	Physical (Temperature)	Atmospheric Temperature	3	3	3	3	3
Mars Surface	Physical (Topography)	Surface Roughness	3	3	3	0	3
		Boulder Size	3	3	3	0	3
		Boulder Distribution	3	3	3	0	3
		Slope Angles	3	3	3	0	3
		Fissures and Fractures	3	3	3	0	3
	Physical (Bearing and Impact Strength)	Density	3	3	3	0	3
		Hardness	3	3	3	0	3
		Resistivity/ Magnetivity	3	3	3	3	3
	Force	Subsurface Forces	3	3	3	3	3
		Acoustics	3	3	2	3	3
	Field	Gravity	3	3	3	3	3
	Physical (Temperature)	Surface Temperature	3	3	3	3	3
	Radiation (Electro-magnetic)	Gamma	0	3	3	3	3
		Hard X-ray	0	3	3	3	3
		Soft X-ray	0	3	3	3	3
		Ultraviolet	0	0	3	3	3
		Visible	0	0	3	3	3
		Infrared	0	0	3	3	3
		Radio	0	0	3	3	3
		Free Particles	0	0	3	3	3
		Free Electrons	0	0	3	3	3
	Radiation (Cosmic)	Electrons and Slow-charged Particles	0	0	2	3	3
		Protons and Mesons	0	0	2	3	3
		Neutrons	0	0	2	3	3
	Matter (Living)	Micro Organisms	0	0	0	3	3
		Macro Organisms	0	0	0	3	3

0 - Knowledge not required
1 - Measure existence
2 - Measure qualitatively
3 - Measure quantitative ranges
4 - Measure specifics

The following is a brief discussion of why knowledge of the various design parameters is required. The discussion is limited, for each parameter, to the system that requires the highest level of information.

Mars Atmosphere

Moisture — The presence of large amounts of mositure in the atmosphere would have a bearing on the design of the launch, roving, and life support systems.

Gases — The presence of highly corrosive or combustible gases may dictate the use of certain types of materials, power plants, etc.

Dust — The quantity of dust in the atmosphere and the size of the dust particles must be known for the design of the roving vehicle and for potential limitations of vision. Consideration must also be given to the electrostatic potential difference and how this may cause dust to collect on the landing vehicle.

Living Organisms — Potentially dangerous living organisms present in the atmosphere must be considered in the design of the life support system. In addition, protection must be provided against possible contamination to a manned module in orbit if samples are returned to it from Mars' surface. Another consideration is the sterilization of the remote module to prevent contamination of Mars by earth organisms.

Wind Velocity — Wind velocity must be known as a function of time and location for the design of certain types of potential landing, launching, and roving systems.

Atmospheric Pressure — The pressure versus altitude relationship must be known as a function of time and location for the design of the roving vehicle.

Atmospheric Temperature — The extreme high and low temperature must be known for the design of all systems.

Mars Surface

Topography Contour — The size and frequency of occurrence must be known for several locations for such parameters as surface roughness, boulder size and distribution, slope angles, and fissures and fractures. This information is needed for the selection of landing sites and for the design of the landing system.

Bearing and Impact Strength — The density, hardness, and resistivity/magnetivity of the surface must be known for several locations for the selection of landing sites and the design of a landing system.

Subsurface Forces — The frequency and magnitude of "quakes" or tremors due to subsurface forces must be known for the design and safety of all systems.

Acoustics — Experimentation must be done to determine the potential harm that may be caused by acoustics during the high noise level landing and launching operations.

Gravity — The magnitude of the gravity of Mars must be known for the design of all systems.

Surface Temperature — The extreme high and low surface temperatures must be known for the design of all systems.

Radiation — The levels of electromagnetic and cosmic radiation at the surface of Mars must be known for the design of the life support system and the communication system.

Living Organisms — The extent to which life exists on Mars must be known for the design of the life support system and, as in the atmosphere, possible contamination must be considered.

Systems can be designed, without the above information, to land man on the surface of Mars with a farily high probability of mission success. With the tight restrictions imposed on such a system by weight and cost, the above information is required to anticipate and design for all potential hazards and to accomplish trade-offs to achieve the highest possible probability of mission success.

This section identifies the information that is required to satisfy the mission objective. Methods of obtaining this information and the most feasible sensor locations were then investigated.

3.2.3 Sensor Location

3.2.3.1 Sources of Information

A study was made utilizing references 4-17 to determine the levels of information attainable for each parameter shown in Table 1, as a function of the distance of the sensor from the surface of Mars. This information is presented in Table 3. Shown at the bottom of the table is the key used to denote the level of information obtainable. These levels are:

1 Can measure existence; if the sensor determines only that the item is or is not part of the environment, level 1 information is obtained.

2 Can measure qualitatively; if the answer is that the item is part of the environment, level 2 information is achieved if it is also determined to what order of magnitude the item is present.

3 Can measure quantitative ranges; this is satisfied if the upper and lower limits can be established for the item as well as the average or mean value.

4 Can measure specifics; in order to achieve this level of information, the statistical distribution of the item must be determined whether it be a function of time or location.

Located at the left end of the figures are various "Mission Profiles" which indicate the location of the sensors with respect to earth.

Two companion tables, 4 and 5, provide data relative to Mars surface operation. If the desired level of information requires

TABLE 3

MARS EXPLORATORY MISSION

SENSOR LOCATION IMPLICATIONS

SENSOR DISTANCE TO TARGET BY MISSION PROFILE	KNOWLEDGE OBTAINABLE FROM	RADIATION												FIELD			FORCE			MATTER													PHYSICAL INFORMATION				
		ELECTROMAGNETIC									COSMIC									NON-LIVING											LIVING						
																				INORGANIC									ORGANIC								
																				ELEMENTS						COMPOUNDS											
		GAMMA	HARD X-RAY	SOFT X-RAY	ULTRA VIOLET	VISIBLE	INFRARED	RADIO	PARTICLES	ELECTRONS	ELECTRONS & SLOW CHARGED PARTICLES	NEUTRONS	PROTONS & MESONS	ELECTROSTATIC	MAGNETIC	GRAVITY	ACOUSTICS	SUBSURFACE FORCES	ATMOSPHERIC FORCES	RARE EARTHS	INERT GASES	NON-METALS	HEAVY METALS	LIGHT METALS	HYDROGEN	SALTS	BASES	ACIDS	AROMATICS	ALIPHATICS	MICRO ORGANISM	MACRO ORGANISM	SURFACE HARDNESS	DENSITY (MATERIAL SURFACE)	SURFACE RESISTIVITY & MAGNETIVITY	TOPOGRAPHY CONTOUR	TEMPERATURE
	EARTH	0	0	0	2	2	2	1	0	0	0	0	0	0	0	2	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EARTH ORBIT	0	0	0	2	2	2	1	0	0	0	0	0	0	0	[illegible]	1	0	1	0	1	1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0
	MARS FLYBY	0	0	0	2	2	2	2	0	0	0	0	0	0	2	2	1	0	1	0	2	1	1	1	1	0	0	0	1	1	0	0	0	2	0	2	2
	PROBE HARD IMPACT ON MARS SURFACE	1	1	1	3	3	3	3	1	1	3	3	3	0	1	2	2	0	2	0	1	1	1	1	2	0	0	0	1	1	0	1	2	2	0	3	2
	MARS CAPTURE ORBIT	0	1	0	3	3	3	3	0	0	3	3	3	0	3	3	2	0	2	1	2	2	2	2	2	0	0	0	2	2	0	0	0	2	0	2	2
	MARS STATIONARY SURFACE PROBE	2	3	3	3	3	3	3	2	2	3	3	3	2	3	3	3	2	3	3	3	3	3	3	3	3	3	3	2	2	1	1	2	2	2	2	3
	*SHORT TERM MARS SURFACE EXPLORATION	3	4	4	4	4	4	4	3	3	4	4	4	2	4	4	4	3	4	3	4	3	3	3	4	3	3	3	3	3	3	3	3	3	3	3	4
	**LONG TERM MARS SURFACE EXPLORATION	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

*SHORT TERM 30–50 DAYS
**LONG TERM 1 YEAR

INFORMATION LEVELS

0 – CAN NOT BE MEASURED
1 – CAN MEASURE EXISTENCE
2 – CAN MEASURE QUALITATIVELY
3 – CAN MEASURE QUANTITATIVE RANGES
4 – CAN MEASURE SPECIFICS

(shaded) INSUFFICIENT INFORMATION

(unshaded) INFORMATION REQUIREMENTS EQUALED OR SURPASSED

TABLE 4
MARS EXPLORATORY MISSION

REQUIRED EXPLORATION DISTANCE ON SURFACE

					RADIUS OF SURFACE AREA THAT MUST BE SENSED					
					CONTACT ONLY	0.1 MI.	1 MI.	10 MI.	100 MI.	1000 MI.
PHYSICAL INFORMATION				TEMPERATURE	3	3	3	4	4	4
PHYSICAL INFORMATION				TOPOGRAPHY CONTOUR	2	2	2	3	4	4
PHYSICAL INFORMATION				SURFACE RESISTIVITY & MAGNETIVITY	2	2	2	3	4	4
PHYSICAL INFORMATION				DENSITY (MATERIAL SURFACE)	2	2	2	3	4	4
PHYSICAL INFORMATION				SURFACE HARDNESS	2	2	2	3	4	4
MATTER	LIVING			MACRO ORGANISM	1	1	2	3	3	4
MATTER	LIVING			MICRO ORGANISM	1	1	2	3	3	4
MATTER	NON-LIVING	ORGANIC		ALIPHATICS	2	2	2	3	4	4
MATTER	NON-LIVING	ORGANIC		AROMATICS	2	2	2	3	4	4
MATTER	NON-LIVING	NORGANIC	COMPOUNDS	ACIDS	3	3	3	3	4	4
MATTER	NON-LIVING	NORGANIC	COMPOUNDS	BASES	3	3	3	3	4	4
MATTER	NON-LIVING	NORGANIC	COMPOUNDS	SALTS	3	3	3	3	4	4
MATTER	NON-LIVING	NORGANIC	ELEMENTS	HYDROGEN	3	4	4	4	4	4
MATTER	NON-LIVING	NORGANIC	ELEMENTS	LIGHT METALS	3	3	3	3	4	4
MATTER	NON-LIVING	NORGANIC	ELEMENTS	HEAVY METALS	3	3	3	3	4	4
MATTER	NON-LIVING	NORGANIC	ELEMENTS	NON-METALS	3	3	3	3	4	4
MATTER	NON-LIVING	NORGANIC	ELEMENTS	INERT GASES	3	4	4	4	4	4
MATTER	NON-LIVING	NORGANIC	ELEMENTS	RARE EARTHS	3	3	3	3	4	4
FORCE				GRAVITY	3	4	4	4	4	4
FORCE				SUBSURFACE FORCES	2	2	2	3	4	4
FORCE				ACOUSTICS	3	3	4	4	4	4
FORCE				ATMOSPHERIC FORCES	3	3	4	4	4	4
FIELD				MAGNETIC	3	4	4	4	4	4
FIELD				ELECTROSTATIC	2	2	2	2	2	4
RADIATION	COSMIC			PROTONS	3	4	4	4	4	4
RADIATION	COSMIC			NEUTRONS	3	4	4	4	4	4
RADIATION	COSMIC			ELECTRONS	3	4	4	4	4	4
RADIATION	ELECTROMAGNETIC			ELECTRONS	2	2	3	3	4	4
RADIATION	ELECTROMAGNETIC			PARTICLES	2	2	3	3	4	4
RADIATION	ELECTROMAGNETIC			RADIO	3	4	4	4	4	4
RADIATION	ELECTROMAGNETIC			INFRARED	3	4	4	4	4	4
RADIATION	ELECTROMAGNETIC			VISIBLE	3	4	4	4	4	4
RADIATION	ELECTROMAGNETIC			ULTRA VIOLET	3	4	4	4	4	4
RADIATION	ELECTROMAGNETIC			SOFT X-RAY	3	4	4	4	4	4
RADIATION	ELECTROMAGNETIC			HARD X-RAY	3	4	4	4	4	4
RADIATION	ELECTROMAGNETIC			GAMMA	2	2	3	3	4	4

INFORMATION LEVELS

0 - CAN NOT BE MEASURED
1 - CAN MEASURE EXISTENCE
2 - CAN MEASURE QUALITATIVELY
3 - CAN MEASURE QUANTITATIVE RANGES
4 - CAN MEASURE SPECIFICS

(shaded) INSUFFICIENT INFORMATION

(unshaded) INFORMATION REQUIREMENTS EQUALED OR SURPASSED

TABLE 5
MARS EXPLORATORY MISSION

REQUIRED SENSING TIME ON SURFACE

				SECONDS	HOURS	DAYS	MONTHS	YEAR
RADIATION	ELECTROMAGNETIC		GAMMA	2	2	3	3	4
RADIATION	ELECTROMAGNETIC		HARD X-RAY	3	3	4	4	4
RADIATION	ELECTROMAGNETIC		SOFT X-RAY	3	3	4	4	4
RADIATION	ELECTROMAGNETIC		ULTRA VIOLET	2	3	4	4	4
RADIATION	ELECTROMAGNETIC		VISIBLE	2	3	4	4	4
RADIATION	ELECTROMAGNETIC		INFRARED	2	3	4	4	4
RADIATION	ELECTROMAGNETIC		RADIO	2	3	4	4	4
RADIATION	ELECTROMAGNETIC		PARTICLES	2	3	3	3	4
RADIATION	ELECTROMAGNETIC		ELECTRONS	2	3	3	3	4
RADIATION	COSMIC		ELECTRONS	2	2	3	4	4
RADIATION	COSMIC		NEUTRONS	2	2	3	4	4
RADIATION	COSMIC		PROTONS	2	2	3	4	4
FIELD			ELECTROSTATIC	1	2	2	2	4
FIELD			MAGNETIC	2	3	4	4	4
FORCE			ATMOSPHERIC FORCES	2	3	4	4	4
FORCE			ACOUSTICS	2	3	4	4	4
FORCE			SUBSURFACE FORCES	2	3	3	3	4
FORCE			GRAVITY	2	3	4	4	4
MATTER	NON-LIVING / NORGANIC	ELEMENTS	RARE EARTHS	0	1	3	3	4
MATTER	NON-LIVING / NORGANIC	ELEMENTS	INERT GASES	0	1	4	4	4
MATTER	NON-LIVING / NORGANIC	ELEMENTS	NON-METALS	0	1	3	3	4
MATTER	NON-LIVING / NORGANIC	ELEMENTS	HEAVY METALS	0	1	3	3	4
MATTER	NON-LIVING / NORGANIC	ELEMENTS	LIGHT METALS	0	1	3	3	4
MATTER	NON-LIVING / NORGANIC	ELEMENTS	HYDROGEN	1	4	4	4	4
MATTER	NON-LIVING / NORGANIC	COMPOUNDS	SALTS	0	1	2	3	4
MATTER	NON-LIVING / NORGANIC	COMPOUNDS	BASES	0	1	2	3	4
MATTER	NON-LIVING / NORGANIC	COMPOUNDS	ACIDS	0	1	2	3	4
MATTER	NON-LIVING / ORGANIC		AROMATICS	0	1	2	3	4
MATTER	NON-LIVING / ORGANIC		ALIPHATICS	0	1	2	3	4
MATTER	LIVING		MICRO ORGANISM	0	2	2	3	4
MATTER	LIVING		MACRO ORGANISM	0	2	2	3	4
PHYSICAL INFORMATION			SURFACE HARDNESS	2	3	4	4	4
PHYSICAL INFORMATION			DENSITY (MATERIAL SURFACE)	2	2	3	3	4
PHYSICAL INFORMATION			SURFACE RESISTIVITY & MAGNETIVITY	2	3	3	3	4
PHYSICAL INFORMATION			TOPOGRAPHY CONTOUR	0	2	2	3	4
PHYSICAL INFORMATION			TEMPERATURE	0	2	2	3	4

SENSING TIME ON SURFACE: SECONDS, HOURS, DAYS, MONTHS, YEAR

INFORMATION LEVELS

0 – CAN NOT BE MEASURED
1 – CAN MEASURE EXISTENCE
2 – CAN MEASURE QUALITATIVELY
3 – CAN MEASURE QUANTITATIVE RANGES
4 – CAN MEASURE SPECIFICS

(shaded) INSUFFICIENT INFORMATION

(outlined) INFORMATION REQUIREMENTS EQUALED OR SURPASSED the sensors to be on the Martian surface, then Tables 4 and 5 provide the requirements for the distance on the surface to be explored and the time required for the sensor to obtain the indicated level of information.

3.2.3.2 Selection of Sensor Location

Table 2 presents the levels of information required to design the systems necessary for subsequent manned landings on Mars. In Table 3, only those levels of information shown below the heavy line meet the requirements as defined by Table 2. The information levels above the heavy line and in the shaded region represent insufficient levels of information. It is then apparent from Table 3 that only two mission profiles are able to achieve, for all parameters, the levels of information necessary to meet the requirements of the mission objective. These mission profiles are (1) Short-Term Mars Surface Exploration, and (2) Long-Term Mars Surface Exploration. Both of these mission profiles require that the sensor module be located on the surface of Mars. It is thus concluded that to obtain the information that is required to satisfy the mission objective, the sensor module should be located on the surface of Mars.

Having determined that the sensor module should be on the surface, then the companion tables, 4 and 5, are to be considered. As described before the information levels above, the heavy line and the shaded region represent insufficient levels of information. It is apparent from these tables that the sensor module should have a capability to rove and that the 30- to 50-day mission duration should be sufficient to collect the information.

The considerations for sensor location set the stage for examination of system approaches to determine how the mission might be accomplished.

3.2.4 System Approaches

It has been shown that to accomplish the mission objective of gathering required levels of information about the environment of Mars, the sensor module should be located on the surface of Mars and will probably be required to have a roving capability. Two types of systems could be made available for the accomplishment of this mission; (1) remotely controlled systems, and (2) automatic systems. These systems are briefly described below.

3.2.4.1 Remotely Controlled Systems

A remote man/machine system is one that has a two-way communication link, one for man to control and reprogram the remote system and the other for transmitting information from the remote system to man. The total system, demonstrated by Figure 2, is grouped into four components: (1) man, (2) command module, (3) remote module, and (4) sensor. These components are basic regardless of mission profile. The distance between the man and the sensor may be a foot or may extend across our solar system, depending on the system role and mission profile. Three different display-control loops are shown by Figure 2. The shortest time loop is closed by man at the operator position; i.e., the interface between the operator and the remote machine requires times of the order of seconds to transfer information for display and control functions. The second time loop is closed by a technical group of men whose analyses may result in redirecting operator control to achieve more significant results from the remote machine. The redirection of operator control may be in terms of minutes, hours, days, or months. The third time loop is given in terms

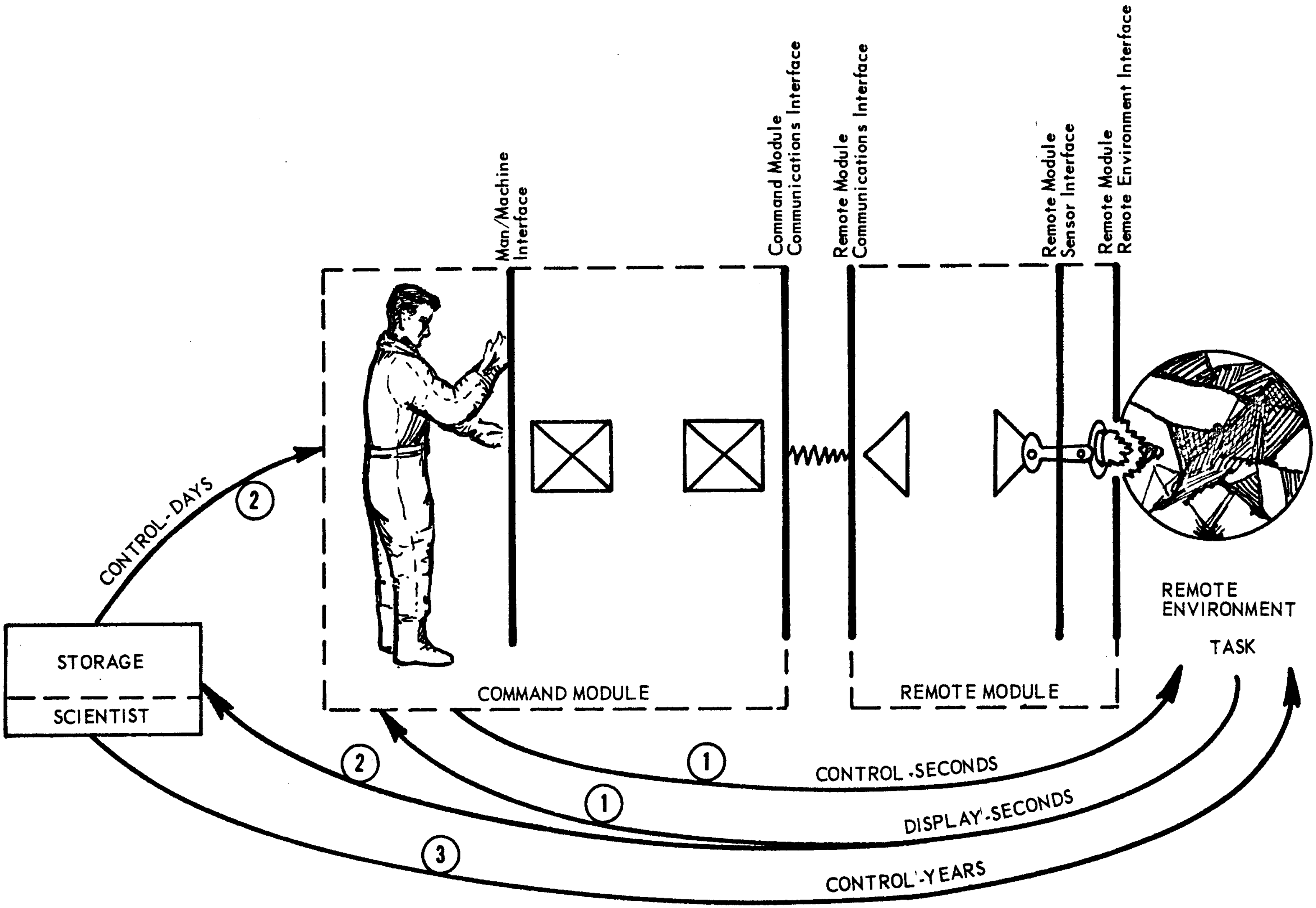


FIGURE 2 REMOTE MAN-MACHINE CONTROL SYSTEM INTERFACE RELATIONSHIPS

of months or years and represents the control exerted by a technical group that redefines or reshapes the remote environment.

Only loop one, which consists of the command module, the remote module, and the remote environment, is considered in this study (see shaded portion of Figure 3). This portion of the RMMS was selected because it includes the major man-machine relationships which are common to all three loops.

The command module is defined as the operator's, or man's, enclosure, whether it be earthbound, spaceborne, in orbit, or planetbound.

The associated interfaces of primary concern are the man/machine interface and the command module/communications interface. The man/machine interface consists primarily of the displays and operator controls necessary for, and compatible with, the efficient extension of man's sensory and physical capabilities. The command module/communications (telemetry) interface, in this context, consists of the receivers and transmitters necessary to provide man with those data required in the performance of his task and to provide a means of transmitting his response outputs back to the remote module.

The remote module is defined as that container or system required to house and manipulate the sensing and functional devices. The remote module/communications interface primarily concerns the receipt of the operator's outputs and the transmission of the data required by man in meeting his objective. The remote module/sensor interface consists of those elements necessary to

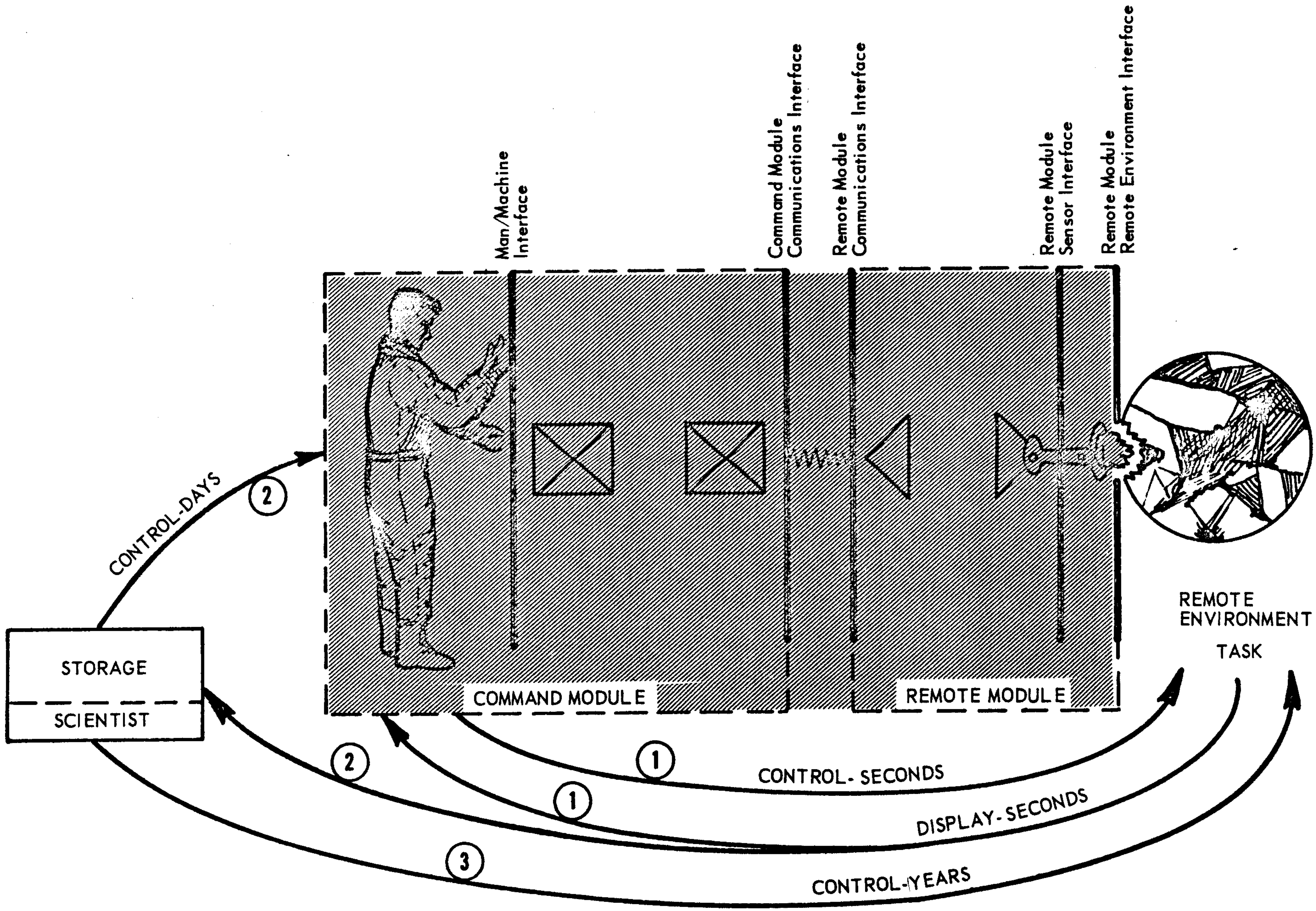


FIGURE 3 SYSTEM INTERFACES CONSIDERED BY THIS STUDY

provide control and/or manipulation functions for the various sensory systems. The remote module/remote environment interface establishes the configuration and material requirements for the design of the remote module and external appendages.

The above model description is valid for any remotely controlled system. The various interface requirements will vary as a function of mission objective and distance between the man's brain and source of information of interest.

3.2.4.2 Automatic System

An automatic system is defined to be one that is preprogrammed by man, with a one-way communication link for transmitting preselected information to man and with no facility for being reprogrammed. Automatic systems replace man and the command communication link found in remotely controlled systems with a command program designed by man prior to the start of the mission.

Two types of automatic systems are considered here. The first, and least complex of the two types, is one where the command program directs the automatic module through a predetermined mode of action regardless of the situation at the time of action. The second type is a highly complex system that has the capability to ascertain some information relative to its immediate situation and to select the predetermined mode of action, of several that are available, that is most suitable to the particular situation.

The first type of automatic system consists of five interfaces of interest. The command program/automatic module interface consists primarily of a computer to provide the proper sequencing of power to the functional elements of the automatic module. The automatic module/sensor interface consists of those elements necessary to control or manipulate the various sensory systems. The automatic module/remote environment interface establishes the configuration and material requirements for the design of the automatic module and external appendages. The automatic module/communications interface is concerned only with the transmission of data to man. The communication/display interface consists of those elements necessary to receive and display to man the information obtained by the automatic module.

The sec ond type of automatic system consists of the interfaces described above plus a remote environment/command program interface. This interface consists of the equipment necessary to detect the immediate surroundings of the automatic module and to select one of the modes of action available to the system.

The complexity of the various interfaces is a function of mission objective; or, the complexity of the tasks to be performed by the automatic system, the amount of information that must be obtained, and the distance over which the information must be obtained, and the distance over which the information must be transmitted from the automatic module to man's display equipment.

3.2.5 Location of Man in the System

It has been shown that the sensor module must be located on the surface of Mars to be able to successfully accomplish the mission objective. The location of man relative to the sensor module must next be considered. Man may be located on earth, in earth orbit, in Mars flyby, or in Mars capture orbit. The two locations considered here are man on earth and man in Mars capture orbit. Automatic and remotely controlled systems may be postulated that could feasibly accomplish the mission objective with man located on earth if time were not important. A manned capsule in Mars orbit can greatly increase the acquisition of information per unit time and also increase the probability of mission success as well as to decrease the weight and complexity of their respective sensor modules. The factors that are most affected by the choice of man's location in the system are discussed below for remotely controlled and automatic systems.

3.2.5.1 Remotely Controlled Systems

The factors most affected by the location of man relative to the sensor module in a remotely controlled system are time and distance considerations and system complexity.

3.2.5.1.1 Time and Distance Considerations

The factors of time and distance enter the remote man-machine system design in two principal areas:

1. Command and Feedback Delay
2. Communication Distance

Each of these considerations has a major effect on the choice of location of the command module relative to the sensor module.

Comand and Feedback Delay

The choice of man's location relative to the controlled machine is influenced heavily by the effects of the time delay in the control loop due to physical separation distance and the finite velocity with which commands and feedback can be transmitted. The major consequences of significant delay times are:

1. Increased task performance time
2. Modified task performance techniques and/or increased equipment complexity.

The extension of a simple remote man-machine combination to Earth-Mars distances, for example, results in several hundred-fold increase in task performance time and required the operator to adopt an entirely different operating technique.

When the operator is separated from the controlled machine by a small distance, the time delays involved are small compared with his perception and reflex times. In this case, the man and machine operate in a familiar, continuous closed-loop fashion comparable to the task of driving an automobile or operating a lathe. When the distance involved incurs a delay of seconds or minutes, however, the man must adopt a radically different strategy. In an Earth-Mars remote control situation, there is a minimum delay of about six minutes between the time the man acts and the time he witnesses the consequence of his act. He is, therefore, forced to adopt a strategy of estimating the action required, acting "open loop," and then waiting to see the consequences of his act. The sequence is then repeated to correct his estimates until the requuired degree of accuracy is achieved and is identified as the "iterated loop." This mode of adaptation is intuitive and has been demonstrated for simple manipulative tasks with delays as short as one second. The increase in task performance time with increasing time delays results in increased mission duration, and means greater system power requirements and a degradation of system reliability due to time.

Command-feedback loops with delays of the same order of magnitude as a man's perception and reaction times (e.g., 0.1 to 1.0 seconds) tend to produce instability in the man-machine loop. The man is caught between the time delay region in which he can function stably on a continuous, closed-loop basis and the region where he must adopt the iterative approach. While the problem of operation in this time-delay region can be mitigated by the use of anticipative displays that synthesize immediate feedback, the consequence of increased equipment complexity must be considered.

The effect of distance on task accomplishment time and operator adaptation is illustrated by Figure 4. The normalized task accomplishment time (i.e., the ratio of time required at a given distance to the time required without delay due to distance) is plotted as a function of distance between the man and the controlled machine. The curve is computed from the theory and data generated by Sheridan, reference 18, in a study of the "Functional Extension of the Human Hands." The time or distance regions for stable, closed-loop operation and for stable, iterated-loop operation are identified with a range described as "critical" in between. The upper limit of the "critical" region is not actually well defined since it is a function of the particular type of task performed; further work is required to develop meaningful interpretations.

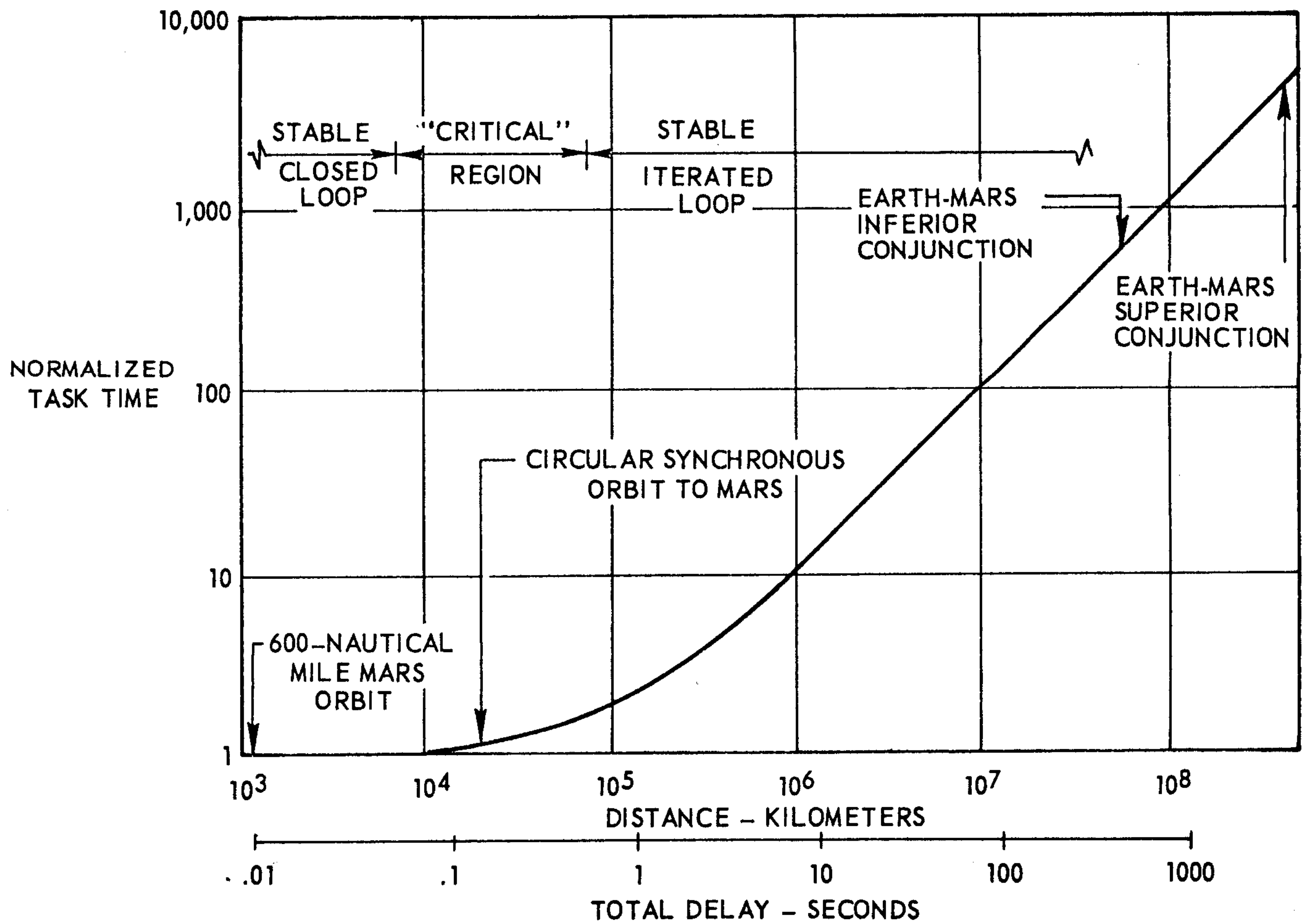


FIGURE 4 TASK TIME VERSUS DISTANCE

Some system design implications can be drawn from Figure 4. The time delay due to distance does not create a problem in the remote man-machine loop for distances less than 4,000 or 5,000 nautical miles. Distances of approximately 5,000 to 50,000 nautical miles are critical. Many tasks, such as simple manipulation, can still be accomplished in a normal fashion from this distance by the incorporation of synthetic feedback techniques, but the system is quite sensitive to the distance parameter and will lack flexibility. A slight increase in operating distance could render some of the control loops unstable, while a small reduction in distance could obviate the requirement for complex synthetic feedback and display equipment.

At distances in the order of hundreds of thousands of nautical miles, the increase in time required to perform a given task is significant; and it becomes profitable, with regard to task time, to endow the controlled machine with a degree of autonomy. The equipment complexity required to give a machine this capability is a function of the task to be performed and would approach that required of an automatic system. If the machine is deisgned to utilize some of its sensor data in the process of carrying out commands, the commands can be more general and less frequent, thereby reducing the task performance time penalty associated with the large man-machine distance. As for example, a machine capabile of effective operation for six-minute periods between commands would suffer only a 2:1 task time penalty rather than the 1000:1 penalty indicated by Figure 4 at the Earth-Mars opposition distances. The two-to-one penalty results from the sequential dependence of command and feedback; i.e., the machine must wait until the result of the last command has been communicated before proceeding with the over-all task. Hence, the normalized task time, or penalty, when the machine is endowed with autonomy is given by:

$$\frac{Td + Ta}{Ta}$$

where Td is the loop delay time which is approximately six minutes for this example, and Ta is the time of effective operation between commands.

The penalties imposed on the remotely controlled system by having the command module located on earth are: (1) extremely long mission durations resulting in greater sensor module power requirements and reduced system reliability, or (2) endowing the controlled machine with a degree of autonomy resulting in increased sensor module complexity approaching that required of automatic systems.

With man located in Mars capture orbit, the above penalties are minimized. The command-feedback delay would approach the stable, closed-loop situation and depending upon the orbit (see Appendix B), man could control the remote machine a large portion of the time.

Communication Distance

The principal effect of distance on the communication link is the increase in transmitter power required with an increase in distance. The required power for the command and feedback loops is proportional to the information rate (bandwidth) and the square of the distance.

The weight or size of a transmitter is roughly proportional to the power output. Normalized transmitter size (i.e., the ratio of required transmitter size at a given distance to transmitter size at a referenced distance) is shown as a function of distance by Figure 5. The dashed curve shows the relative transmitter size required as a function of distance for a constant information rate. The solid curve shows the relative transmitter size when the reduced information rate resulting from the increased task performance times of Figure 4 are taken into account. When a given remote man-machine system is extended to large distances, the task performance time is increased due to the increased time delay. The total information that must be communicated around the loop remains constant. Hence, the information rate diminishes in inverse proportion to the task performance time.

The task performance time may be reduced by incorporating a degree of autonomy in the remote machine as previously discussed. The information rate in the command-feedback loop, however, is not increased in this case. Rather, the information rate in the data link from the remote machine is increased as a consequence of speeding up the data-gathering function of the remote machine. Hence, in this system the information rate and, therefore, transmitter size will be several orders of magnitude greater for the link from machine to man than for the link from man to machine, with the exact ratio being dependent upon the nature of the task to be performed.

The transmission from Mars to earth of pictorial data such as conventional television, at a frame rate of 30 frames

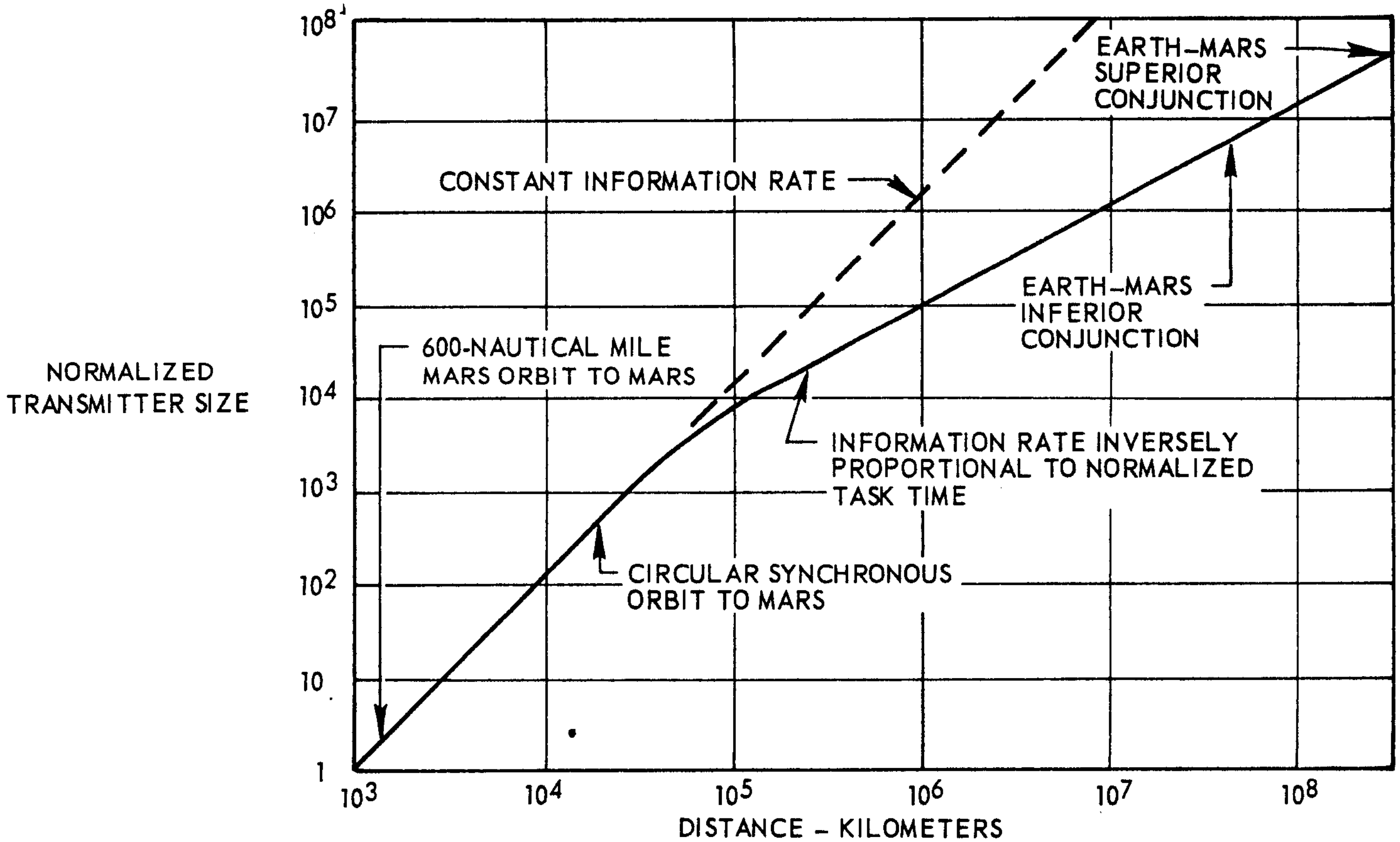


FIGURE 5 TRANSMITTER SIZE VERSUS DISTANCE

per second, would require a tremendous amount of power at the sensor module as illustrated in Table 6. It is possible, however, to drastically reduce the power requirement by reducing the rate at which frames are transmitted. Pictorial data may be transmitted from Mars to earth with a frame rate of less than one frame per minute, which would reduce the power requirements to a reasonable amount. This would require that a permanent record be made of each frame at the receiving station. This technique would result in extremely long data transmission and, therefore, task performance and mission duration times.

The data needed from the sensor module on Mars by the man on earth to control the remote machine require a trade-off between either a tremendous amount of power at the remote module, or less power and resulting slower data rate and longer task time. With man in Mars capture orbit, the sensor module power requirements are reduced by several orders of magnitude, resulting in a lighter weight, less complex, and, therefore, a more reliable sensor module

3.2.5.2 Automatic Systems

The location of man relative to the sensor module in an automatic system affects the amount of information available at the time of programming the automatic sensor module and the communication distance.

With man located on earth, the automatic sensor module must be programmed prior to launch from earth, with only the knowledge about the environment of Mars available at that time usable as inputs. With man located in Mars orbit, information

TABLE 6

Transmitter power required to send pictorial data from Mars to Earth.

Frame Rate	Power
1 per 30 min.	19.5 dbw = 89 watts
1 per min.	34.2 dbw = 2.63 kilowatts
1 per sec.	52.0 dbw = 159 kilowatts
*30 per sec.	66.8 dbw = 4.79 megawatts

*Conventional television signals require a frame rate of 30 frames per second.

gained via orbital reconnaissance may be input into the automatic sensor module program just prior to ejecting the sensor module from Mars orbit to the surface of Mars.

The problems of transmitting information from the automatic sensor module located on Mars surface to man located on earth are the same as those discussed previously for the remotely controlled system. The power requirements and sensor module complexity are greater for the system with man on earth than for the system with man in Mars orbit.

Other advantages of having man in Mars orbit with the automatic system are the assistance man can give while the system is enroute to Mars and in helping to get the system into the correct Mars capture orbit. To apply mid-course corrections automatically require stellar navigation equipment and computers. For the system to get into the proper Mars capture orbit automatically would require a radio altimeter. Man can monitor the mission and apply the necessary inputs to perform these functions with the help of computers and tracking systems located on earth. Man in Mars orbit can also select sensor module location sites prior to launching the automatic system to the surface which greatly improves the probability of mission success.

3.2.6 System Comparisons

This study has not progressed through the system requirements and system concepts phases which provide the basis for true system comparisons. It is the intent of this section to advance some qualitative comparisons to indicate the capabilities and limitations of automatic and remotely controlled systems in the performance of the chosen mission objective. This comparison is made with man on earth and with man in Mars orbit.

It is appropriate to first present the criteria for the measurement of system effectiveness.

3.2.6.1 Measures of Effectiveness

The factors used to determine the relative effectiveness of systems to accomplish a mission are (1) probability of mission success (Ps) and (2) system cost. As shown in Section 3.2.3.2, to accomplish the mission objective, the sensor module must be located on the surface of Mars. Therefore, the mission may be described as being made up of three major phases which are (1) placing the sensor module on the surface of Mars, (2) gathering the required information, and (3) transmitting the information back to earth. The probability of mission success may be expressed as:

$$Ps = P_{AM} \times P_{GD} \times P_{TD}$$

where:

P_{AM} = probability of sensor module successfully arriving on Mars surface

P_{GD} = probability of sensor module successfully gathering required data

P_{TD} = probability data are successfully transmitted to earth

The factor P_{AM} is dependent upon the probability of the successful occurrence of the following events: launch and flight from earth to earth orbit; rendezvous, orbital launch, and flight from earth orbit to Mars orbit; getting into the proper Mars capture orbit; and the ejection of the sensor module from Mars orbit to the surface of Mars. The factor P_{GD} depends on the successful collection and testing of samples, the detection and measurement of parameters, and the survey of the general locale. As shown in Section 3.2.3.2, P_{GD} also depends on the successful roving of the sensor module about the surface of Mars in search of information. The reliability of the components and subsystems required by each system to accomplish the above events and tasks combine to give the probability of mission success for the particular system. System reliability may be increased by the addition of redundant components and subsystems to the system. Redundancy tends to increase system complexity and weight.

System cost is a function of the system complexity and weight. As system complexity and weight increases, the production cost increases; but much more significant is the increase in cost to launch the system from earth. Using currently accepted performance data, each pound of payload placed on the surface of

Mars requires approximately twelve pounds to be launched from earth orbit and about 900 pounds to be launched from earth.

Another cost factor to be considered when evaluating the expected cost of the mission is the cost to the space program should the mission fail. This cost is difficult to estimate because it is made up of several factors, the size of which depends on the degree of failure. Total mission failure, or one where very little information is received, would require that the mission be performed a second time after the necessary corrections to the system are made. If the mission is mostly successful, but fails to obtain the required information regarding one or several parameters, the spacecraft in which man is to land on Mars must be modified to provide protection against the unknown parameters, thus increasing the weight, complexity, and cost of the manned landing module. The most nebulous, and possibly the largest, cost due to failure is that caused by delaying the over-all space program, or those programs dependent upon the successful completion of this mission.

3.2.6.2 Automatic Versus Remotely Controlled

The issue here is not whether man is located on earth or in Mars capture orbit, but which type of system — automatic or remotely controlled — offers the greatest potential with respect to mission success for a given location of man in the system.

The different methods used by automatic and remotely controlled systems to accomplish the major events that make up the mission are identified in Tables 7 and 8, for man located

TABLE 7

SYSTEM COMPARISON/MAN ON EARTH

Event	Completely Automatic	Remotely Controlled
<u>Basic to All Events</u>		
Command System	- Requires highly complex computer system - adds weight, complexity, and cost	+ Input from man on earth - highly reliable
Data Link	+ One-way communication system required	- Two-way communication required - adds weight, complexity, and cost
Repair - Selection of redundant elements	- Requires computer routine to test and select elements - adds complexity and cost	+ Elements tested and selected via remote control - high reliability
<u>Getting to Mars</u>		
Earth to Earth Orbit	Both systems require similar equipment	Same as automatic
Earth Orbit to Mars Orbit		
Mid-course correction	- Redundant stellar navigation system required - adds weight, complexity, and cost	+ Input from earth tracking and computers - high reliability
Enter correct Mars orbit	- Redundant radio altimeter required - adds weight, complexity, and cost	+ Input from earth - high reliability
Mars Orbit to Mars Surface		
Orbital reconnaissance	- Camera orientation system required - adds complexity, weight, and cost	+ Camera orientation remotely controlled - high reliability
Select landing sites	- Sites selected prior to leaving earth	+ Information from orbital reconnaissance available for site selection
<u>Gather Data</u>		
Collect and test samples, detect and measure other parameters, and survey locale	- An automatic system programmed to accomplish these functions in an unknown environment is restricted by the limited information available when programmed and is vulnerable to unexpected hazards	+ Select area for sampling + Alternate tools and subsystems may be substituted for defects with man supplying the techniques - adds reliability - With man on earth, task times are extremely long
Rove about surface	- Requires additional sensors and a computer to help module avoid potential hazards - adds weight, complexity, and cost	+ Safely guided via remote control - high reliability but extremely long task times required with man on earth
<u>Transmit Data</u>	Both systems require similar equipment	Same as automatic

TABLE 8

SYSTEM COMPARISON/MAN IN MARS ORBIT

Event	Completely Automatic	Remotely Controlled
Getting to Mars	This phase of the mission would be similar for both systems with man along	Same as automatic, except: + Remotely assist sensor module landing on Mars surface
Basic to Data Gathering and Transmission Events		
Command System	- Requires highly complex computer system - adds weight, complexity, and cost	+ Input from man in Mars orbit - highly reliable
Data Link	+ One-way communication system required	- Two-way communication system required - adds weight, complexity, and cost
Repair - Selection of redundant elements	- Requires computer routine to test and select elements - adds complexity	+ Elements tested and selected via remote control - high reliability
Gather Data		
Collect and test samples, detect and measure other parameters, and survey locale	- An automatic system programmed to accomplish these functions in an unknown environment is restricted by the limited information available when programmed and is vulnerable to unexpected hazards	+ Select areas for sampling + Alternate tools and subsystems may be substituted for defects with man supplying the techniques - adds reliability
Rove about surface	- Requires additional sensors and a computer to help module avoid potential hazards - adds weight, complexity, and cost	+ Safely guided via remote control - high reliability
Transmit Data	Both systems require similar equipment	Same as automatic

on earth or in Mars orbit, respectively. A plus (+) sign denotes a system capability, whereas a minus (-) sign denotes a system limitation.

The tables indicate that with man located on earth or in Mars orbit, the remotely controlled systems appear to be more reliable and require less complexity, weight, and cost than the respective automatic systems.

A representative mission profile may now be described by which a remotely controlled system, incorporating the required roving surface operation (Section 3.2.3.2) and man located in Mars orbit (Section 3.2.5), would accomplish the mission objective.

3.2.7 Mission Description

The preceding discussion presents the factors for consideration in the selection of a mission profile. A review of the planned Mars manned missions indicates a flyby, a capture, and a landing as being scheduled during the 1970's and 1980's.

The manned Mars capture mission is compatible with the RMMS mission and objective selected for this study. A representative mission description is presented and includes typical remotely controlled systems.

Phase I — Earth Launch — A concept presented in reference 3 involves the use of orbital launch operations; i.e., the interplanetary vehicle is constructed from several individually launched modules which are assembled in earth orbit. Phase I is considered to cover the launching of these several modules into an earth parking orbit.

Phase II — Earth Orbit — The individual modules that make up the interplanetary vehicle remain in the parking orbit until such time as they are properly aligned with the orbital launch facility. At this time, the execution of a Hohmann transfer trajectory is initiated and the modules ascend to and rendezvous with the orbital launch facility. In addition to the orbital launch facility, the referenced document identifies the requirement for an orbital support assembly vehicle and a remote maneuvering unit. In this phase, remotely controlled syatems play an important part; as shown by Figure 6, for example, the remote maneuvering unit is shown to be particularly important in hazardous operations involving nuclear engines. The assembly and fueling is accomplished utilizing

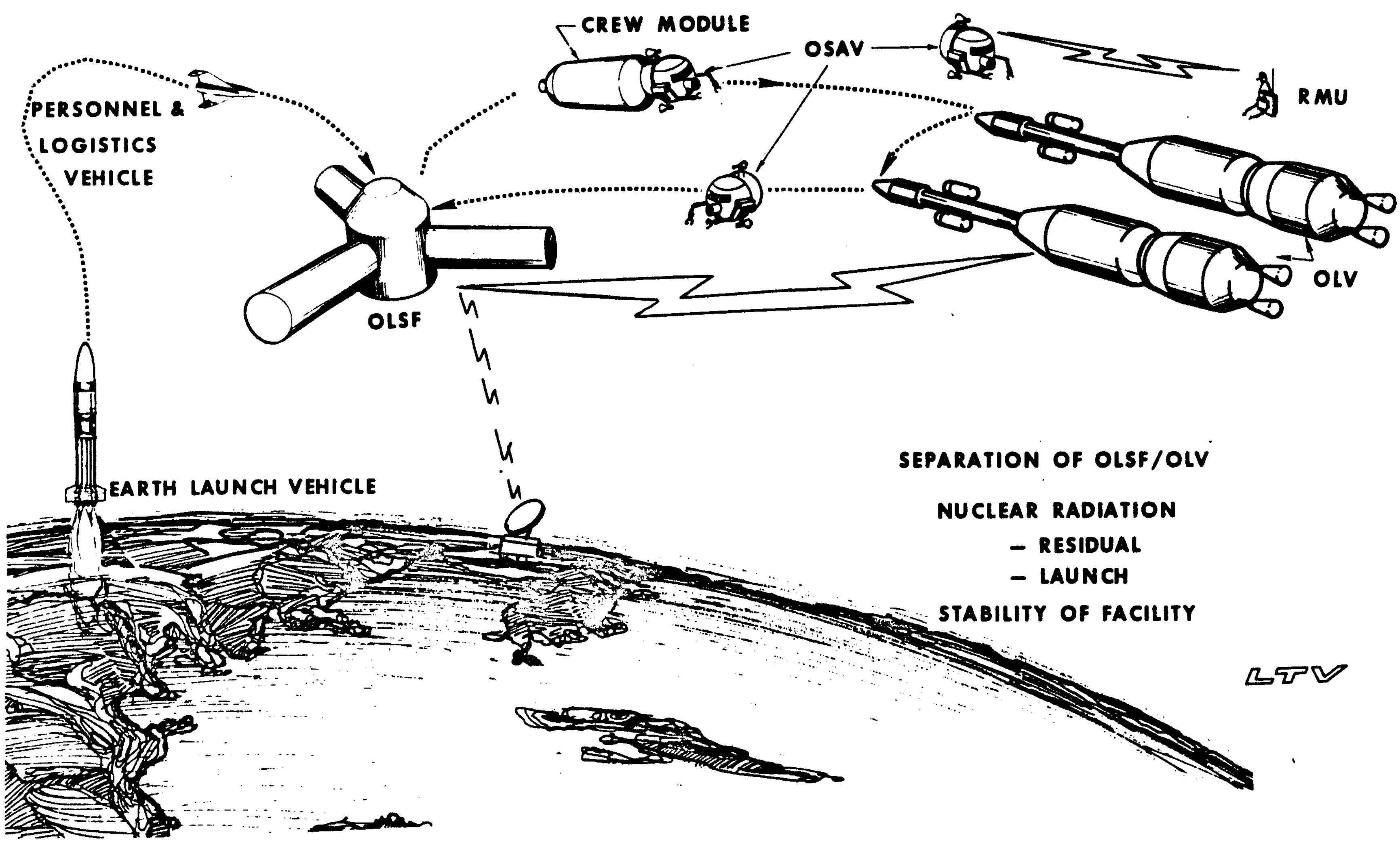


FIGURE 6 OLSF SUPPORT MODE

the orbital support assembly vehicle and remote maneuvering unit. The orbital support assembly vehicle also performs the task of crew transfer from the orbital launch facility. After system checkout, the spacecraft is injected into a cisplanetary trajectory from an elliptical orbit.

Phase III — Cisplanetary Outbound — The cisplanetary outbound portion of the mission may consist of one spacecraft or a convoy of two or three. The other convoy vehicles would be robots, controlled remotely from the manned spacecraft. For maintenance and repair enroute, both the remote maneuvering unit (Figure 7) and an astronaut maneuvering unit may be employed. One of the major events in this phase would be course correction.

Phase IV — Planetary Orbital — The initial planetary capture retrothrust maneuvers provide an elliptical orbit which may subsequently be converted into a circular orbit. The orbit about Mars which is depicted by Figure 8 is based on data obtained from reference 2. This document points out that a savings in fuel of 25% is attainable for an elliptical orbit versus a circular orbit. The ellipticity for such a savings is represented by

$$n = \frac{r_a}{r_p} = 4$$

where r_a is the radius of apogee and r_p is the radius of perigee.

Since energy conservation is a big factor for the time period being considered, the elliptical orbit was viewed as the most likely orbit that would be used during the Mars capture mission.

It must be pointed out that in both a circular and elliptical orbit, the perturbations brought about by the moons, Phobos and Deimos, may have implications on stationkeeping. Figure 8

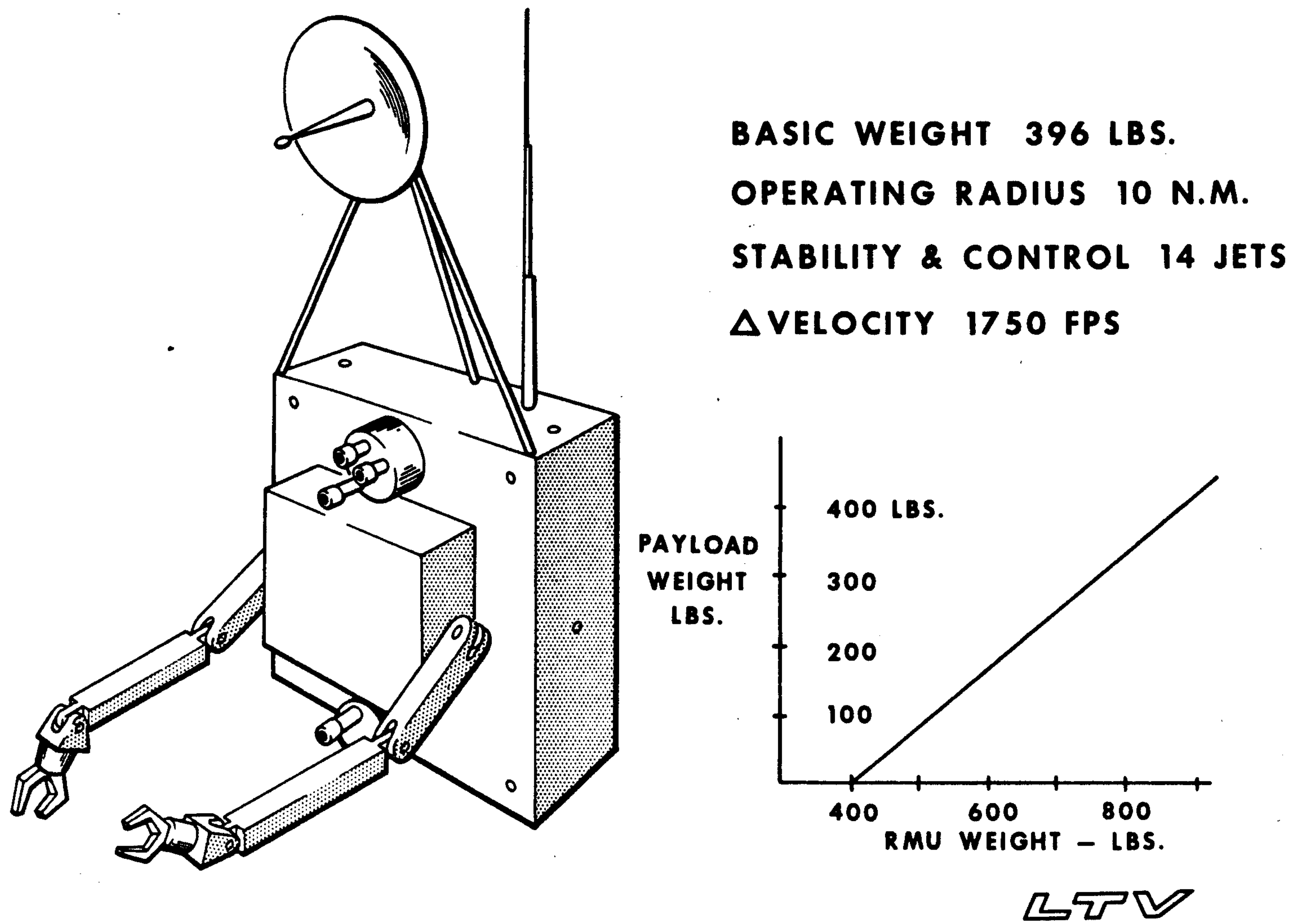


FIGURE 7 REMOTE MANEUVERING UNIT

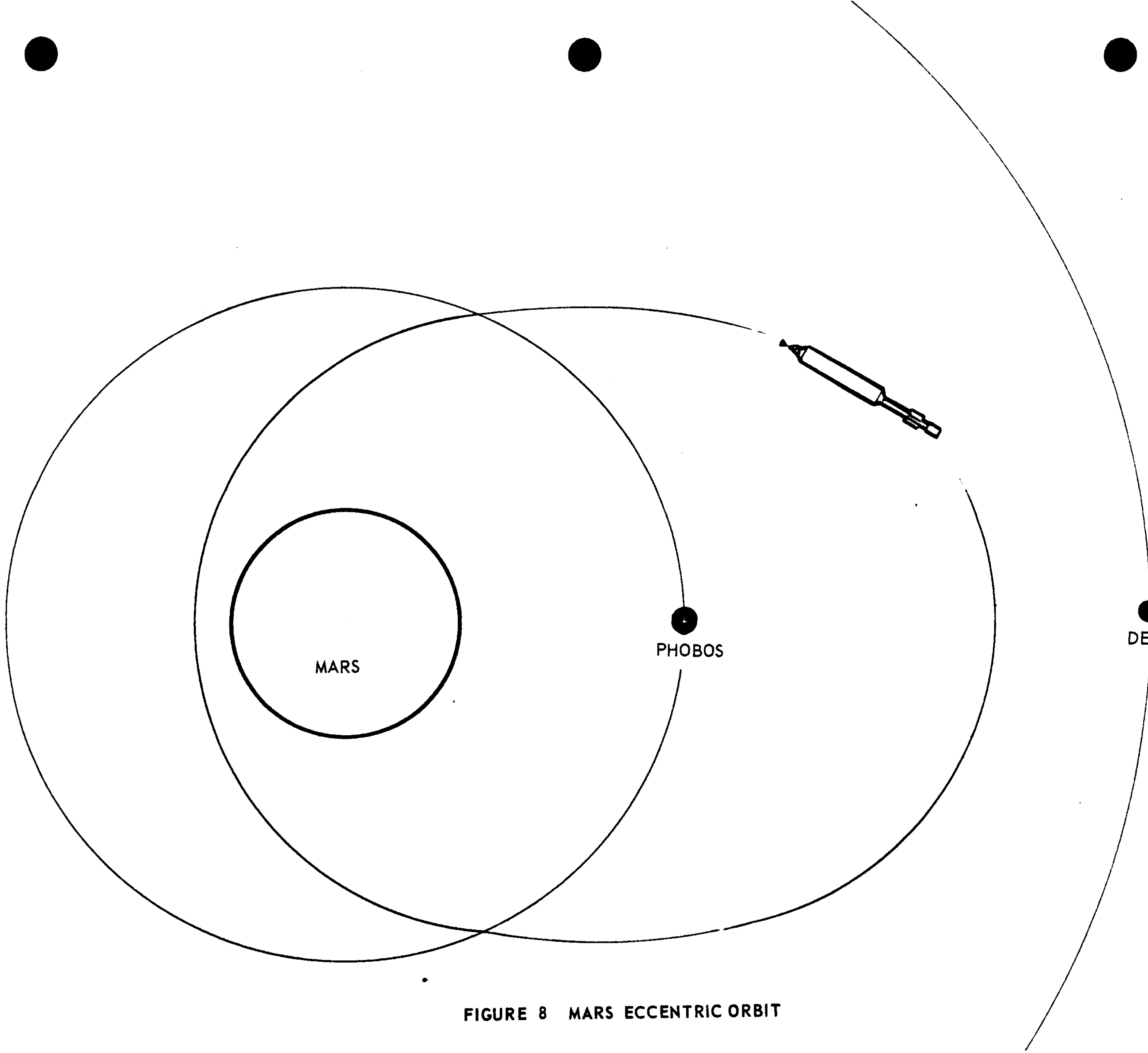


FIGURE 8 MARS ECCENTRIC ORBIT

portrays a probable orbit meeting the $n = 4$ criteria stated in reference 2. Perigee in this case represents 600 nautical miles above the surface of Mars.

Consideration of the effect that such a profile might have on the remote man/machine control system prompted the Mars orbital analysis found as Appendix B. The implications of this parametric study of orbital profiles are discussed in Section 3.3.1.

Figure 9 represents an over-all concept for an orbiting command spacecraft and a surface roving remotely controlled system. Considering that the maximum information is to be derived from this mission, the figure portrays the command spacecraft as performing the functions of a mapper of the surface of Mars; observing through a telescope the moons, Phobos and Deimos; launching probes to Phobos and Deimos to gather preliminary information about their environment; sending out a remote maneuvering unit for possible retrieval of small sample capsules returned from the Mars surface operations; and launching and operating the remotely controlled surface vehicle.

<u>Phase V — Planetary Surface</u> — A remotely controlled system will be deployed to the surface from orbit to perform the required tasks. At the appropriate time, data and surface samples will be returned to the orbiting spacecraft.

The surface operation represents the greatest source of environmental data about the planet. To maximize this data collection, a roving vehicle is assumed. An area for surface operation was selected as an example, Figure 10. This particular area is between the Margaritifer Sinus and the Meridiani Sinus at the

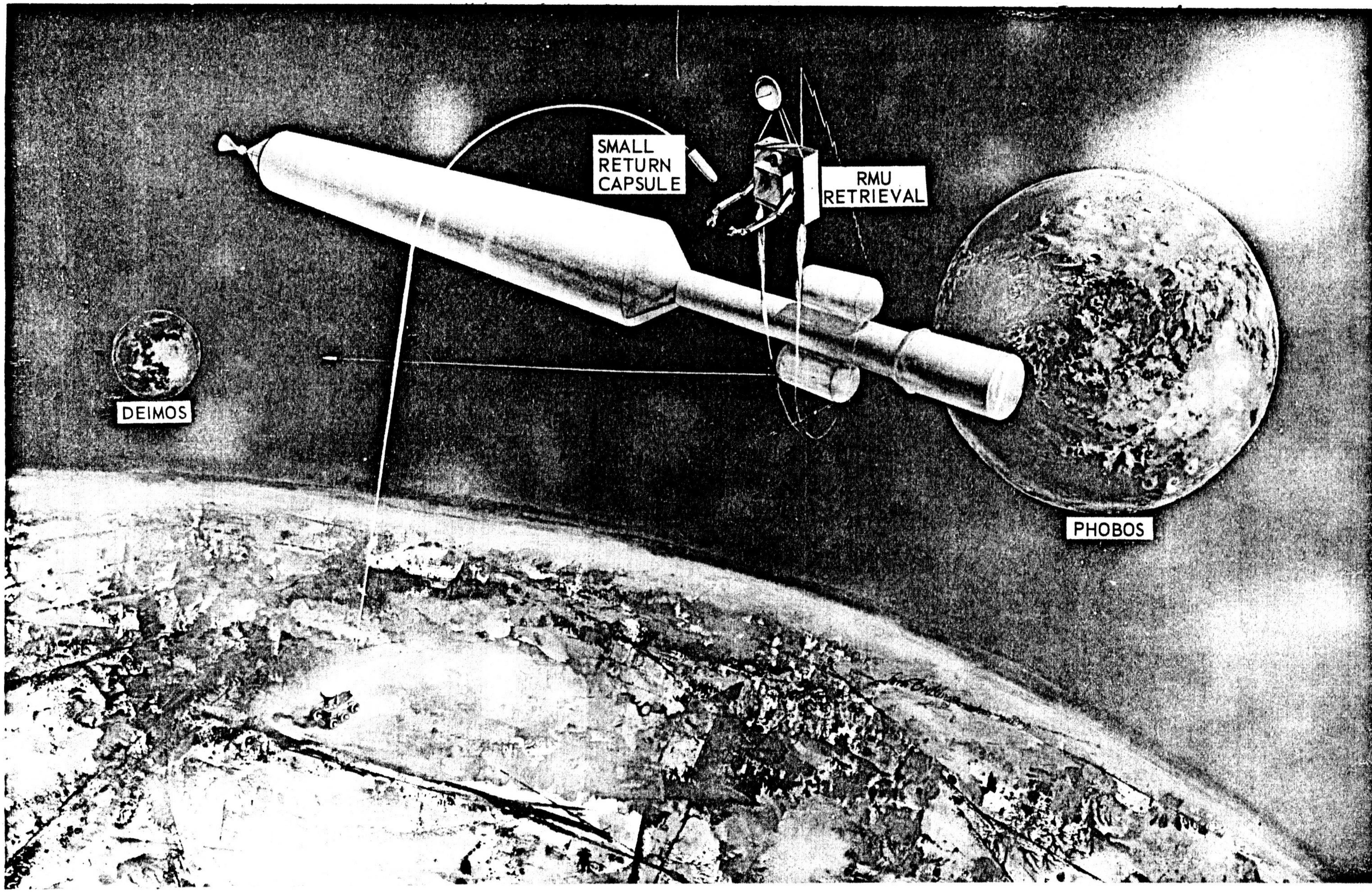


FIGURE 9 MARS EXPLORATION

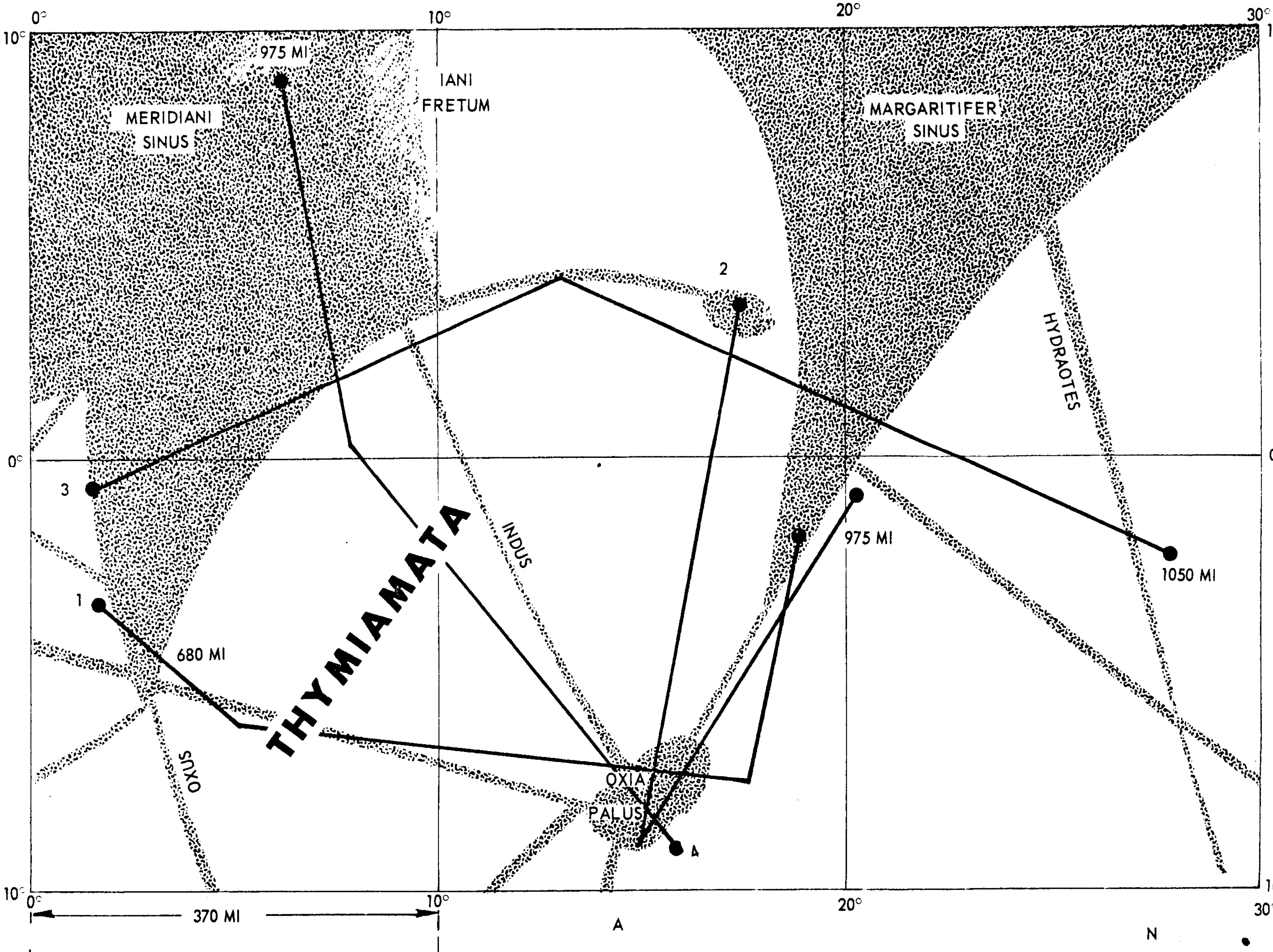


FIGURE 10 TYPICAL ROVING OPERATIONS

equator of Mars and is one of the most likely selected sites for future manned landing. Some typical roving vehicle tracks are presented ranging in distance from 630 to 1050 miles.

The time on station for this operation is assumed as 30-50 days. This period is in agreement with the stated period in references 1 and 2. During this period, the roving vehicle shall conduct the task of determining the meteorological, biological, and planetological conditions.

Phase VI — Cisplanetary Return — When the proper launch window occurs, the earth-return maneuvers are initiated.

Phase VII — Earth Capture and Re-entry — Deceleration is performed by a combination of retrothrusts and by executing successive passes through the earth's atmosphere to achieve a circular orbit. Following rendezvous in orbit, the crew transfers to a specialized landing module. The earth landing module re-enters and maneuvers to a landing area.

The preceding typical mission description has provided the point of departure necessary for determining the system requirements and identifying the role of man and machine.

3.3 SYSTEM REQUIREMENTS METHODOLOGY

The methodology presented in this section has been developed so that the requirements for man and machine may be delineated. The role of man in the loop is one of information management. This philosophy is carefully considered in the development of the methodology.

The flow diagram, Figure 11, illustrates the major steps in the determination of total system requirements.

3.3.1 Environmental Sampling Schedule

Appendix B reports, parametrically, the implications of three types of orbits — eccentric, circular, and synchronous — upon communication line of sight and total daily illumination of the remote surface module. These factors define the total available time each day that a man in the command module will have control of a given remote module on the Martian surface. Proper scheduling of environmental sampling is required for optimum utilization of the time that man has control of the remote module. Illustrative summary charts for scheduling environmental sampling are shown as Figures 12, 13, and 14.

Note that the eccentric orbit limits the daily operational time to about 12 hours; the circular orbit limits man to less than seven hours of operational time, which is distributed over nine periods of 40-45 minutes each; the synchronous orbit provides continuous contact. However, because the latter moves over the same surface area, it is limited in its range of reconnaissance and, hence, would be poor for the command modules alternate role of topographical survey of the entire planet.

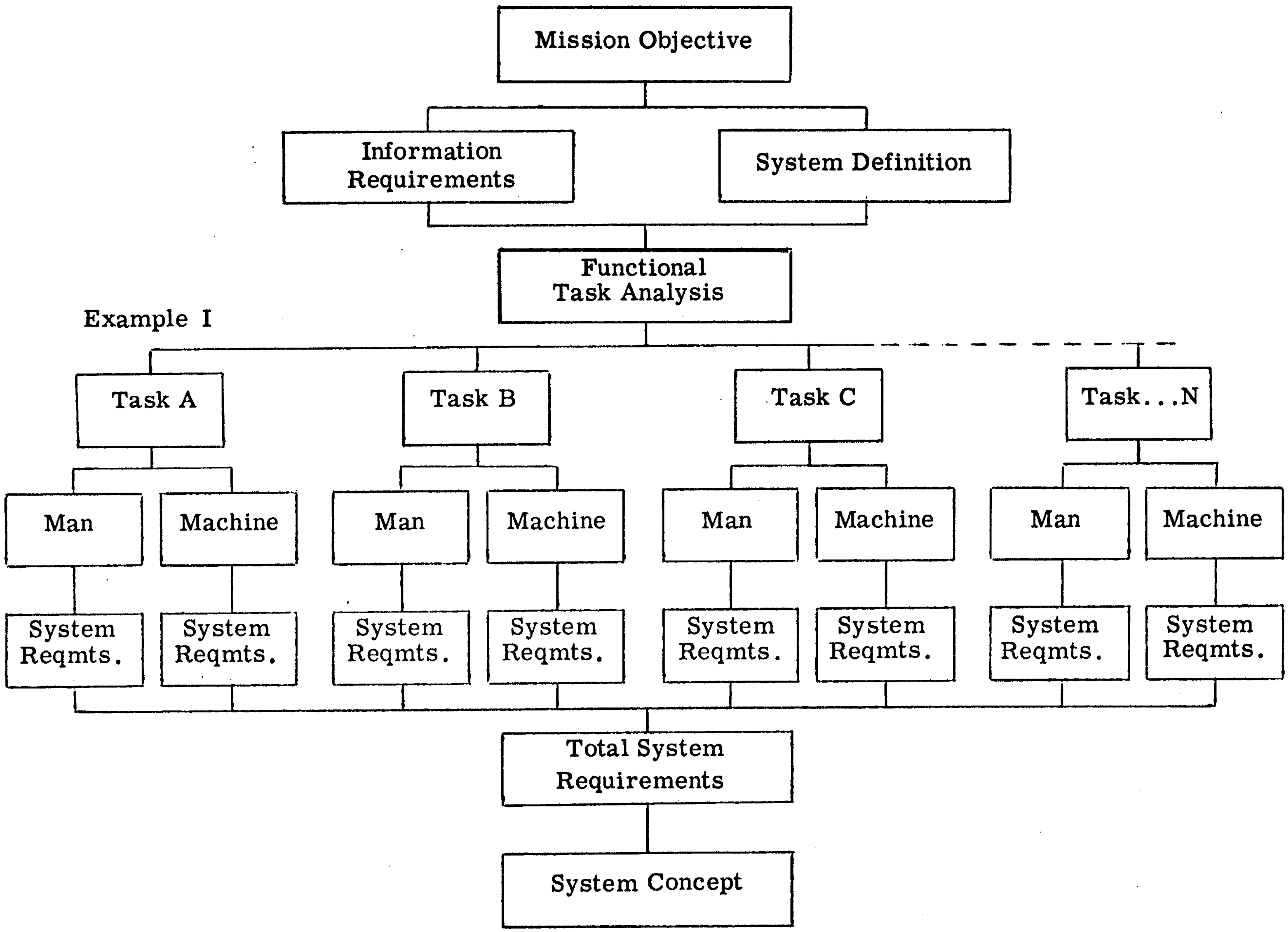
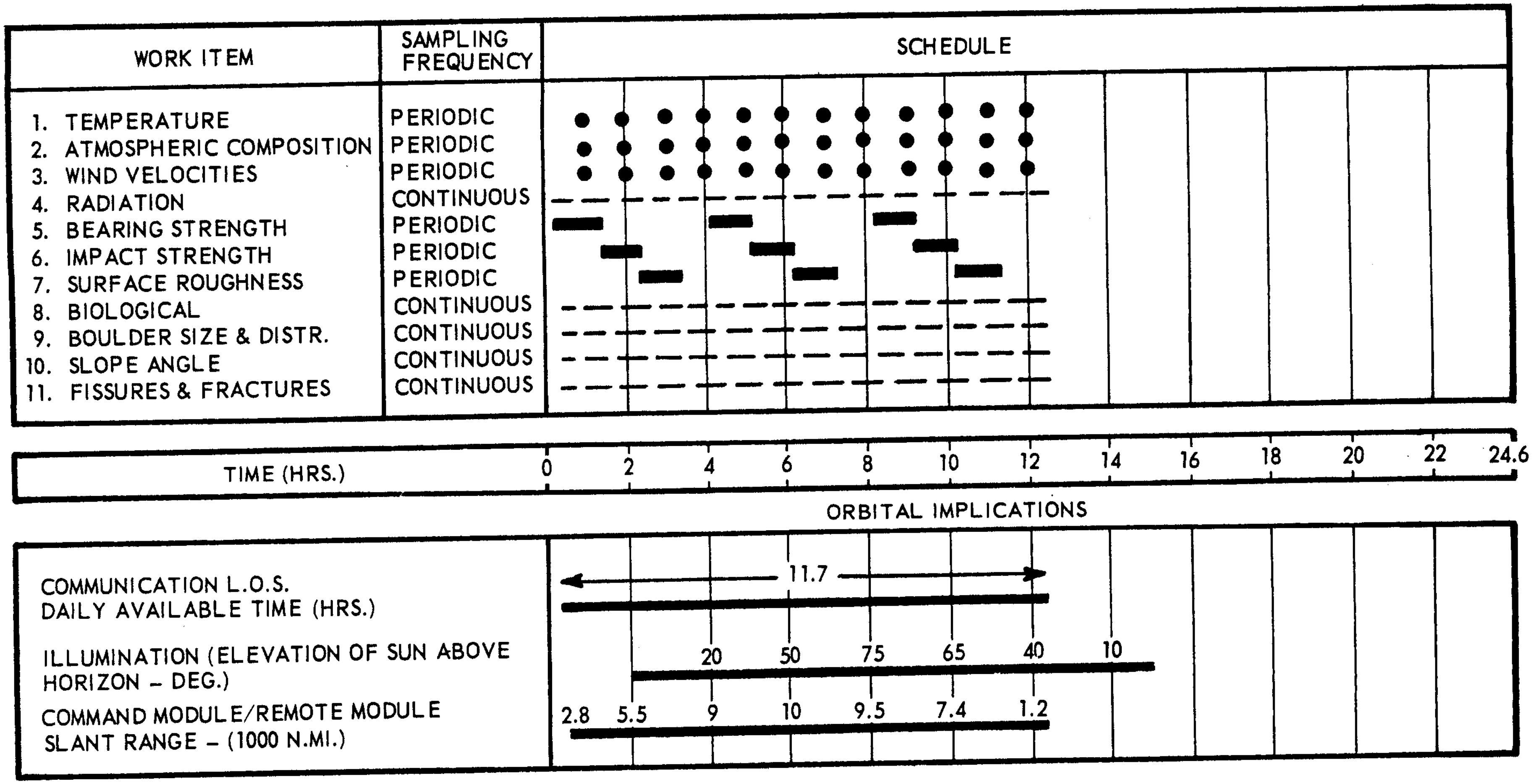


FIGURE 11 SYSTEM REQUIREMENTS FLOW DIAGRAM



NOTES:

1. ECCENTRIC ORBIT (REF. FIGURE B–6, APPENDIX B)

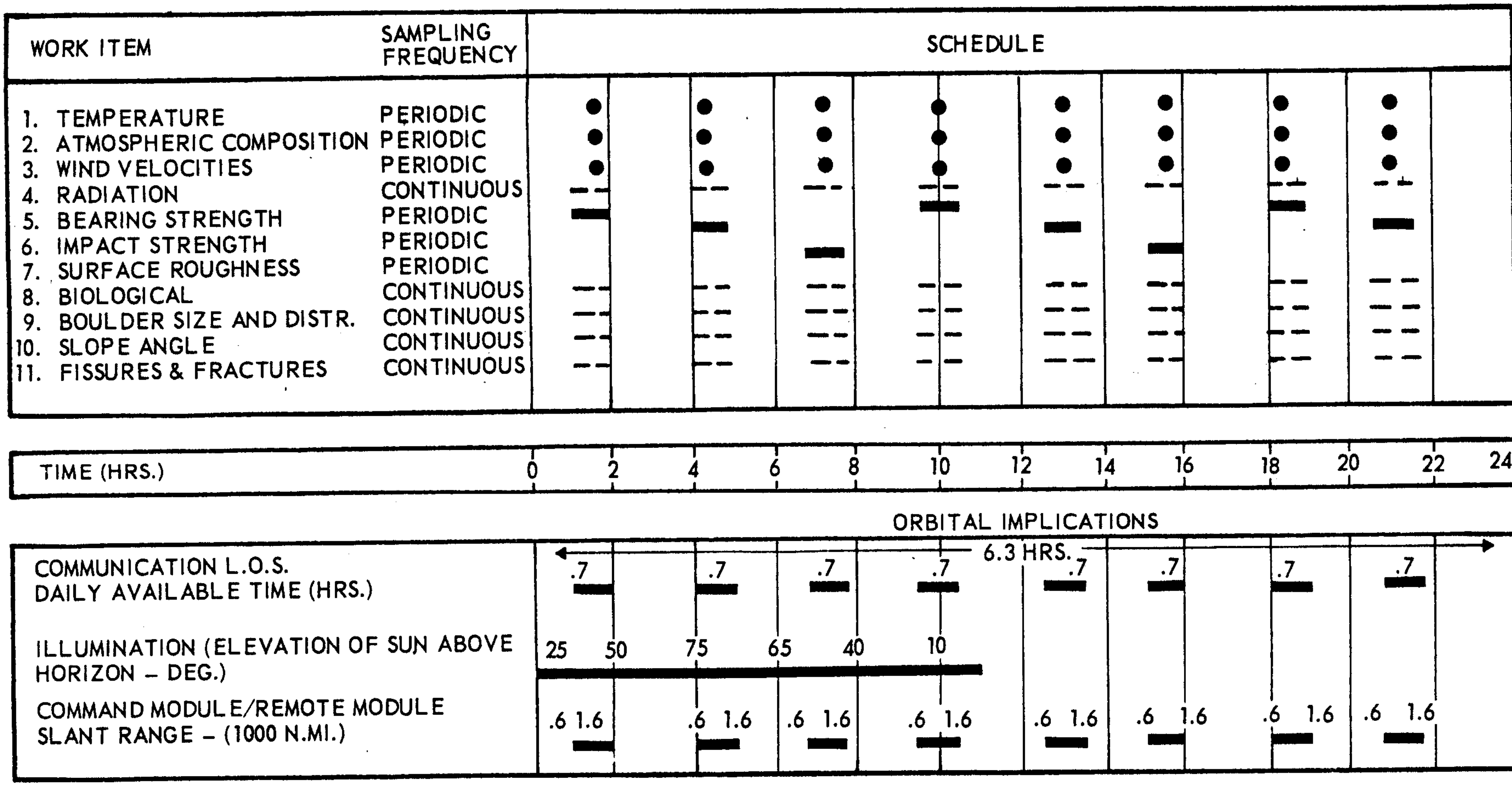
   PERI-APSIS = 600 N. MI.
   APO-APSIS = 9612 N. MI.

2. REMOTE MODULE LANDING SITE #2 (REF. FIGURE 2, APPENDIX B)

3. TWO-WAY TIME DELAY MIN. 0.014 SECONDS, MAX. 0.12 SECONDS

4. COMMAND MODULE ORBITAL PERIOD = ONE HALF MARTIAN DAY

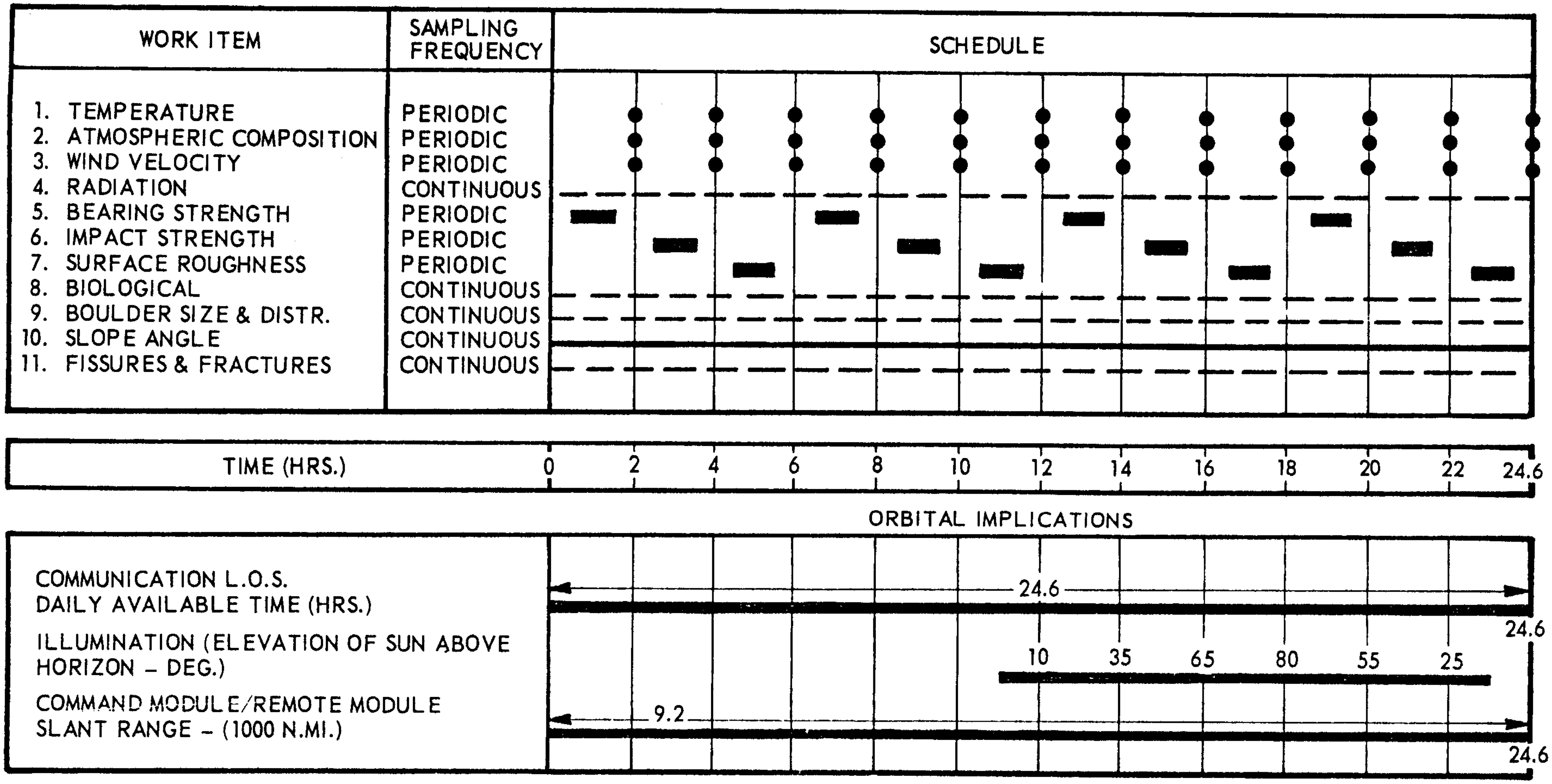
FIGURE 12 ENVIRONMENTAL SAMPLING SCHEDULE – ECCENTRIC ORBIT



NOTES:

1. CIRCULAR ORBIT, (REF. FIGURE B–29, APPENDIX B)
   PERI-APSIS = 600 N. MI.
   APO-APSIS = 600 N. MI.
2. REMOTE MODULE LANDING SITE #1 (REF. FIGURE 2, APPENDIX B)
3. TWO-WAY TIME DELAY APPROXIMATELY 0.006 SECONDS

FIGURE 13 ENVIRONMENTAL SAMPLING SCHEDULE—CIRCULAR ORBIT



NOTES:

1. CIRCULAR SYNCHRONOUS ORBIT (REF. FIGURE B–30, APPENDIX B)
   PERI-APSIS = 9199 N. MI.
   APO-APSIS = 9199 N. MI.
2. REMOTE MODULE LANDING SITE #4 (REF. FIGURE 2, APPENDIX B)
3. TWO-WAY TIME DELAY APPROXIMATELY 0.10 SECONDS

FIGURE 14 ENVIRONMENTAL SAMPLING SCHEDULE – CIRCULAR SYNCHRONOUS ORBIT

The operational times of both the eccentric and circular orbits could be extended by the availability of an additional remote vehicle on the opposite side of Mars, or by two additional remote vehicles approximately equally spaced. By sampling widely separated "continents," intelligence may be provided on different kinds of terrain and different periods of the day.

3.3.1.1 Orbital Profile Implications

3.3.1.1.1 Eccentric

Certain environmental parameters are said to be time-varying; e.g., one might expect considerably different data if they were collected at night rather than day. Examples are temperature, wind velocity, atmospheric factors, radiation, and biological. Conversely, terrain features or planetological data vary little with time.

Note in Figure 12 that sampling from an eccentric orbit with a period of one-half Martian day may not provide minimum temperature data and perhaps not maximum temperature data. Time sampling from predawn to early afternoon would not be suitable for many time-varying parameters. An eccentric orbit with one-third, one-fourth, or one-sixth Martian day would provide better sampling, but would tend to consistently miss certain periods each day.

Note also that the variable slant range introduces a variable time lag of up to approximately .12 second, which may present a tracking problem unless corrected by synthetic devices.

3.3.1.1.2 Circular

The daily circular orbit permits only periodic sampling throughout the Martian day. Like the eccentric orbit, it consistently omits certain intermediate time periods. However, with spot checks at two-hour intervals, the probability of missing important continuous data is minimized.

The short sampling periods may present a sampling problem of another variety. Continuous contact of less than an hour may be poorly adapted to certain sampling operations which require considerable set-up and testing time. Also, reconnaissance missions, which provide no assurance as to exactly when an object of interest will be noted, are poorly adapted to a 45-minute mission. This is especially true if macroorganisms or microorganisms should be detected, but would likely be lost during the two-hour interval of loss of contact. The possibility of loss of contact occurring when the remote module is in undesirable terrain presents a planning problem. The potential weight penalty should be considered for providing the remote module with multiple starting and stopping capability.

The circular orbit is best suited to mapping the Martian terrain from the command module due to its low altitude and encirclement of the planet. Because a single remote vehicle provides less than seven hours daily contact, the feasibility of additional remote vehicles should be considered.

3.3.1.1.3 Synchronous

The synchronous orbit may also be circular, but is distinct in moving over the same surface terrain. This is advantageous for control of a single remote vehicle, but poorly adapted to controlling two or more vehicles at great distances. As indicated earlier, it is unsuited for mapping the topography of the entire planet.

The circular synchronous orbit avoids the problem of variable time delays and permits continuous closed-loop control during night and day since the time delay is only about .1 second. However, the elliptical, synchronous orbits introduce a variable time lag of up to .18 seconds, which is within the lower limit of the critical region (reference Section 3.2.5.1.1).

The advantage of continuous line-of-sight communications is that it permits more time for task accomplishment, thereby allowing more tasks to be pursued, or tasks of particular interest to be pursuied for indefinite periods of time. Also possible is the staggering of work to relieve the operator workload.

The gross considerations of what is to be done and when must be followed by the allocation of functions to either man or equipment.

3.3.2 Allocations of Functions to Man and Equipment

The previous section discussed a method for scheduling of mission work items which is designed to effectively utilize the man but not overburden him.

Another factor for maximizing system effectiveness is to determine which system functions could best be taken away from the operator's control without sacrificing system performance and to assign these functions to equipment. The operator may continue to operate in a redundant or back-up role upon warning, and he is free to monitor the function periodically but does not require the continuous scan responsibilities of a primarily manned function.

The "search" or "no-search" requirement also provides an important basis for function allocation. Man is uniquely superior to equipment in his ability to detect minute stimuli, to interpret them correctly through perceptual constancy, and to make a decision on course of action. A requirement for search is one of the strongest indications of a manned function. An analysis of the various environmental parameters in terms of whether they are heterogeneous or present in only a relatively few positions is important. It follows that if a parameter is ever-present, little or no search is required to find it; whereas if it is sparsely distributed throughout an area, considerable search may be required.

Life detection is the most obvious illustration of a search function. Other illustrations are looking for suitable terrain for a manned landing, in terms of surface impact strength, and looking for a safe path for a manned roving vehicle, in terms of bearing strength or relative absence of topological obstacles — boulders, steep slopes, fissures, general surface roughness, etc.

3.3.2.1 No-Search Functions

If an environmental parameter is homogeneous, the sensor merely needs to be deployed, or perhaps be rotated, for the environmental stimuli to begin to impinge upon it. A decision must be made as to whether or not the parameter should be sensed continuously or only periodically by the sensor. This depends essentially upon whether the parameter is likely to change quickly or slowly with the passage of time.

In general, environmental data that do not require search, and are not essential to the safety and effectiveness of the translating vehicle itself, are continuously sampled and may be monitored only periodically by the operator. The data may be stored in a computer on the command module for analysis at leisure, or they may be transmitted directly without human meditation, depending upon the complexity of analysis. Data that do require periodic sampling may employ human initiation or may be initiated automatically. Another consideration is an evaluation of whether the data need to be displayed to the operator in order for him to manage the translating and navigating functions of the vehicle; for example, topological contour immediately forward of the vehicle in its direction of movement requires display. The general characteristics of topology elsewhere may or may not be mediated by the operator, depending upon whether or not he can contribute to acquisition of the continuously accrued, homogeneous data. This decision depends upon the variety in the terrain.

3.3.2.2 Search Function

Each of the work items requiring continuous search will likely be culminated by a series of distinct steps which must be accomplished. It is these steps, or subfunctions, which are the subject of subsequent allocation and man-machine loop analysis, for these effectively define the information and output requirement for the system. The specifics of the steps are unique to the item being measured and will require a considerable survey of current and projected techniques for sampling the parameter.

In general, the steps involved are: scan and discover, inspect via zoom lens, translate to the vicinity of the object, inspect with narrow-view lens, initiate sample collection (which may involve remote manipulator arms especially adapted to sampling requirements), sampling recovery, analysis, and data transmission. Post-sampling steps would include stowage of the sample collection equipment and return to an initial position.

The merits of real-time analysis of samples versus deferred analysis of samples are an area which requires further consideration. One of the surface mission objectives is to collect as much data as is feasible within the constraints of available time. One method of expediting the process might be to transmit the defining characteristics or symptons of the object sampled, rather than analyzing the data on locale and transmitting decisions. However, a factor against deferring analysis and decision-making would be the possibility that the reported data were later determined to be ambiguous or insufficient and a requirement for interrogation for more information became evident. This would imply that the vehicle should stay at the scene until something meaningful was established.

3.3.2.3 Function Analysis

Function analysis is the process of examining various human capabilities and machine capabilities and determining which is best suited for accomplishment of the function under consideration. The following presents an abbreviated list of areas wherein one or the other capability should be employed. A plus (+) before the statement represents a capability, and a minus (-) represents a limitation.

RELATIVE CAPABILITIES OF MAN AND MACHINE

	MAN		MACHINE
	DATA SENSING		
+	Can monitor low-probability events which occur in great number.	-	When there are a large number of possibilities and for each event a number of alternatives, the program complexity becomes too great to handle the events adequately.
+	Can detect and report information incidental to the primary activity.	-	Discovery and selection of incidental information not feasible in present design.
+	Can detect masked signals effectively in an overlapping noise spectrum.	-	May not be useful when noise spectra overlap signal detection.
-	Absolute threshold of sensitivity in various sense modalities is very low (judging distance, velocity, acceleration values).	+	Generally not as low absolute thresholds as the human's thresholds.
+	Not subject to jamming by ordinary methods.	-	Subject to disruption by noise sources and other countermeasures.

	MAN		MACHINE
	DATA PROCESSING		
+	Able to recognize and use the information (redundancy patterns) of the real world to simplify complex situations. Perceptual constancy permits recognizing the same object from a variety of vantage points and against a variety of backgrounds.	-	Little or no perceptual constancy; great difficulty in recognizing similar patterns in either spatial or time domain.
+	Can make inductive decisions in situations not previously encountered; can generalize from a few data.	-	No capacity for creative or inductive functions.
-	Computation is weak and relatively inaccurate. Optimal theory of games strategy cannot be routinely expected.	+	Can be programmed to use optimum strategy for high probability situations.
-	Channel capacity limited to relatively small information transduction rates.	+	Channel capacity can be made as necessary for the task.
-	Short-term memory is rather poor.	+	Short-term memory and access time is excellent.
+	Fair reliability in accomplishing a given purpose by different approaches; i.e., can be reprogrammed.	+	May have high reliability at increased cost and complexity. Especially reliable for routine repetitive functions.
+	Can handle a variety of transient overloads, and some permanent overloads, only with temporary disruption.	-	Transient and permanent overloads may lead to disruption of the system.
	DATA TRANSMISSION		
-	Relatively slow speed of response.	+	High speed of response is possible.
-	Performance may deteriorate with time.	+	Performance decrement relatively small with time.

	MAN		MACHINE

DATA TRANSMISSION (continued)

	MAN		MACHINE
+	Usually recovers with rest. Failure is usually gradual rather than complete.	-	Wear maintenance and product quality control is necessary. Repair of failure may be improved.
-	Can impart only small forces and for short durations; can tolerate only small imposed forces.	+	Can impart very large forces and can withstand very large forces for long periods of time.
+	Not especially good at tracking, but may be satisfactory where situation requires frequent reprogramming. Can adapt to the situation; is best at position tracking with changes under three radians per second.	+	Good tracking characteristics may be obtained over a limited set of requirements.

ECONOMIC PROPERTIES

	MAN		MACHINE
+	Relatively inexpensive for the complexity provided.	-	Complexity limited by high costs and time.
+	In good supply.	-	Supply limited by cost and time.
-	Must be trained and retrained.	+	Performance is built in.
+	Light in weight and small in size for level of functioning achieved.	-	Equivalent complexity and functioning would generally require heavier components and enormous power and cooling resources.
-	Nonexpendable. In exceptionally hazardous situations, life support requirements may be excessive.	+	Expendable
-	Emotional and interested in personal survival.	+	Unaware of personal existence; performs without distraction from problems outside of the task.
+	Easy to maintain with a minimum of "in task" extras.	-	Maintenance and redundancy problems become disproportionately serious as complexity increases.

During the course of this study, a literature search was conducted to determine the maximum and minimum thresholds for certain physiological parameters. These data were selected to provide preliminary information to display designers and to attempt to categorize the nonlinearity and variability that is characteristic of man. The results of this literature search is presented in Appendix A. An illustrative format for the functional analysis is presented as Table 9.

3.3.2.4 Function Allocation

The assignment of functions to the human or to the machine should not be viewed as a competitive process, but rather the objective is to determine in what manner the capabilities of man and machine may be best employed in order to maintain specific system parameters within selected tolerances. As indicated previously, the man or machine may fit in at various levels of management and may hold this responsibility only under certain conditions. The function allocation summary chart should define the working relationship between man and equipment to a level adequate for subsequent analyses.

Table 10 presents a more advanced data collection format for conducting a function analysis. A refinement of the usual procedure of placing an "X" under the appropriate "Man" or "Machine" column following function analysis is to place a percentage value under the appropriate heading indicating the proportion of responsibility assigned to that function. To illustrate, if for a given parameter the man decided at every phase of the mission whether system tolerances are within desired limits,

TABLE 9

FUNCTION ANALYSIS

SUBPHASE —
Surface Reconnaissance Translating Mode

FUNCTIONS	SUBFUNCTION	COMMAND MODULE (MAN) Moni-toring	COMMAND MODULE (MAN) Control	COMMAND MODULE (MAN) Compu-tation	REMOTE VEHICLE Control (Servo)	REMOTE VEHICLE Control Automata
1. Vehicular Locomotion Management						
° Position and Course	° Establish vehicles surface location	x		x		
	° Evaluate position with respect to selected exploration site	x		x		
	° Establish recommended course	x		x		
	° Maintain course unless pre-empted by high priority objects of interest (see below)	x	x			
° Ground Path	° Establish and maintain course	x	x			
	° Maintain vehicular attitude within safe limits	x	x			
	° Maintain planned velocity and acceleration profile	x	x			
	° Take contingency action (avoid obstacles, switch to redundant modes)	x	x			x
2. ° Environmental Data Collection	° General Functions only					
° Homogeneous parameters	° Set-up sensors, checkout	x	x		x	
° Atmospheric composition and forces	° Deploy sensors		x		x	
	° Rotate sensors (if required)		x		x	
° Radiation	° Transmit and store data				x	x
	° Monitor periodically (if required)	x				x
	° Take contingency action	x	x		x	x
° Hetrogeneous parameters	° Observe general scene through 360° rotation, wide-angle view	x				
° Density	° Select (Gross)					
° Hardness	° Change to narrow view; move zoom lens	x			x	
° Resistivity	° Change field of view, select area by moving TV camera	x	x		x	
° Magnetivity	° Establish range to target	x				
° Roughness	° Traverse					
° Boulder size ° Boulder distribution	° Orient target with vehicle's attitude, heading	x	x		x	
° Slope angles ° Fissures/fractures	° Align vehicle's course with target	x	x			
	° Move vehicle toward target (see above)	x	x			
	° Select (fine) - view with narrow view lens	x	x		x	
	° Deploy sensors (sample collector)		x		x	x
	° Collect sample (pick up), recover sample, analyze, transmit data, stow equipment (procedures are unique to sampling operation)	x	x	x	x	

TABLE 10

FUNCTION ALLOCATION SUMMARY

Parameters	Tolerance Data		Responsibility for Assessing if Parameters Are Within Tolerances		Responsibility for Selecting Corrective Action (If Action Required)		Responsibility for Deciding Whether Corrective Action Was Effective		Remarks
	Desired Value to be Maintained	Discrepancy from Value Permitted	Man	Machine	Man	Machine	Man	Machine	

plus or minus a discrepancy, then a value of 100 would be placed under the "Man" heading. If man and machine share equally in the selection of appropriate corrective action, then a value of 50 would be placed under both "Man" and "Machine" headings. Under the remarks column would be given the conditions under which one or the other would assume responsibility. If man always decides when corrective action was effective in implementing control, then a "100" is placed under this column. In general, the remarks column is used to provide a rationale for the decision based upon the relative capabilities of man and machine in this area.

The derivation of tolerance data for this type of analysis is generally not available at this stage of development, but it is not mandatory that specific values be defined before function assignments can be made. The advanced data collection format is an approach to the problem which has not been previously employed and may prove useful in subsequent definition of equipment requirements.

The analysis that more directly affects hardware requirements is the complete system loop analysis.

3.3.3 Man/Machine Loop Analysis

The man/machine loop analysis is a continuation of the analytic process which defines the personnel functions and equipment functions for the system. The loop analysis shall specify the system requirements for the remote man/machine system at the five interfaces described in Section 3.2.4.1.

The loop analysis considers:

1. Operator information requirements
2. Human engineering display requirements
3. Display physical requirements and display medium
4. Data to be sensed
5. Display visual change
6. Computations
7. Data transmission requirements
8. Display data conversion requirements
9. Remotely controlled function requirements
10. Remotely controlled system requirements
11. Operator control function

The consideration of these 11 steps provides the design crtieria for generation of system concepts. To illustrate the methodology, Tables 11 through 13 are presented. The example used relates to the task of general observation and locomotion.

The total system requirements for the RMMS is obtained from a summation of the Tasks A...N, as shown by Figure 11, Section 3.3, which are necessary to accomplish the mission objective of "Conducting Detailed Reconnaissance of the Martian Surface and Its Environment."

MAN/MACHINE LOOP ANALYSIS

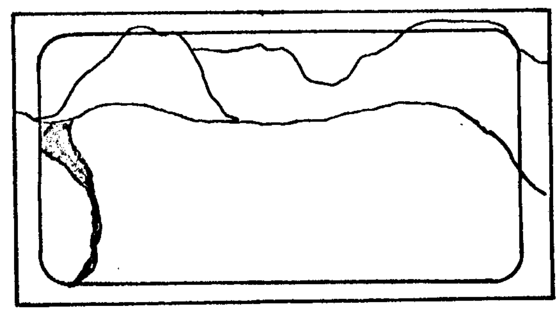
Operator Information Requirements	Human Engineering Display Requirements	Display Physical Requirements and Display Medium	Data to Be Sensed
° Observation to define general scene	**Visual Cues** ° Orient the scene ° Est. size ° Distinguish shapes ° Distinguish color **Integration** ° TV monitor ° Operator Function ° Subjective transformation of the displayed scene into the actual environment on surface below ° Function use of Information ° Input for control ° Input for general reconnaissance Sample	° Actual reproduction of scene on Mars surface as viewed by TV camera ° Scene oriented to remote vehicle ° Black and white ° Color ° Variable scan rate  Visual Display	° Optical view of the scene

TABLE 11A

MAN/MACHINE LOOP ANALYSIS

Display Visual Change	Computations	Data Transmission Requirements	Display Data Conversion Requirements
° Actual change of scene as viewed through TV camera on surface	° Range ° Slope	° TV scene at selected scan rate ° Range ° Angular measurement e.g., slopes	

Sample

TABLE 11B

MAN/MACHINE LOOP ANALYSIS

Remotely Controlled Function Requirement	Remotely Controlled System Requirements	Remotely Controlled System	Operator Control Function
° Optical viewing ° Variable data rate ° Capability for viewing 360° from point of observation ° Large field of view, low resolution ° Small field of view, high resolution ° Distinguish shapes ° Distinguish color ° View dark areas; e.g., caves and holes ° See over objects	° TV camera ° Variable scan rate ° 360° AZ capability for camera ° Wide angle and narrow angle lens system ° Black and white TV TV camera system ° Color TV camera system ° High intensity light source ° Vertical (20 feet) capability for TV camera	° Videcon tube with shutter and assoc. electronics for variable read out ° Turret with fixed camera and AZ position read out ° Lens system with zoom capability ° Redundant camera system for black-and-white and color ° High intensity light source mounted on turret with camera ° Aux. videcon on 20-foot telescoping pole	° On-Off — TV system ° Scan rate — Adj. ° Camera AZ control ° Zoom control ° Mode or system selection ° On-Off — Light ° On-Off Aux. camera ° Height control ° Zoom control

Sample

TABLE 11 C

MAN/MACHINE LOOP ANALYSIS

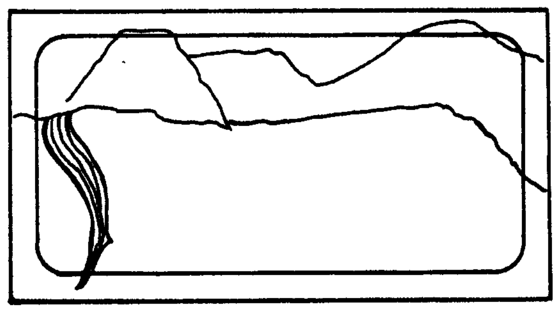
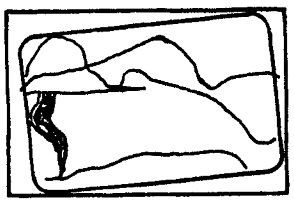
Operator Information Requirements	Human Engineering Display Requirements	Display Physical Requirements and Display Medium	Data to be Sensed
° Locomotion - Vehicle Attitude - Pitch - Roll - Heading	**Visual Cues** | **Integration** ° Vehicle oriented frame | ° Visual display ° Digital Indicator ° <u>Operator Function</u> Sense attitude of remotely controlled surface vehicle plus prediction of results based on continuation of present condition ° <u>Function use of Information</u> ° Input for control of velocity and heading	° Frame represents windshield oriented to vehicle attitude — visual display  Sample	° Vehicle attitude pitch roll Heading azimuth

TABLE 12A

MAN/MACHINE LOOP ANALYSIS

Display Visual Change	Computations	Data Transmission Requirements	Display Data Conversion Requirements
° Scene is stable ° Reference to vehicle position 	<u>Sliding</u> $V_S = \sqrt{gm\ r_c}$ <u>Tipping</u> $V_T = \sqrt{\dfrac{gm\ r_c N}{H}}$ <u>Acceleration</u> ° Frictional soil $a = gm \tan \emptyset$ ° Plastic soil $a = \dfrac{Ac\ gm}{w}$ r_c = turn radius gm = gravity N = dist. from G. G. to wheel H = height of C. G. $\emptyset$ = angle of friction w = norm. force c = coeff. of soil cohesion	° Course Memory trace Local terrain ° Digital output of velocity vectors ° Attitude ° Heading ° Range ° Range rate to selected target ° Sliding ° Tipping ° Acceleration	° Screen scan rate variable ° Digital display of velocity ° Screen sweep intensity modulation ° Memory trace ° Tipping warning ° Sliding warning

Sample

TABLE 12 B

MAN/MACHINE LOOP ANALYSIS

Remotely Controlled Function Requirement	Remotely Controlled System Requirements	Remotely Controlled System	Operator Control Function
° Maintain stable scene ° Sense - Attitude - Tipping - Sliding - Acceleration - Velocity Vector	° Stabilized camera for visual display ° Attitude Sense for vehicle orientation	° Television ° Computer ° Attitude sensors ° Directional reference ° Inertial table ° Power drive ° Power source ° Data transmission ° Data storage ° Accelerometers	° Scan rate ° Velocity ° Direction

Sample

TABLE 12C

MAN/MACHINE LOOP ANALYSIS

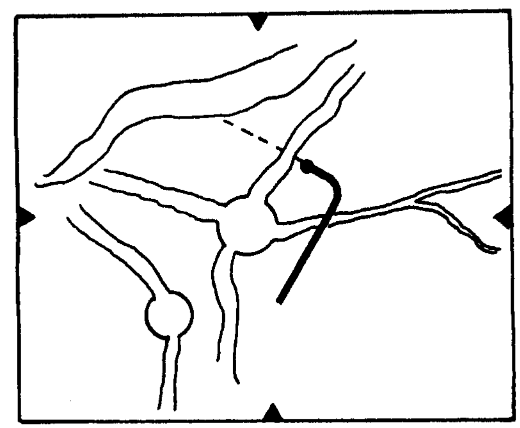
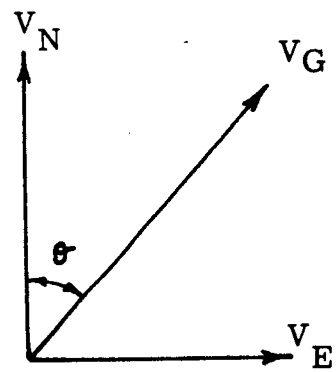
Operator Information Requirements	Human Engineering Display Requirements	Display Physical Requirements and Display Medium	Data to be Sensed
° Locomotion Determine situation of remote controlled surface vehicle Sa	**Abstract Cues:** ° Symbol line super-imposed over repre-sentation of Mars surface **Integration:** ° Situation display ° Operator function - Subjective transformation of analogous information into real situation of Mars surface below - Prediction of results based on continuation of present conditions ° Functional use of information - Inputs for control mple	° A decaying line or memory trace will appear behind the surface vehicle symbol on situation display ° Length of memory trace will be a function of ground speed  Situation display w/memory trace and prediction	° Ground velocity ° Heading

TABLE 13A

MAN/MACHINE LOOP ANALYSIS

Display Visual Change	Computations	Data Transmission Requirements	Display Data Conversion Requirements
∘ Angular position change of decaying trace line	The course angle is referenced  $V_G = \sqrt{V_N^2 + V_E^2}$ where components V_N = Vel. north V_E = Vel. east	∘ Velocity of remote machine referenced vectorially to north-east relationship	Map scale and map projection modified by ground speed input

Sample

TABLE 13B

MAN/MACHINE LOOP ANALYSIS

Remotely Controlled Function Requirement	Remotely Controlled System Requirements	Remotely Controlled System	Operator Control Function
° Velocity ° Reference direction ° Acceleration limits ° Tip or turn over safety limits	° Capable of traversing various types of terrain and slopes ° Flexible power capability for adapting vehicle to variable terrain situations	° Articulated wheeled vehicle ° Electrically driven and power control with magnetic clutches ° Free wheel to drive capability for all wheels	° Manual 0-max velocity control ° Forward and reverse switch ° Manual direction control

Sample

TABLE 13C

3.3.4 Time-Line Analysis

Figures 12, 13, and 14 in Section 3.3.1 illustrate the effects of orbital time factors upon scheduling of environmental data collection functions. Note that at this level, the details of sampling and specific tasks to be performed by man have not been assessed. However, following task analysis, the sequence of activities have been defined to such a level that estimates can be made of approximately how long it would take to accomplish a given task; e.g., environmental data collection for a given parameter. By comparing task times required to total time available per orbit, it is possible to calculate: (a) how much information can be processed on a given orbit, and (b) how many orbits would be required to collect all of the environmental data required. This information is very important for it establishes the feasibility of discovering all of the required information for a manned landing vehicle within the constraints of a single 30- to 50-day RMMS mission.

In order to collect realistic time data, it is necessary to consider the various elements of the man-machine loop: (1) data acquisition time; (2) transmission time; (3) system time constants; and (4) data management time, which includes reading and interpreting the displayed data, conversion of the data, decision-making, control actuation, and transmission time required to actuate manipulator arms (if required), etc. As indicated by Figures 12, 13, and 14, many of the activities will be concurrent; and overlap must be considered in calculating the total mission time. However, concurrent operations imply an increased system load and possible additional equipment, such as additional operator displays, controls, transmission channels, etc.

4.0 FUTURE WORK

Remotely controlled systems include a very broad spectrum of systems for space exploration. The selection of the Martian stream for evaluation is considered timely for advanced concepts while providing significant inputs to contemporary systems.

A series of studies and simulations are recommended for implementation.

The future work, considered near term, can be divided into two categories.

A. Study Phase

This includes the determination of system requirements, generation of system concepts, and the evaluation of these concepts.

B. Simulation Phase

This includes the investigation of variable time-delay problems to the remote man/machine control system, the determination of the minimum display and control requirements for task implementation, and a ground test breadboard of the system concept for evaluation.

A subsequent phase would include the design, fabrication, test, and evaluation in earth orbit and/or lunar orbit.

4.1 RECOMMENDED STUDY EFFORT FOR NEXT PHASE

The next logical step in the program is to implement the requirements methodology developed in this study. This effort would include the following:

1. Mission Definition and Refinement — To update the mission profile in support of the RMMS program.

2. Time/Distance and Space Mechanics Analysis — To establish tentative limits with respect to variable time delay.

3. Assess Parametric Implications to Operational Requirements — To determine the effects of increased launch weight, number of modules, and deployment methods upon operational requirements.

4. Allocation of Functions to Man and Equipment — To derive the functions to be performed by the RMMS and to allocate the functions to man, automatic systems, or manual override.

5. Man/Machine Loop Analysis — To specify the system requirements for the remote man/machine system at the five interfaces.

a. Man/Machine

b. Command Module/Communications

c. Remote Module/Communications

d. Remote Module/Sensor

e. Remote Module/Remote Environment

6. Task Scheduling and Work Load Derivation — To determine the utilization of available task time.

7. System Requirements Delineation and Summary — To summarize system requirements for the RMMS.

The results of this effort will provide the system requirements necessary for the generation of candidate systems for evaluation.

4.2 RECOMMENDED SIMULATION EFFORT FOR THE NEXT PHASE

A. Variable Time Delay Effect on RMMS Concept

Considering the remote man/machine system requirements, it is noted that the combination of activities necessary for executing a task in most cases include remote visual observation, locomotion, and manipulation. It is the intent of this effort to perform somewhat complex tasks more nearly approaching those anticipated in the RMMS and evaluate the effects of variable time delay.

The work plan will include:

1. Review the latest contributions to the time-delay problem.

2. Develop a simulation plan. This plan must carefully consider the tasks and events anticipated in the Remote Man/Machine System. Time delays on the order of zero to two seconds are to be included as well as provisions for variable delays that might be encountered by the relationship of an elliptical orbit and a surface roving vehicle.

3. Construct a simulation model. The envisioned model would be about 18" x 10" x 10" and would have the capability to be propelled via a variable speed electric motor and have some sort of manipulator. A variable delay would be provided in the control loop to simulate the time delay anticipated in an elliptical orbit about Mars. Simulations would utilize television loops.

4. Select test subjects. Test subjects will be selected and assigned to the program exclusively for assurance of a controlled experiment.

5. Perform simulated activities. Having developed a plan and selected the test subjects, the experiment shall be implemented, being careful to keep in mind the true application of the data. Based on preliminary results, the simulation plan shall be reassessed to assure a true simulation of the real situation is being approached.

6. Reduce and analyze data.

7. Define implications of time and distance to the Remote Man/Machine System.

The importance of the results of this study is such that the design criteria for a Mars Capture of Flyby Mission may well be based on these findings. Therefore, care must be taken in the generation of data as well as the interpretation of results. The probability of mission success may well be affected by the quality of the time-distance considerations.

B. Determine Minimum Visual Information Required for Locomotion and Manipulation

A TV camera as a remote sensor and a visual display to provide the input to the man in the loop serves as an extension of man's eyes into the remote environment. The intent of this effort is to determine the minimum visual information required to perform specific mission tasks.

The work plan includes:

1. Review of the latest contributions in display and television sensor technology. Considerations of predictor displays and random noise injection techniques, analog versus digital systems will be studied, as they apply to the Remote Man/Machine System.

2. Parametric analysis shall be performed to select candidate systems for simulation tests.

3. Task selections, test plan development, and implementation of typical tasks anticipated in the Mars Exploration Mission will be selected. From these selected tasks, a test plan will be developed and implemented to obtain experimental data on minimum visual informational requirements.

4. Evaluation criteria will be developed to assess the relative effectiveness of various displays and sensors.

5. Visual displays and sensors will be evaluated (extent of this item to be determined).

6. Integrated display requirements will be determined.

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APPENDIX A

HUMAN SENSOR CAPABILITY PARAMETERS

PRELIMINARY STUDY

Remote Man-Machine Systems
NASA Contract No. NASw-744
LTV Astronautics
Life Sciences

Prepared by:

L. R. Carpenter
L. R. Carpenter
Life Sciences

FOREWORD

This paper has been compiled for designers of display systems for the RMMS.

Standard metric units have been used, and it is assumed that the reader is familiar with both engineering and biological terminology.

These data included charts and tables which have been selected carefully from the literature. The selection criteria have included discarding all animal data except for a very few cases, and these are clearly marked. Only those data verified and reducible to physical metric units applicable to the sensing of machine-generated displays were considered for inclusion. The scarcity of data in this report is indicative of the difficulty encountered when attempts are made to categorize the non-linearity and variability that is characteristic of man.

The tables in this report include the maximum and minimum thresholds for certain sensory modalities.

The references are by name and date of work, and where possible the references refer to the original work and not later work that verify the original.

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CONTENTS
(continued)

GLOSSARY

Scotopic Luminosity Curve

Levels where only the rod receptors (black and white perceptors) are functioning.

Photopic Luminosity Curve

Levels at which the cone receptors (color perceptors) are definitely functioning.

Fovea

Area of retina containing mostly cones receptors.

Periphery

Area of retina containing mostly rod receptors.

Lambert

One lumen per sq. cm.

Contrast

$$C = \frac{B_s - B_o}{B_o}$$

B_o = Brightness of surrounds

B_s = Brightness of test object

Visual Acuity

The reciprocal of the minimal effective visual angle in terms of minutes of arc. This notation is used in order to make high numerical values of acuity reflect high degrees of excellence in visual acuity rather than the reverse.

Troland

Unit of retinal illuminance equal to that produced by viewing a surface whose luminance is 1 candle per sq. cm. through an artificial pupil whose area is 1 sq. millimeter centered on the natural pupil. E (trolands) = A (sq. millimeter) x B (candles per sq. meter).

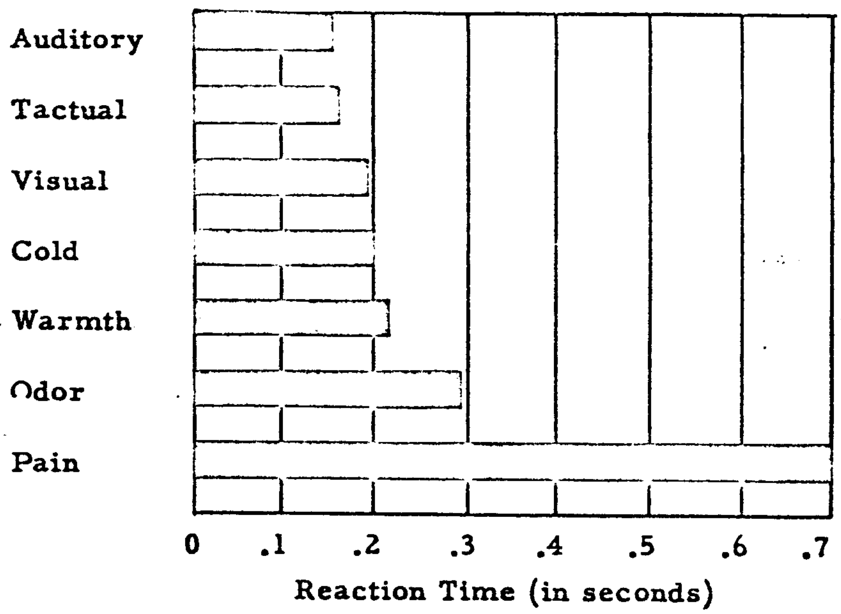
Sone

The loudness of a 400-cycle tone, 40 db above threshold.

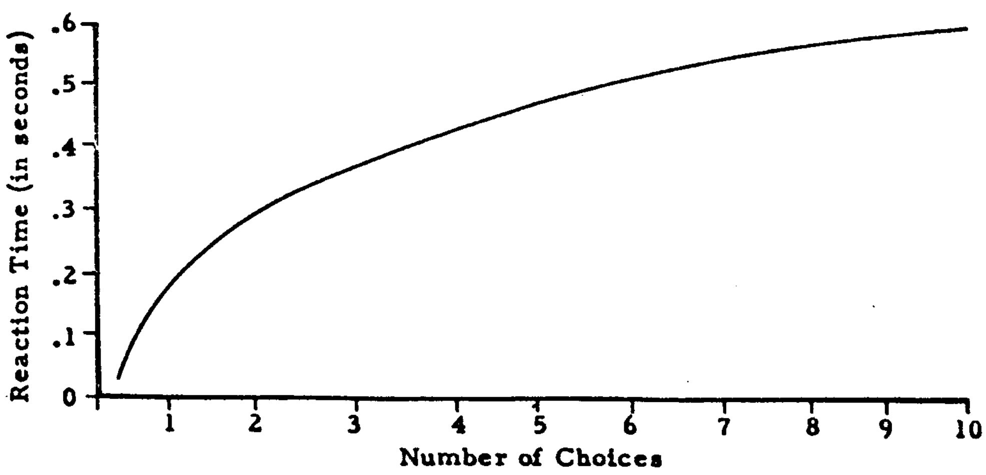
Mel

The pitch of a 1000-cycle tone, 40 db above threshold, is defined as 1000 mels.

REACTION TIMES



Simple reaction times for seven sense modalities, showing the time advantage of using sight, sound and touch as opposed to odor or pain. A number of factors increase the simple reaction time in real situations, for example the number of signals and choices to be made, as shown below.



Reaction times as a function of the number of choices, i.e. the number of signals, increases. The curve applies only when (1) each signal and response are perfectly paired and distinct, (2) there are no variables or distractions in the situation except the array of signals, and (3) the operator is practiced and well motivated. (From Ely et al., WADC TR 57-582, after Hick, Q. J. Exper. Psychol. 4: 11, 1952, and Teichner, Psychol. Bull. 51: 128, 1954.

CHART I — SENSORY INTENSITY RANGES

INTENSITY RANGE / SENSE	VISION	AUDITION	MECHANICAL VIBRATION	TOUCH PRESSURE	SMELL	TASTE	TEMPERATURE	KINESTHESIS	ANGULAR ACCELERATION	LINEAR ACCELERATION
Smallest Detectable	2.2 to 5.7 x 10^{-10} ergs (Ref. 1)	1 x 10^{-9} ergs cm^2 (Ref. 1)	For a small stimulator on the fingertip, average amplitudes of 0.00025mm can be detected (Ref. 6)	Varies considerably with body areas stimulated and the type of stimulator. Some representative values: ball of thumb - 0.026 erg.	Widely variant with type of odorous substance. Some representative values: Vanillin - 2 x 10^{-7} mg/m^3, Mercaptan (C_2H_5SH) — 4 x 10^{-5}mg/m^3, Diethyl ($C_2H_5OC_2H_5$) 1.0mg/m^3 (Ref. 8)	Widely variant with type and temperature of taste substance. Some representative values: Sugar 0.02 molar concentration. Quinine Sulfate 4 x 10^{-7} molar concentration. (Ref. 8).	Sensation of heat results from a 3-sec. exposure of 200 cm^2 of skin at rate of 1.5 x 10^{-4}gm-cal/cm^2/sec. (Ref. 8).	Joint movements of 0.2 deg. to 0.7 deg. at a rate of 10 deg/min. can be detected. Generally, the larger joints are the most sensitive. (Ref. 8)	Dependent on the type of indicator used: 1. Skin and muscle senses 1°/sec^2. 2. Nystagmic eye movements 1°/sec^2. 3. Oculogyral illusion 0.12°/sec^2. (Ref. 8)	In aircraft -0.02g for accelerative forces and 0.08g for decelerative forces (Ref. 8)
Largest Practical	Roughly, the brightness of snow in the mid-day sun, or about 10^9 times the threshold intensity (Ref. 2).	Roughly, the intensity of the sound produced by a jet plane with the after-burner or about 10^{14} times	Varies with size of stimulator, portion of body stimulated and individual. Pain is usually encountered about 40 db above threshold (Ref. 7).	Pain threshold.	Largely unknown.	Not known.	Pain results from a 3-sec. exposure of 200 cm^2 of skin at a rate of 0.218gm-cal/cm^2/cm. (Ref. 8).	Unknown.	Unconsciousness or "blackout" occurs for positive "g" forces of 5 to 8g lasting one sec. or more. (Ref. 9).	For forces acting in the direction of the long axis of the body, the same limitations as for angular acceleration apply.

CHART II — SENSORY INTENSITY DISCRIMINATION

SENSE		VISION	AUDITION	MECHANICAL VIBRATION	TOUCH PRESSURE	SMELL	TASTE	TEMPERATURE	KINESTHESIS	ANGULAR ACCELERATION	LINEAR ACCELERATION
INTENSITY DISCRIMINATION	Relative	With white light, there are about 570 discriminable intensity differences in a practical range (Ref. 1).	At a frequency of 2000 cps, there are approximately 325 discriminable intensity differences (Ref. 4).	In the chest region a broad contact vibrator with amplitude limits between 0.05 mm and 0.05 mm provides 15 discriminable amplitudes (Ref. 8).	Varies enormously for area measured duration of stimulus contact and interval between presentation of standard and comparison stimuli (Ref. 6).	No data available.	No data available.	No data available.	No data available.	No data available.	No data available.
	Absolute	With white light, 3 to 5 absolutely identifiable intensities in a range of 0.1 to 50 ml. (Ref. 3).	With pure tones about 3 to 5 identifiable steps (Ref. 5).	3 to 5 steps (Ref. 6).	Unknown.	No data available.	No data available.	No data available.	No data available.	No data available.	No data available.

VISION

Parameters of "Normal" vision applicable to data display systems	Maximum Threshold	Minimum Threshold	Explanation and Reference	Maximum Effective
Resolution		0.5 sec. of arc	A single line on a homogenous background may be resolved when it subtends on visual angle of 0.55 sec. of arc. Hecht & Mintz Hdb of Psychol.	Not applicable
Visible Spectrum — Scotopic	1050 m μ of intensity of = 100 decibels Fig. 1	400 m μ at intensity of 27 decibels. Fig. 1.	The human eye appears to be sensitive only to a limited band of radiation, and its limits depend on the intensity of radiation involved. See visibility curve. Hecht & Yun Hsia (1945)	511 m μ Fig. 2
Visible Spectrum — Photopic	980 m μ of intensity of -100 decibels Fig. 1	320 m μ of intensity of -47 decibels Fig. 1		554 m μ Fig. 2
Dark Adaptation	5 log m μ lamberts at T = 0	1.3 log m μ lamberts at T = 30 min.	The quantity of light intensity required for vision following various dark periods. Hecht, Haig & Wald (1935)	See Fig. 3
Brightness Discrimination	2.5 log visual angle in minutes for -5 log foot - lamberts Field intensity with test object contrast = 0.30	-0.1 log visual angle in min. for 3.2 log foot lamberts field intensity with test object contrast = 0.3	The size of the test object and the degree of contrast between test object and surrounds is important to discrimination. Blackwell (1946)	See Fig. 4
Visual acuity.	0.45 log visual acnity for 5 log trolands	-1.5 log visual acuity for -3 log trolands	Human visual ability to distinguish small spatial separations between portions of the visual field. Shlaer (1937)	See Fig. 5
Flicker Frequency	40 cycles per second for retinal illumination of 5 log trolands for object size of 20 minutes of arc or 50 cycles per second at 2 log millilamberts for large objects.	8 cycles per second for retinal illumination of 0 log trolands for object size of 20 minutes of arc or 2 cycles per second at -6 log millilamberts for large objects.	The critical flicker frequency (cff) is the flicker rate in flashes per second at which the field just becomes steady. This parameter is a function of contrast, illumination, test object size, and frequency of occurance. Hecht & Smith (1936)	See Fig. 6 & Fig. 7.
Size Discrimination	An object of 27 degrees in diameter may be distinguished at a distance of a length subtended by an angle of 120 degrees.	An object 2 degrees in diameter may be distinguished at a distance of a length subtended by an angle of 10 degrees	The ability to adjust the size of a comparison object at constant distance until it matches a standard object at a variable distance. Holway & Boring (1941)	See Fig. 8
The Limits of Stereoscopic-Vision (Unaided)	R_{lim}, 495 yds.	The minimum limits may be considered the same as for accommodation $\approx$ 25cm.	The limiting range, R_{lim}, of stereoscopic vision is the greatest at which an object can be just detected as nearer than an object at infinity. Graham (1960)	As near the point of accommodation as possible, $\approx$ 25cm.
Perception of Movement	Limited by the critical flicker frequency or visual acuity.	30 seconds of arc per second. Aubert (1886) Bourdon (1902)	Determinations of real movement involves the just perceptual movement of a stimulus through a distance S at rate ds/dt.	Not applicable.

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Horizontal and Vertical Angular Limits of the Human Visual Field

MOVEMENT PERMITTED	TYPE OF FIELD AND FACTORS LIMITING FIELD	HORIZONTAL LIMITS: Temporal Ambinocular Field (each side)	HORIZONTAL LIMITS: Nasal Binocular Field (each side)	VERTICAL LIMITS: Field Angle Up	VERTICAL LIMITS: Field Angle Down
a. Moderate movements of head and eyes, assumed as:	Range of fixation	60°		45°	
Eyes: 15° right or left 15° up or down	Eye deviation (assumed) Peripheral field from point of fixation	15° 95°	15° (45°)	15° 46°	15° 67°
Head: 45° right or left 30° up or down	Net peripheral field from central fixation Head rotation (assumed)	110° 45°	60°*** 45°	61° 30°*	82° 30°*
	Total peripheral field (from central body line)	155°	105°	91°	112°**
b. Head fixed Eyes fixed (central position with respect to head)	Field of peripheral vision (central fixation)	95°	60°	46°	67°
c. Head fixed Eyes maximum deviation	Limits of eye deviation (= range of fixation) Peripheral field (from point of fixation)	74° 91°	55° Approx (5°)	48° 18°	66° 16°
	Total peripheral field (from central head line)	165°	60°***	66°	82°
d. Head maximum movement Eyes fixed (central with respect to head)	Limits of head motion (= range of fixation) Peripheral field (from point of fixation)	72° 95°	72° 60°	80°* 46°	90°* 67°
	Total peripheral field (from central body line)	167°	132°	126°	157°**
e. Maximum movements of head and eyes	Limits of head motion Maximum eye deviation	72° 74°	72° 55°	80°* 48°	90°* 66°
	Range of fixation (from central body line) Peripheral field (from point of fixation)	146° 91°	127° Approx (5°)	128° 18°	156°** 16°
	Total peripheral field (from central body line)	237°	132°	146°	172°**

*Estimated by the authors on the basis of tests on a single subject.

**Ignoring obstruction of body (and knees if seated). This obstruction would probably impose a maximum field of 90° (or less, seated) directly downward; however, this would not apply downward to either side.

***This is the maximum possible peripheral field; rotating the eye in the nasal direction will not extend it, because it is limited by the nose and other facial structures rather than by the optical limits of the eye. The figures in parentheses on the line above are calculated values, chosen to give the maximum limit thus indicated.

NOTES

1. All data except as noted are from Hall and Greenbaum[6-3]

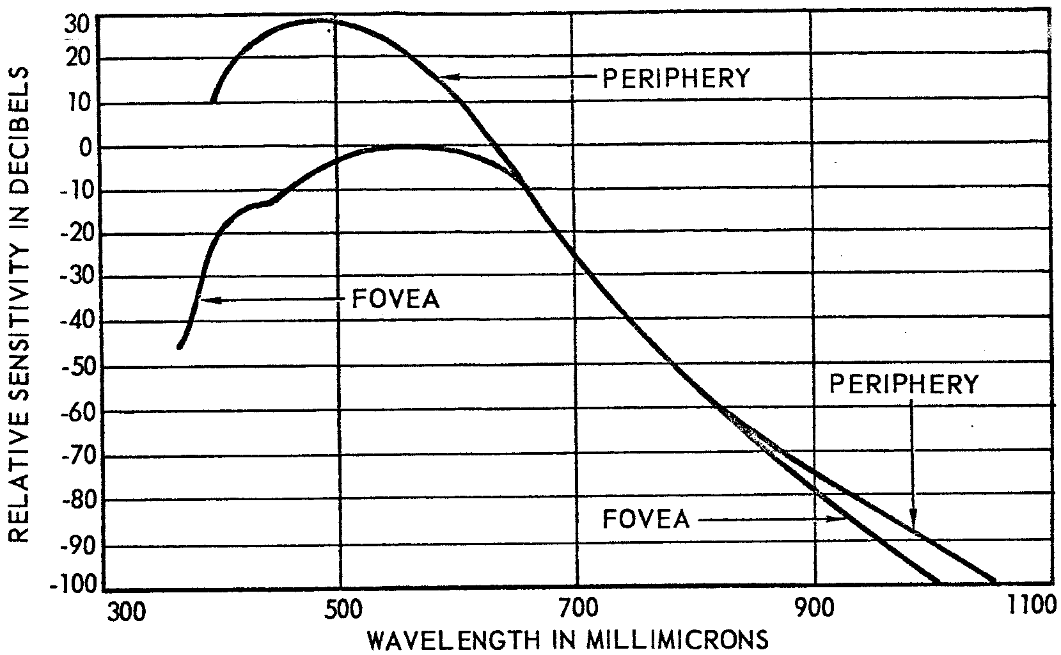
2. The ambinocular field is defined here as the total area that can be seen by either eye; it is not limited to the binocular field, which can be seen by both eyes at once. That is, at the sides, it includes monocular regions visible to the right eye but not to the left, and vice versa.

3. The term binocular is here restricted to the central region that can be seen by both eyes simultaneously (stereoscopic vision). It is bounded by the nasal field-limits of the eyes.

(Reference is to Hall and Greenbaum, Trans. Amer. Acad. Ophthal. Otolaryng., Sept.-Oct. 1950.)

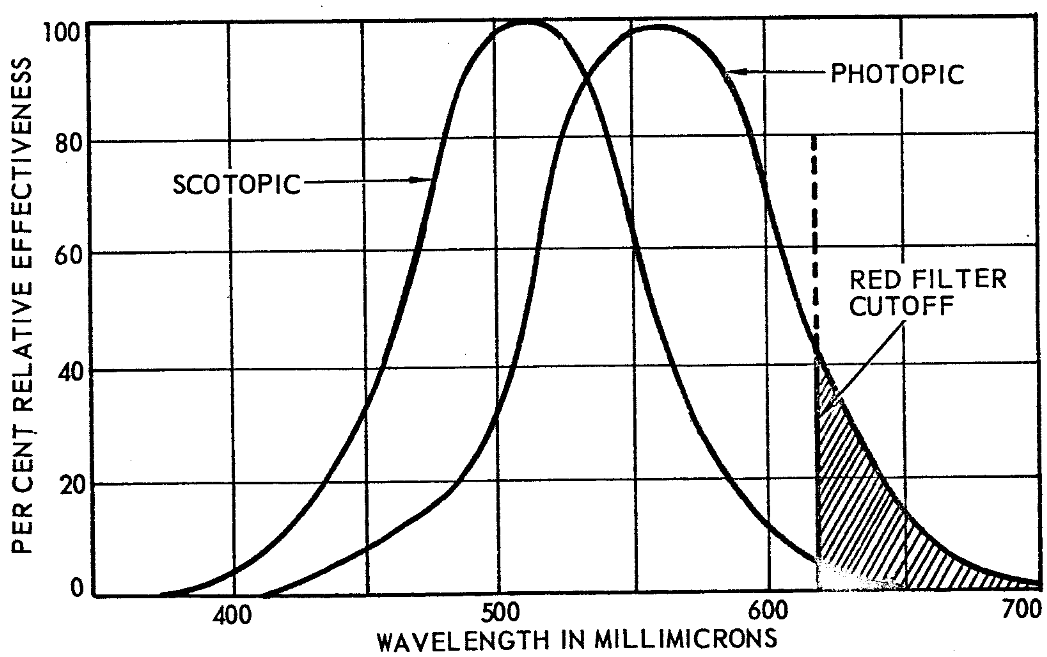
TABLE 2

(From Wulfeck et al., WADC TR 58-399, 1958.)



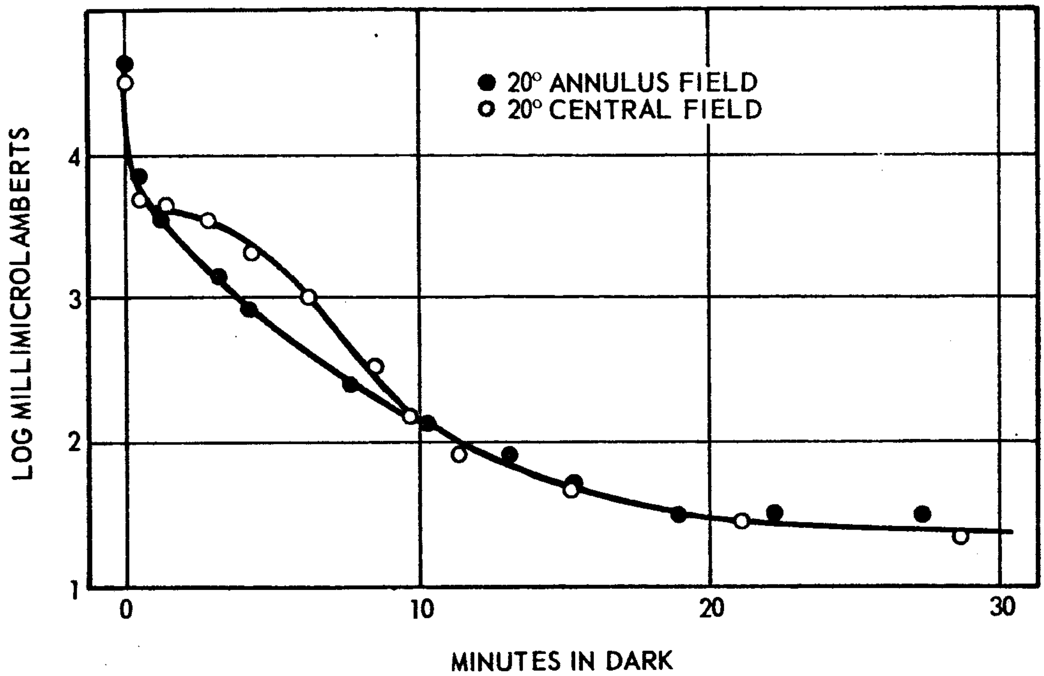
The relative spectral sensitivity of the dark-adapted fovea and the peripheral retina. The curves represent 1-degree test objects either fixated or placed 8 degrees above fixation, and exposed for 1 second. (From Griffin, Hubbard, and Wald, 1947.)

FIGURE 1



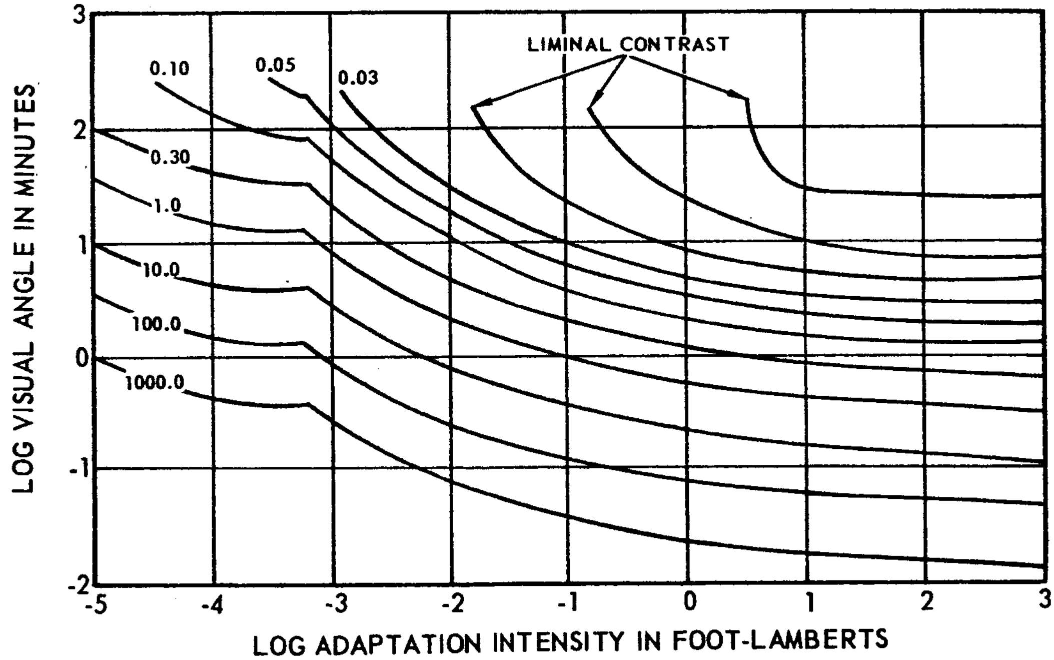
Luminosity curves for scotopic (rod) and photopic (cone) vision. Since the maxima are arbitrarily set at 100, these curves give no information about the relative sensitivity of the rods and cones. The vertical line indicates the place at which a common red filter cuts off. It transmits 1/10 of the light involved in the cone curve, and 1/100 of that in the rod curve. (Hecht and Yun Hsia, 1945.)

FIGURE 2



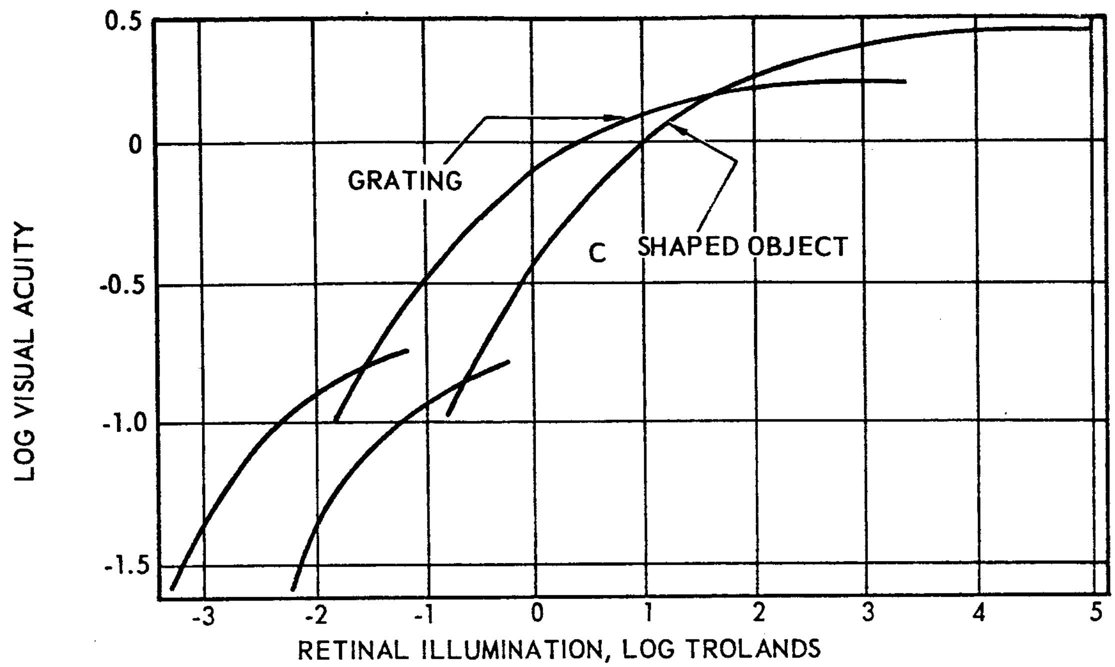
A comparison between thresholds under dark adaptation for a centrally fixated 20-degree field and for a narrow 1-degree annulus, 20 degrees in diameter. (Hecht, Haig, and Wald, 1935.)

FIGURE 3



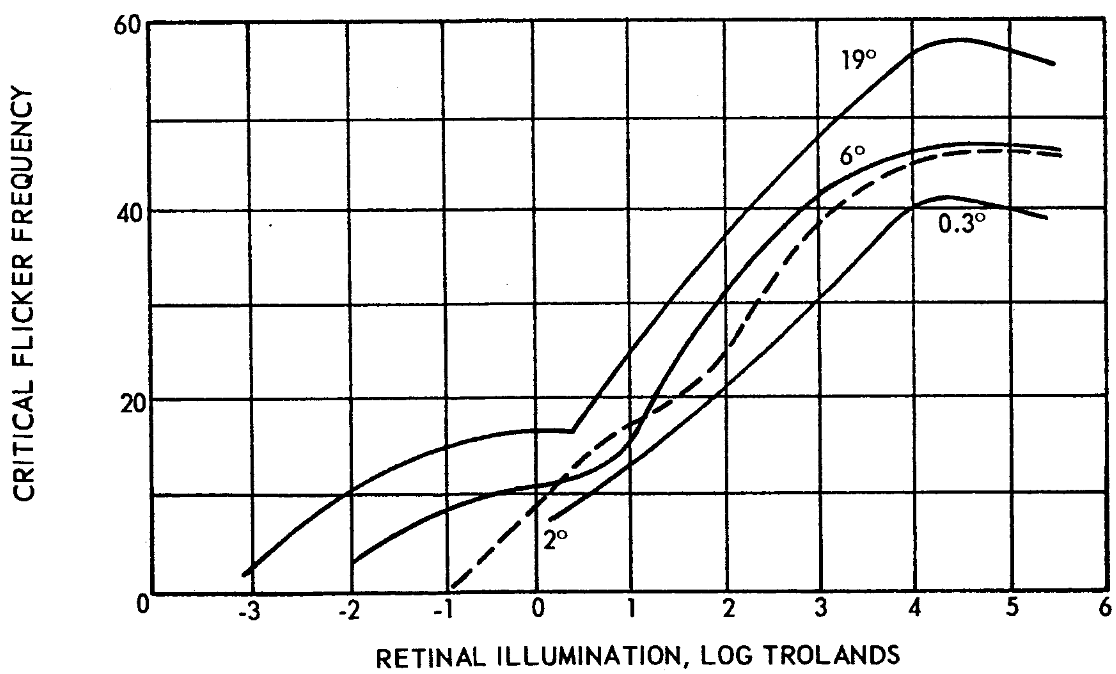
The relation between test-object area and adaptation level for test objects of threshold contrast with their background (field). Adaptation level is that produced by the stated intensity level of the field given on the abscissa. (Blackwell, 1946.)

FIGURE 4



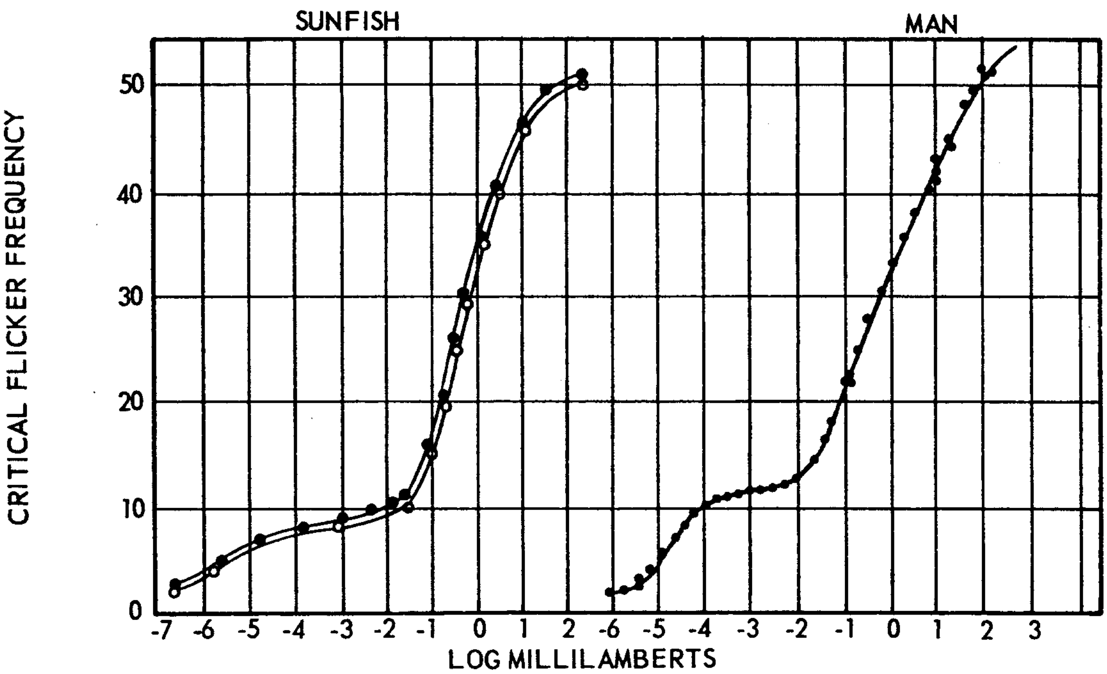
Curves showing visual acuity for two different test objects. On this log-log plot each curve appears to be composed of two segments. The lower segment represents rod function; the upper segment represents cone function. Below approximately 30 trolands the grating yields better visual acuity values, whereas the C is superior at higher intensities. At low intensities about ten times more light is necessary for the C than for the grating. (Shlaer, 1937)

FIGURE 5



Influence of the area of the test field on the relation between critical flicker frequency and retinal illumination. (Hecht and Smith, 1936.)

FIGURE 6

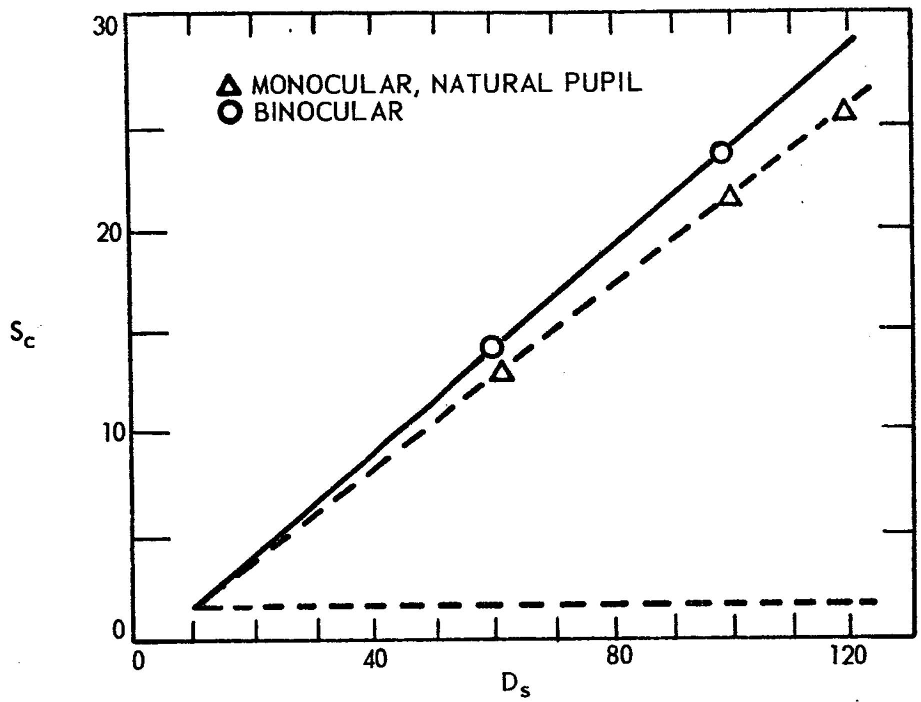


Left. Cff for the sunfish (Lepomis). The two curves are for two procedures: (1) in which the rotation of the stripes was held constant, and the illumination was varied to obtain the cff (open circles), and (2) in which illumination was held constant at each of the various levels, and the rotation speed was varied to obtain the cff. *Right.* Cff for man. Same type of apparatus used as with lower animals, i.e. a revolving drum with alternate black and white stripes. The data shown were taken on a series of successive days, after considerable practice. Each plotted point is the mean of ten readings. (Crozier, Wolf, and Zerrahn-Wolf, 1937b.)

FIGURE 7

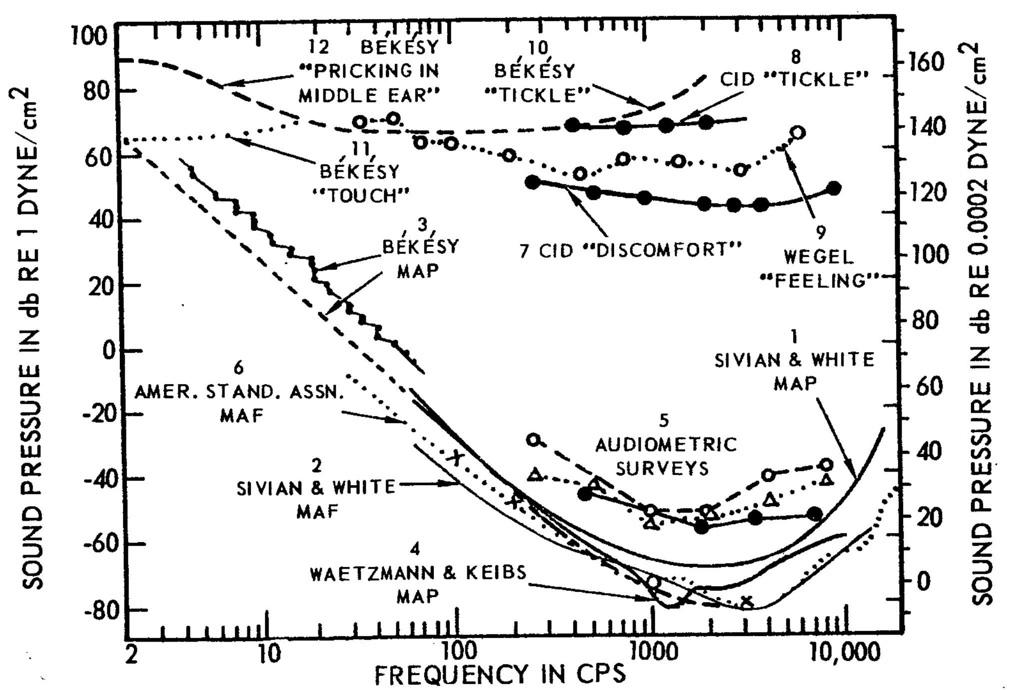
HEARING

Parameters of "Normal" Hearing applicable to data display systems	Maximum Threshold	Minimum Threshold	Explanation and Reference	Maximum Effective
Absolute threshold for sound	20,000 cycles per second at sound level of - 60 db re 1 dyne/cm^2 literature not consistant. See Fig. 8	20 cycles per second at sound level of 20 db re 1 dyne/cm^2 Literature not consistant. See Fig. 8.	The intensity at which a sound is just discriminable from silence is called the absolute threshold for that sound. Sivian and White (1933) Fig. 8	Fig. 9
Differential threshold for sound	4,000 cps must be raised 2.6 db above threshold of 5 db. approximation See Fig. 9 for finer estimate.	63 cps must be raised to 5.7 db. above threshold of 5 db. Approximation See Fig. 9 for finer estimate.	The differential threshold is an inverse measure of discriminatory capacity. It answers the question: How small a change in sound stimulus can an average observer detect? Riesz (1928)	Fig. 10
Loudness	See Fig. 8, Curve 7, Discomfort as a function of sound pressure and frequency	See Fig. 8, Curve 7, Discomfort as a function of sound pressure and frequency	Loudness is a dimension of auditory experience, and is consequently subjective. However empirical values have been established See glossary for defination of sones. Stevens & Davis (1938)	Increments in the region of 300 cps at an intensity of 60 db re 0.0002 dyne/cm^2, Fig. 11.
Pitch	Same as for loudness	Same as for loudness	Same as for loudness. See glossary for defination of Mels. Stevens & Volkmann (1940)	Increments in the region of 300 cps. Fig. 12.
Sound Masking	10,000 cps at 80 db against background of 60 db re. 0.0002 dyne/cm^2	Quiet background, see Fig. 8, Curves 1 through 6.	The ability to distinguish a particular sound from a background of sounds. Hawkins and Stevens (1950)	Fig. 13
Temporal effects in hearing 1. Differential threshold as function of duration	Not applicable	Signal durations less than 30 milliseconds are not discernable.	The ability to perceive subsequent increments of a pulse signal. Fig. 14a Garner and Miller (1944)	Sound increments that last 0.5 sec. are as readily detectable as longer ones, but shorter durations require greater intensity.
2. Duration thresholds	Above 1000 cps the threshold is milliseconds for predominate pitch	Below 1000 cps 2 or 3 cycles of the signal must be heard for a predominate pitch	The shortest duration at which the listener can just discern pitch (Click or tone) Doughty and Garner (1947)	Fig. 14b



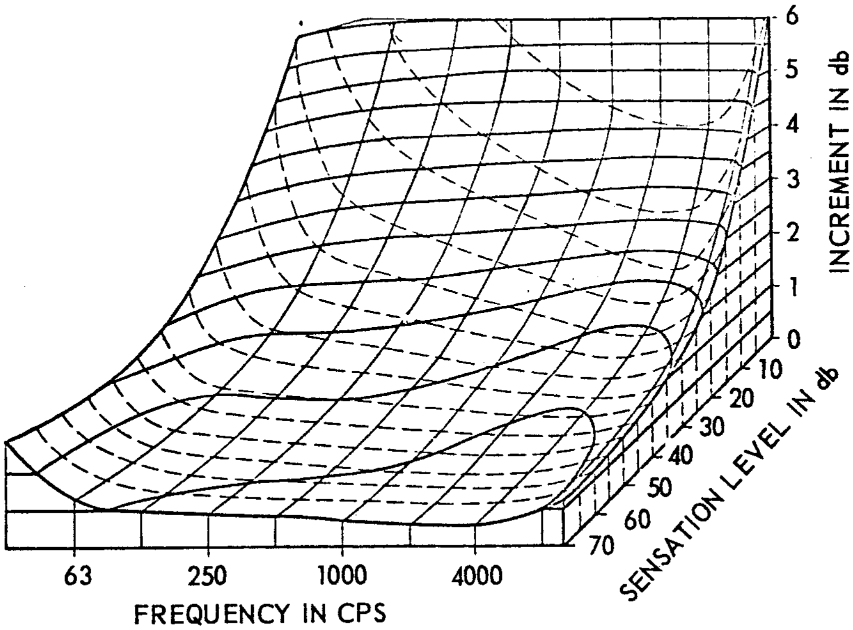
The diameter of the comparison stimulus S_c plotted against the distance of the standard stimulus D_s for the conditions of observation in Holway and Boring's experiment (1941). The inclined dashed line represents an expectation based on size constancy. The horizontal dashed line represents an expectation based on the law of the visual angle.

FIGURE 8



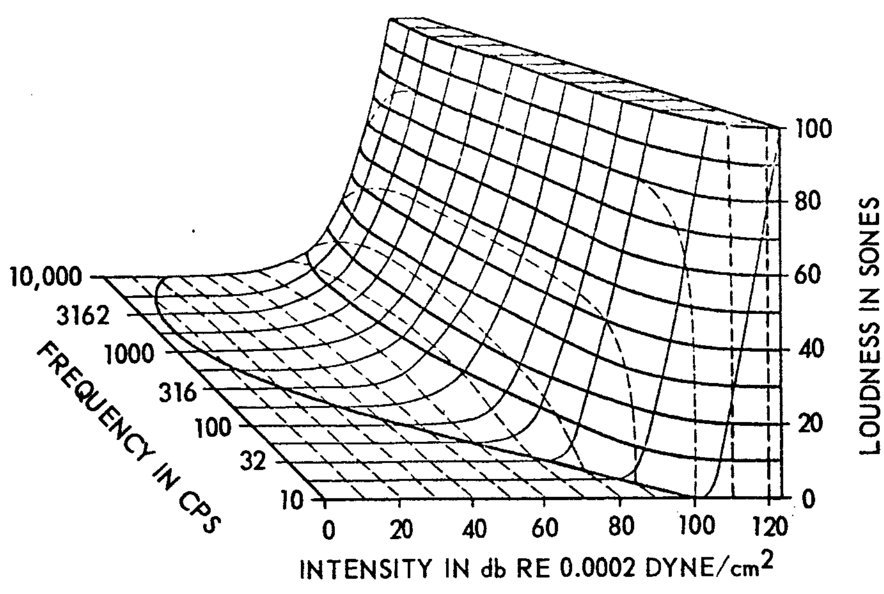
Determinations of the threshold of audibility and the threshold of feeling. Curves 1 to 6 represent attempts to determine the absolute threshold of hearing at various frequencies. MAP = minimum audible pressure at the eardrum; MAF = minimum audible pressure in a free sound field, measured at the place where the listener's head had been. Curves 7 to 12 represent attempts to determine the upper boundary of the auditory realm, beyond which sounds are too intense for comfort, and give rise to nonauditory sensations of tickle and pain, etc.

FIGURE 9



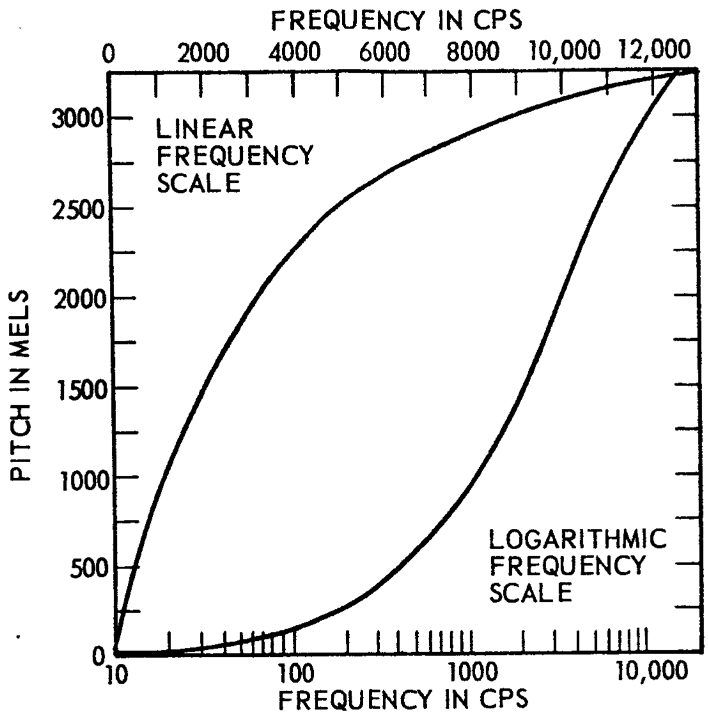
Three-dimensional surface showing the differential intensity threshold as a function of the frequency and the intensity of the standard tone. The threshold is represented as the difference in decibels between the standard intensity and the standard plus the increment. Following the contour lines from 1000 cps and 30 db, we see, by way of illustration, that the intensity of a 1000-cycle tone must be raised 1.0 db from a level 30 db above threshold before the average observer can detect the change. If we start with levels 60 or 70 db above threshold, we find that an increment of less than 0.5 db is detectable. (Based on the data of Riesz, 1928.)

FIGURE 10



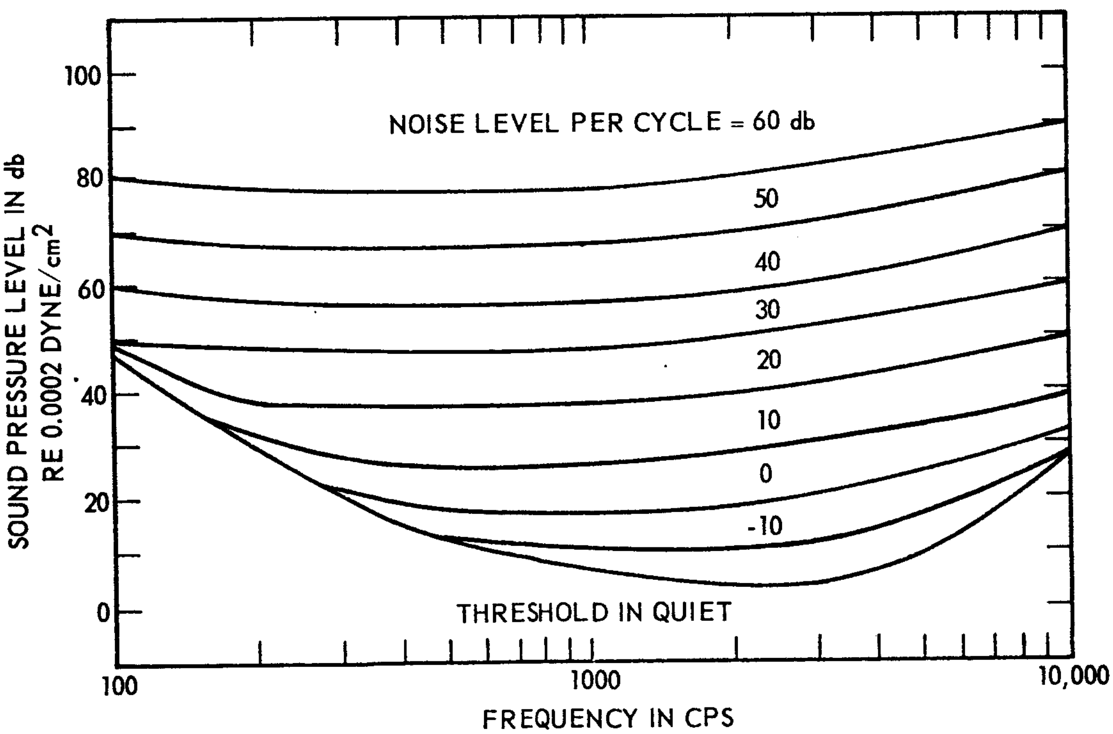
Three-dimensional surface showing loudness as a function of intensity and frequency. Subjective loudness in sones is represented vertically above the intensity-frequency plane. The heavy curves coursing from front to rear in the diagram are equal-loudness contours for pure tones. (After Stevens and Davis, 1938.)

FIGURE 11



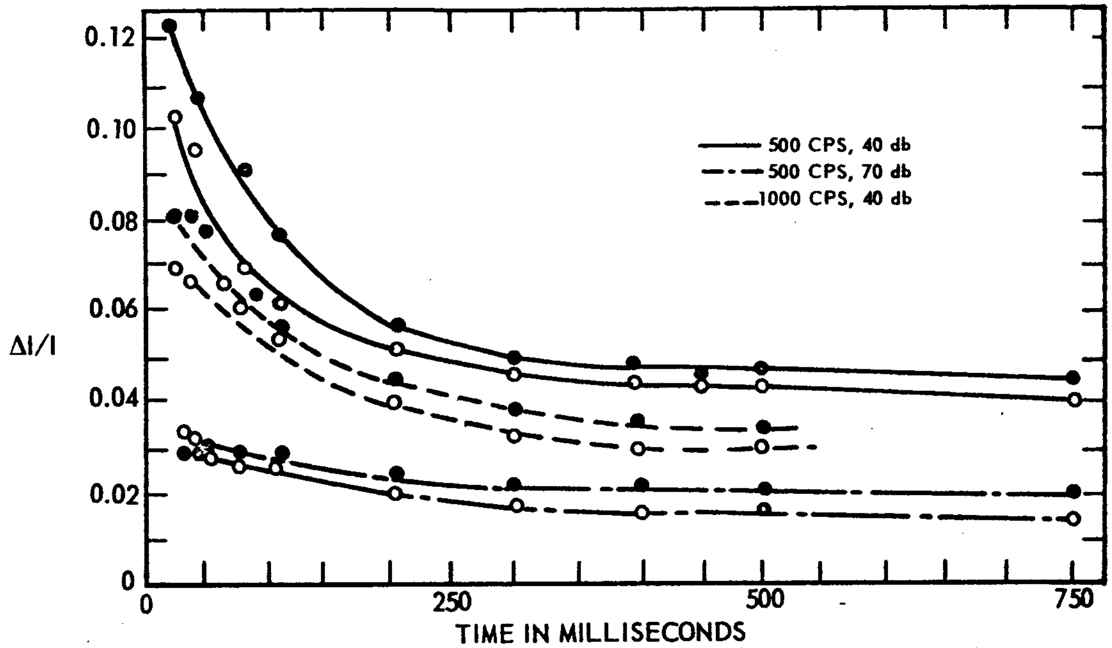
Pitch as a function of frequency. The upper curve shows that subjective pitch (in mels) increases less and less rapidly as the stimulus frequency is increased linearly. The lower curve shows that subjective pitch increases more and more rapidly as stimulus frequency is increased logarithmically. (The musical scale is a logarithmic scale.) The pitch of a 1000-cycle tone, 40 db above threshold, is defined as 1000 mels. (After Stevens and Volkmann, 1940.)

FIGURE 12



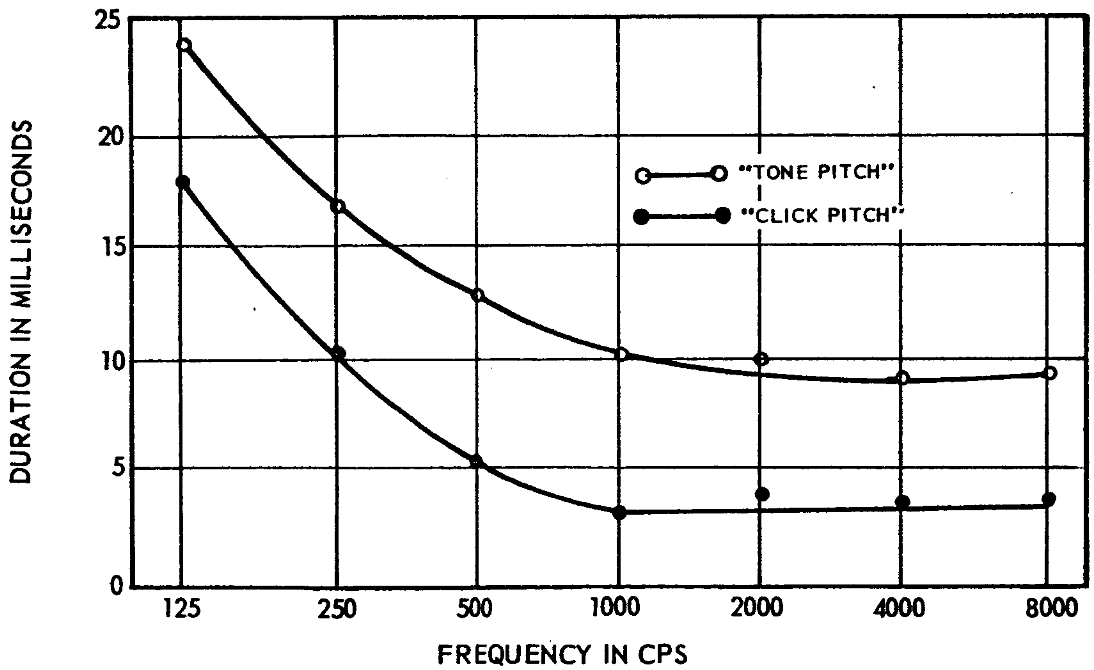
The masked threshold for pure tones presented against a background of white noise. The ordinate gives the sound pressure that the sinusoid must reach to be audible against random fluctuation noise of the spectrum level shown as the parameter. (From Hawkins and Stevens, 1950.)

FIGURE 13



The differential threshold for intensity as a function of the duration of the added increment. ΔI/I is the ratio of the sound-pressure increment to the standard sound pressure. Increments that last 0.5 second are as readily detectable as longer ones, but shorter durations require greater intensity. The open and the closed circles distinguish two listeners. (From Garner and Miller, 1944.)

FIGURE 14a



The duration thresholds for two degrees of 'pitchedness' as functions of frequency. Below 1000 cps, two or three cycles of the wave must be heard for the sound to have any predominant pitch at all, whereas above 1000 cps the threshold is not a fixed number of cycles but a fixed length of time. (From Doughty and Garner, 1947.)

FIGURE 14b

SKIN

Parameters of the tactile senses applicable to display and control systems	Maximum Threshold	Minimum Threshold	Explanation and Reference	Maximum Effective
Warmth by radiation	Burn	0.019 g - cal/cm^2/Sec for 0.2 cm^2 on forehead to 0.00015 g - cal/cm^2/sec whole dorsal surface	The human skin can respond to radiation both visible and infrared. The sensation is that of warmth. Hardy & Oppel (1937)	Literature ambigious requires more work.
Thermal adaptation by contact	45 degrees C. Highest temperature sensed as cold no matter how much skin is pre-warmed.	25 degrees C. Lowest temperature sensed as warm, no matter how much skin is precooled.	A pre-cooled hand feels warm and a pre-warmed hand cool when both are dipped into water of neutral temperature ∴ Threshold exist for adaptation. Hahn (1930)	Not applicable
Vibratory stimulation	Vibration can be sensed up to 250 cycles per second	Touches can be sensed as discrete up to 20 cycles per second	Touches melt into a smooth sense of vibration at 20 cps, above 250 cps the sense of vibration no longer exist. Geldard, (1940)	Varies widely, depending on application

PROPERTIES OF THE SKIN

Approximate values of the physical dimensions of whole skin for the "average man" - 154 lb, 5'7"

Weight	8.8 lb	4 kg
Surface area	20 sq ft	1.8 m^2
Volume	3.7 qt	3.6 l
Water content	70 - 75%	
Specific gravity	1.1	
Thickness	0.02 - 0.2 in.	0.5 - 5.0 mm

Approximate values for thermal properties of skin:

Pain threshold temperature	113°F (45°C)
Heat production	240 kcal/day
Conductance	9 to 30 kcal/m^2hr °C
Thermal conductivity (k)	$(1.5 \pm 0.3) \times 10^{-3}$ cal/cm sec °C, at 23 - 25°C ambient
Diffusivity (k/ρc)	7×10^{-4} cm^2/sec (surface layer 0.26 mm thick)
Thermal inertia (kρc)	90 to 400 x 10^{-5} cal^2/cm^4 sec$(°C)^2$
Heat capacity	~0.8 cal/gm

Approximate optical properties of skin:

Emissivity (infrared)	~0.99
Reflectance (wave-length dependent)	Maximum 0.6 to 1.1 μ Minima <0.3 and >1.2 μ
Transmittance (wave-length dependent)	Maxima 1.2, 1.7, 2.2, 6, 11 μ Minima 0.5, 1.4, 1.9, 3, 7, 12 μ
Solar reflectivity of surface	
Very white skin	42%
5 "white" subjects	28 - 40%, average 34%
6 "colored" subjects	19 - 24%, average 21%
Very black skin	10%
Solar penetration - very white skin	45.5% passes 0.1 mm depth 39.6% " 0.2 " " 32.0% " 0.4 " " 19.0% " 1.0 " " 10.2% " 2.0 " "
Solar penetration - very dark skin	75% passes 0.1 mm depth 40% absorbed in the melanin layer 35% passes 0.2 mm depth

(Data of Stoll, Amer. Soc. Mech. Eng. paper No. 59-A-138, 1959; and Buettner, J. Appl. Physiol. 5: 207, 1952.)

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APPENDIX B

COMPARISON OF COMMUNICATION AND VISIBILITY SCHEDULES OF SEVERAL REMOTE MODULE LANDING SITES ON MARS AS OBSERVED FROM A FAMILY OF CIRCULAR AND ECCENTRIC COMMAND MODULE SATELLITE ORBITS

REMOTE MAN-MACHINE SYSTEMS

NASA CONTRACT NO. NASw-744 LTV ASTRONAUTICS

Prepared by:

G E Reins

G. E. Reins

SUMMARY

This appendix presents communication and visibility schedules for a large combination of Mars-centered command module orbits and remote module landing sites. Two groups of orbits are considered: (1) orbits with periapsis altitudes of 600 n.mi. which complete an integer number of revolutions per Martian day and (2) synchronous orbits with a period of one Martian day, i.e., a fixed major axis, but different peri- and apo-apsis altitudes. In all, (10) orbits and (6) landing sites are evaluated. Results for each combination of orbit and landing sites are illustrated graphically.

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APPENDIX B

COMPARISON OF COMMUNICATION AND VISIBILITY SCHEDULES OF SEVERAL REMOTE MODULE LANDING SITES ON MARS AS OBSERVED FROM A FAMILY OF CIRCULAR AND ECCENTRIC COMMAND MODULE SATELLITE ORBITS

B.1.0 INTRODUCTION

Selection of a command module orbit about Mars and establishment of a remote module landing site on the surface of Mars entails a trade-off between retro velocity requirements to establish the command module capture orbit and communication system weight requirements. Highly eccentric, high energy command module orbits generally provide several long periods of continuous communication time, while low altitude circular orbits result in many short-time communication periods. The total cumulative communication time between the command module and the remote module depends on the particular orbit and remote module landing site. Characteristically, establishment of highly eccentric command module orbits requires small retro velocity increments and the attendant propellant savings can be converted into additional payload for the command module. Communication distances for the highly eccentric orbits become extremely large near the apo-apsis of the orbit, however, and communication system weights increase accordingly. On the other hand, retro velocity requirements to place the command module into a circular capture orbit are generally higher than those for eccentric orbits, but the communication distances are smaller. Thus, it can be seen a trade-off between capture orbit characteristics and communication system requirements is essential. Another aspect to be considered in the selection of the remote module landing site is the illumination of the landing site when the command module is above the local horizon of the landing site, i.e., a communication link exists between the command and remote modules. If the landing site is illuminated the remote module can, by use of a TV camera, scan the area and relay the pictures directly to the command module.

This appendix is intended to provide communication and illumination information to facilitate the above mentioned parametric trade-off study. The objective of this appendix, therefore, is to explore various combinations of remote module landing sites and command module orbits, consistent with typical transmartian trajectory constraints, to ascertain communication and visibility schedules.

In the sections to follow, the analysis of the communication problem is presented and parametric communication distance data and visibility schedules are illustrated graphically.

B.2.0 ANALYSIS

To determine communication and visibility schedules for the various combinations of command module orbits and remote module landing sites, a typical transmartian trajectory for a favorable earth-orbit departure mission is selected as a reference trajectory to provide realistic arrival conditions at the peri-apsis of the martian approach hyperbola. Retro velocity requirements to reduce the hyperbolic approach velocity to the peri-apsis velocity of the desired command module orbits are then derived. The transmartian design trajectory and retro velocity requirements are defined below. Selection of the various command module orbits and location of the remote module landing sites are also described in the following sections, as are the ephemeris calculations and associated communication and visibility information.

B.2.1 MISSION DESCRIPTION

The over-all mission can be categorized into five distinct phases: (1) Earth departure, (2) transmartian trajectory, (3) approach hyperbola, (4) Mars orbit of command module and (5) de-orbit and landing of remote module on Mars. The first three phases are considered only insofar as they provide the approach asymptote of Mars and the time of arrival. A typical reference mission, obtained from Reference B.1, provided the required arrival velocity, coordinates, and time. The arrival data at the peri-apsis of the approach hyperbola is 4 November 1975 (Julian Date = 2442720.5) which is considered timely for the purposes of the present study. The orbital elements of the approach hyperbola at peri-apsis are:

Peri-apsis Altitude, H_{π_V} = 600 n.mi.

Peri-apsis Velocity, V_{π_V} = 21279.72 fps

Eccentricity, e = 3.430485

Longitude of Ascending node, Ω_V = 254.222°

Inclination to Mar's Equator, i_V = 0.550°

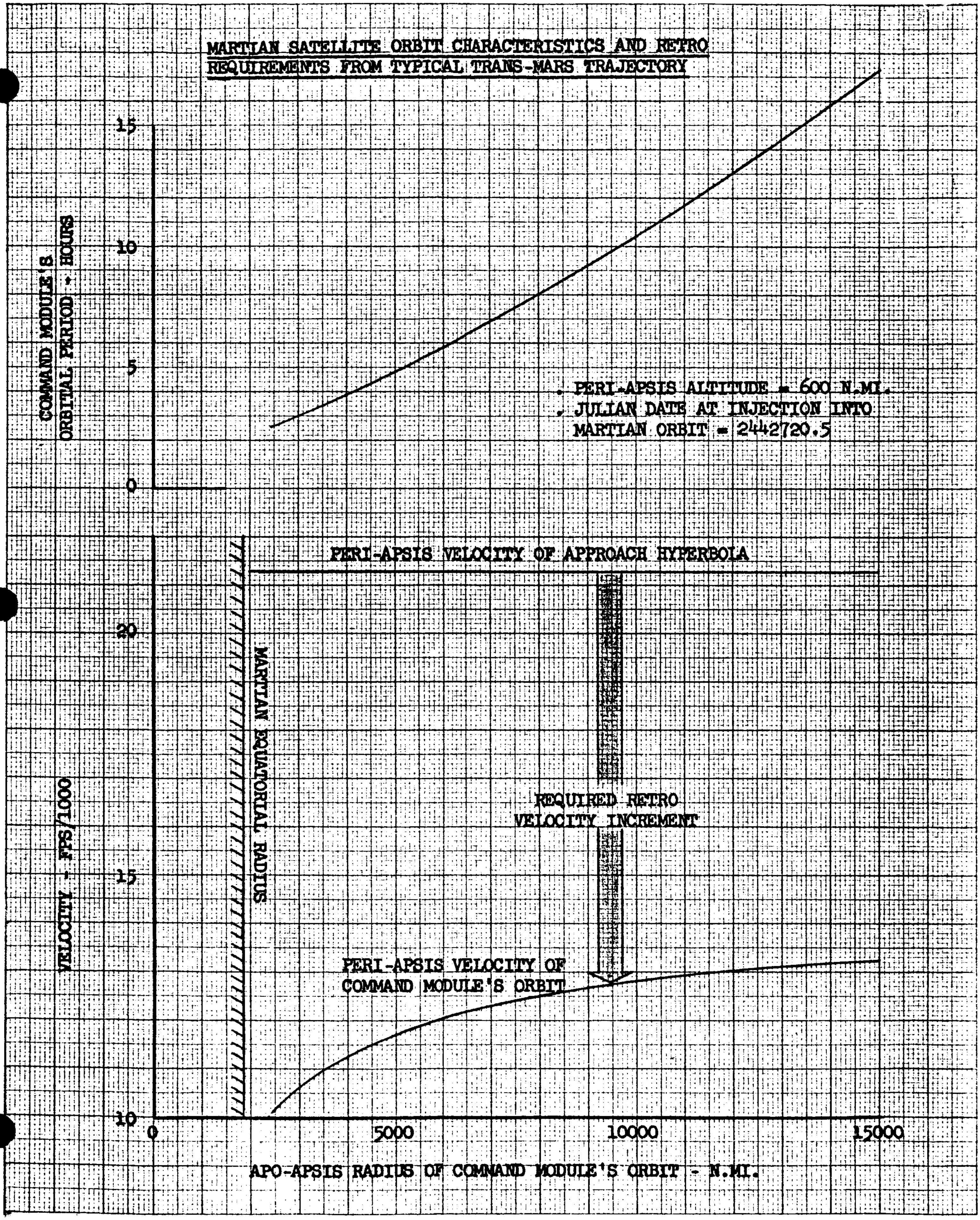
Argument of Peri-apsis, π_V = 196.345°

The longitude of the ascending node (right ascension) is measured east from the vernal equinox of Mars. The above elements are derived and calculated in Appendix C.

Upon arrival at peri-apsis, the retro maneuver is initiated to place the command module into a Mars-centered, elliptic or circular orbit. Figure B-1 illustrates the peri-apsis velocity of the command module after completion of the retro maneuver as a function of apo-apsis radius. Corresponding orbital periods are also shown. The required retro velocity increments to reduce the hyperbolic approach velocity to the peri-apsis velocity of the command module's orbit can also be obtained from Figure B-1, as indicated. Separation and de-orbit of the remote module is pre-determined for each selected landing site location. De-orbit may be accomplished by a single Hohmann transfer maneuver or by first placing the remote module into a circular parking orbit and then ejecting from the parking orbit at the proper time to affect impact at the preselected landing site. Meanwhile, the command module maintains contact with the remote module when the command module is above the local horizon of the remote module landing site.

B.2.2 COMMAND MODULE SATELLITE ORBITS

Two groups of Mars-centered command module orbits were analyzed. The first group consists of orbits with a common peri-apsis altitude of 600 n.mi. and variable apo-apsis altitude. The second group is characterized by synchronous orbits, i.e., orbits with a period of one Martian day. For these orbits, the major axis remains constant but peri-apsis and apo-apsis vary.


MARTIAN SATELLITE ORBIT CHARACTERISTICS AND RETRO
REQUIREMENTS FROM TYPICAL TRANS-MARS TRAJECTORY
COMMAND MODULE'S
ORBITAL PERIOD - HOURS
15
10
5
0
. PERI-APSIS ALTITUDE = 600 N.MI.
. JULIAN DATE AT INJECTION INTO
MARTIAN ORBIT = 2442720.5
PERI-APSIS VELOCITY OF APPROACH HYPERBOLA
MARTIAN EQUATORIAL RADIUS
VELOCITY - FPS/1000
20
15
10
REQUIRED RETRO
VELOCITY INCREMENT
PERI-APSIS VELOCITY OF
COMMAND MODULE'S ORBIT
0
5000
10000
15000
APO-APSIS RADIUS OF COMMAND MODULE'S ORBIT - N.MI.

In the first group, five orbits, four eccentric and one 600 n.mi. circular orbit, were examined. The eccentric orbits were selected such that they complete an integer number of revolutions per Martian day, i.e., their periods are even divisors of the Martian day. The characteristics of orbits of the first group are given in the following table:

$P_{CM}/P_♂$	H_π	H_A	$V_{\pi_{CM}}$	e
-	n.mi.	n.mi.	fps	-
1/2	600	9612	12979.8	.648360
1/3		6321	12542.9	.539257
1/4		4471	12139.8	.441949
1/6		2400	11389.6	.269206
.1041		600	10109.8	0

where P_{CM} = Period of Command Module's Orbit

$P_♂$ = Period of Mars Rotation ($24^h\ 37^m\ 23^s$)

H_π = Peri-Apsis Altitude

H_A = Apo-Apsis Altitude

$V_{\pi_{CM}}$ = Peri-Apsis Velocity of Command Module after Retro Maneuver

e = Eccentricity of Mars-centered Orbit

By electing periods of the eccentric orbits which are integer fractions of the Martian day, the ground tracks of the orbits are such that the nodal change per revolution is an integer part of 360° and the ground tracks essentially superimpose after each day. Secular effects due to oblateness are practically negligible at these altitudes, as are atmospheric effects. Thus, ephemerides for each orbit need to be determined for only one day and the results may be assumed to recur each day for the duration of the 50 day capture period.

Four eccentric and one circular orbit were also evaluated in the second group. The orbital characteristics of this group are given below:

$P_{CM}/P_{♂}$	H_π	H_A	$V_{\pi\,CM}$	e
-	n.mi.	n.mi.	fps	-
1.000	9199	9199	4756	0
	7156	11241	5735	.184997
	5156	13241	6982	.366109
	3156	15241	8791	.547221
	2106	16291	10230	.655000

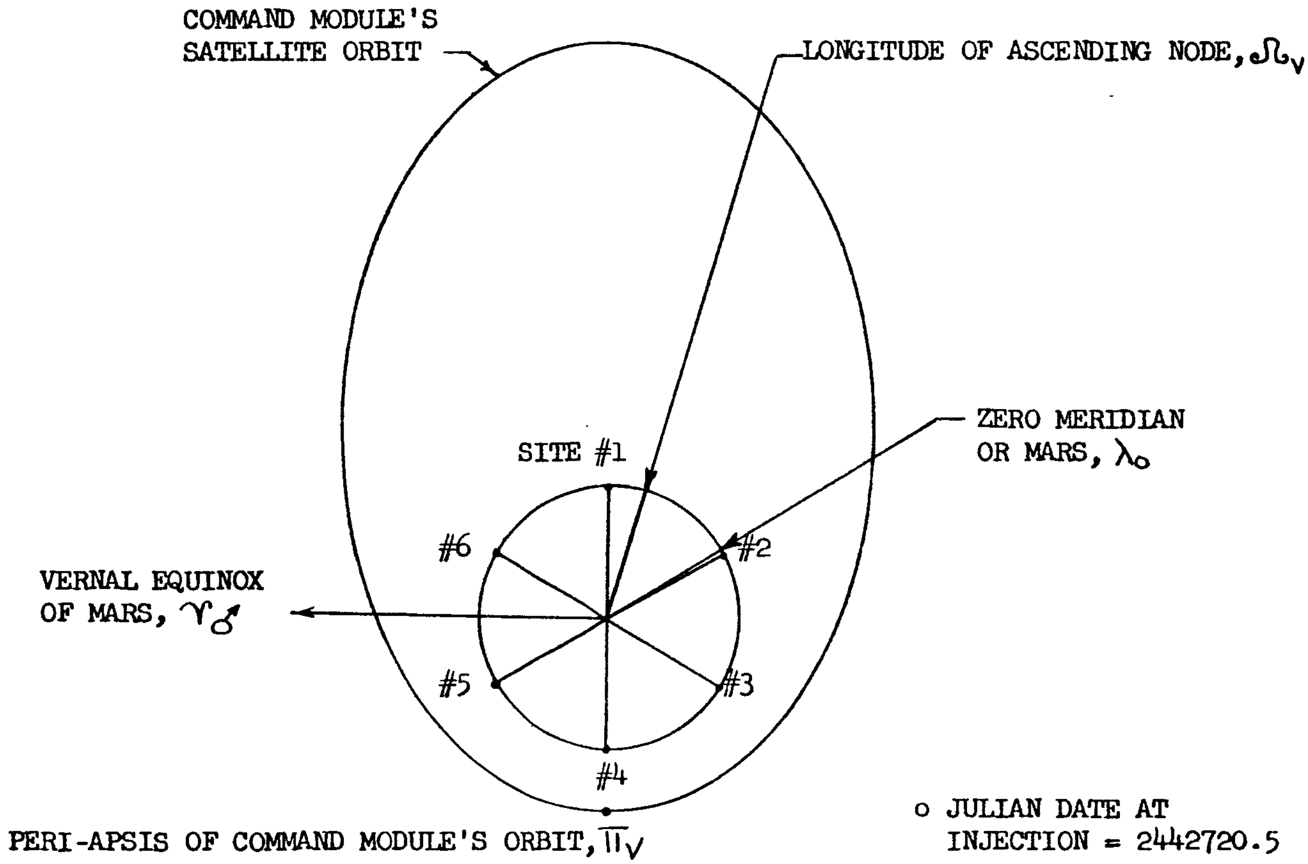
For the circular orbit, the ground track consists of a singular subsatellite point since the command module has no relative motion with respect to Mars. As the synchronous orbits become eccentric, the subsatellite point traces out a ground track which resembles a figure eight. The last orbit shown in the above table was chosen for analysis because the elevation of the command module (measured from the horizontal established by the subsatellite point at peri-apsis) oscillates from horizon to horizon, but never falls below the horizon. (See Figure B-35).

The effects of the two moons of Mars, Phobus and Deimos, with mean distances from Mars of 5100 and 12700 nautical miles, were not considered in the selection of the above command module orbits.

B.2.3 REMOTE MODULE LANDING SITE LOCATIONS

Six remote module landing sites were evaluated in conjunction with the various command module orbits. The locations of these sites are graphically illustrated in Figure B-2. The sites are all situated on the Martian

LOCATION OF REMOTE MODULE LANDING SITES



o JULIAN DATE AT INJECTION = 2442720.5

SITE	W. LONGITUDE
1	301.548
2	1.548
3	61.548
4	121.548
5	181.548
6	241.548

equator because of temperature considerations. Also, green areas near the equator of Mars may reflect vegetation in this vicinity thus making this area attractive for exploration.

Longitudes of the various sites are tabulated in Figure B-2. Note that longitudes on Mars are measured west from the zero meridian, as shown in Figure B.3. (At the Julian date of injection, the right ascension of the zero meridian of Mars, RA_o, is 219.568 degrees, measured eastwards.) The longitudes of the landing site locations were picked to provide parametric data on communication distance and visibility on Mars.

The geometry of the communication and visibility problem is illustrated in Figure B-4. Thus, when the elevation of the command module is positive, i.e., the command module is above the local horizon of the landing site, radar contact between the remote module and command module is possible, provided the radar range is sufficient. Similarly, when the elevation of the Sun is positive, the landing site is illuminated. If both the elevation of the command module and that of the sun is positive, visual and/or radar contact between the command module and remote module is feasible and television pictures, taken by the remote module, may be directly transmitted to the command module.

B.2.4 COMPUTATION OF EPHEMERIDES

Command module ephemerides were calculated on a LTV-developed satellite ephemeris routine (Ref. B.2). This computer program uses the method of perturbation of orbital elements. Only those non-inverse-square accelerations which cause disturbances to the two-body reference orbit are considered. These include accelerations which arise from the second harmonic of the planet's gravity potential and from the atmosphere. The resulting changes

FIGURE B-3 DEFINITION OF MARTIAN LONGITUDE, LATITUDE, AND DIRECTION OF ROTATION

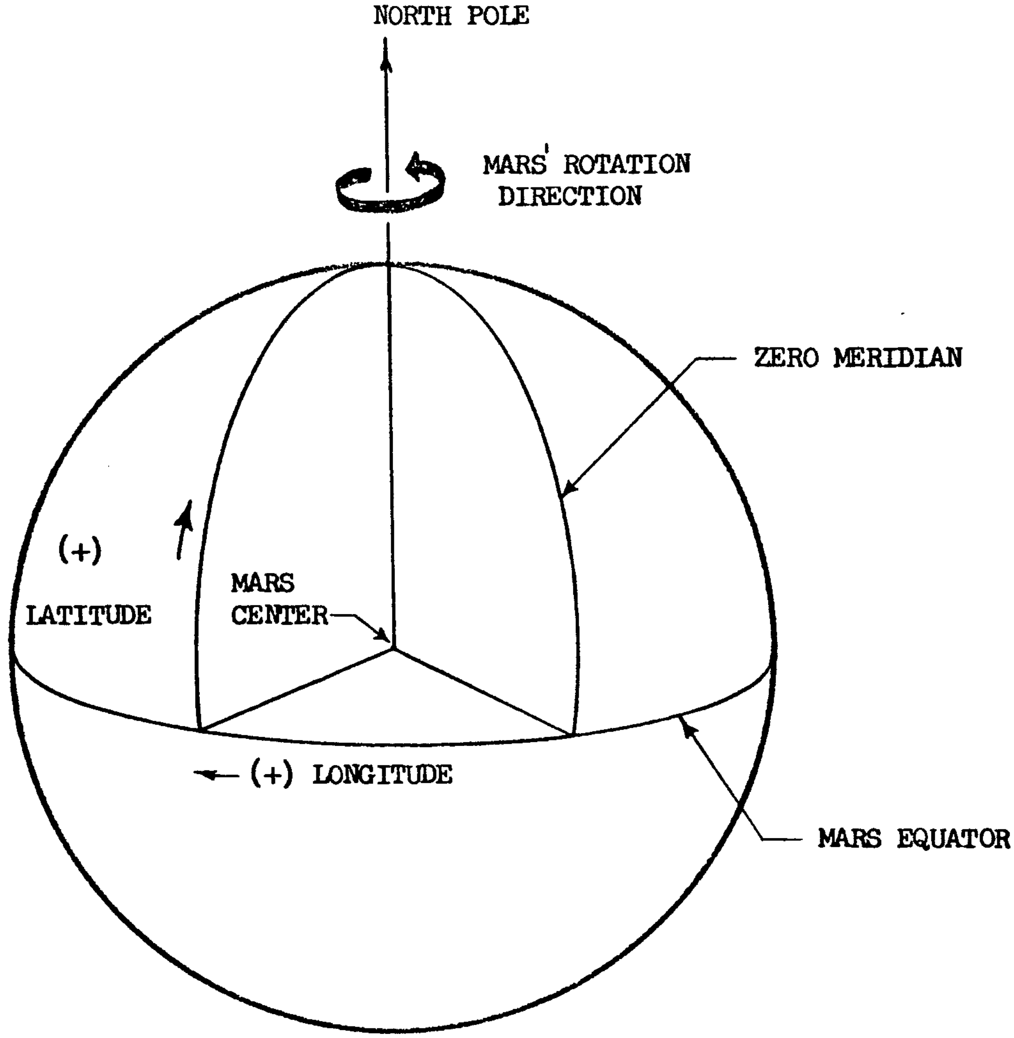
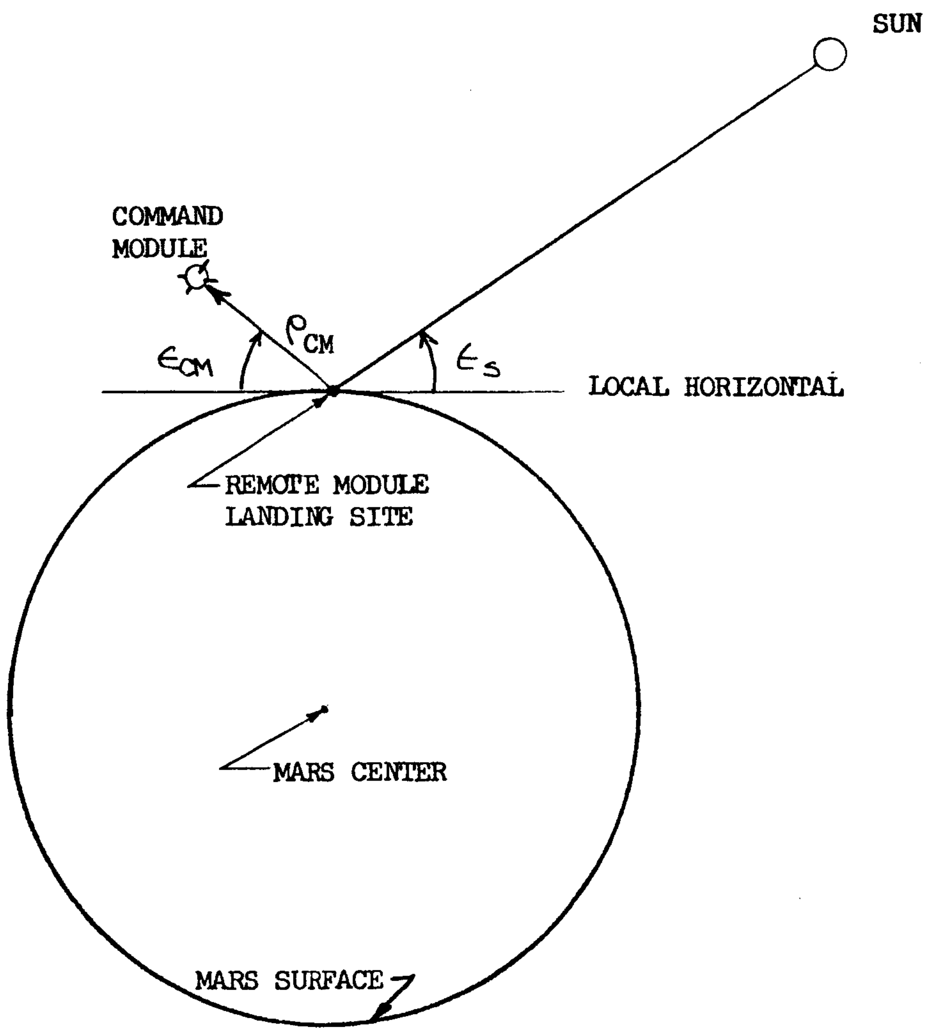


FIGURE B-4 COMMUNICATION AND ILLUMINATION GEOMETRY



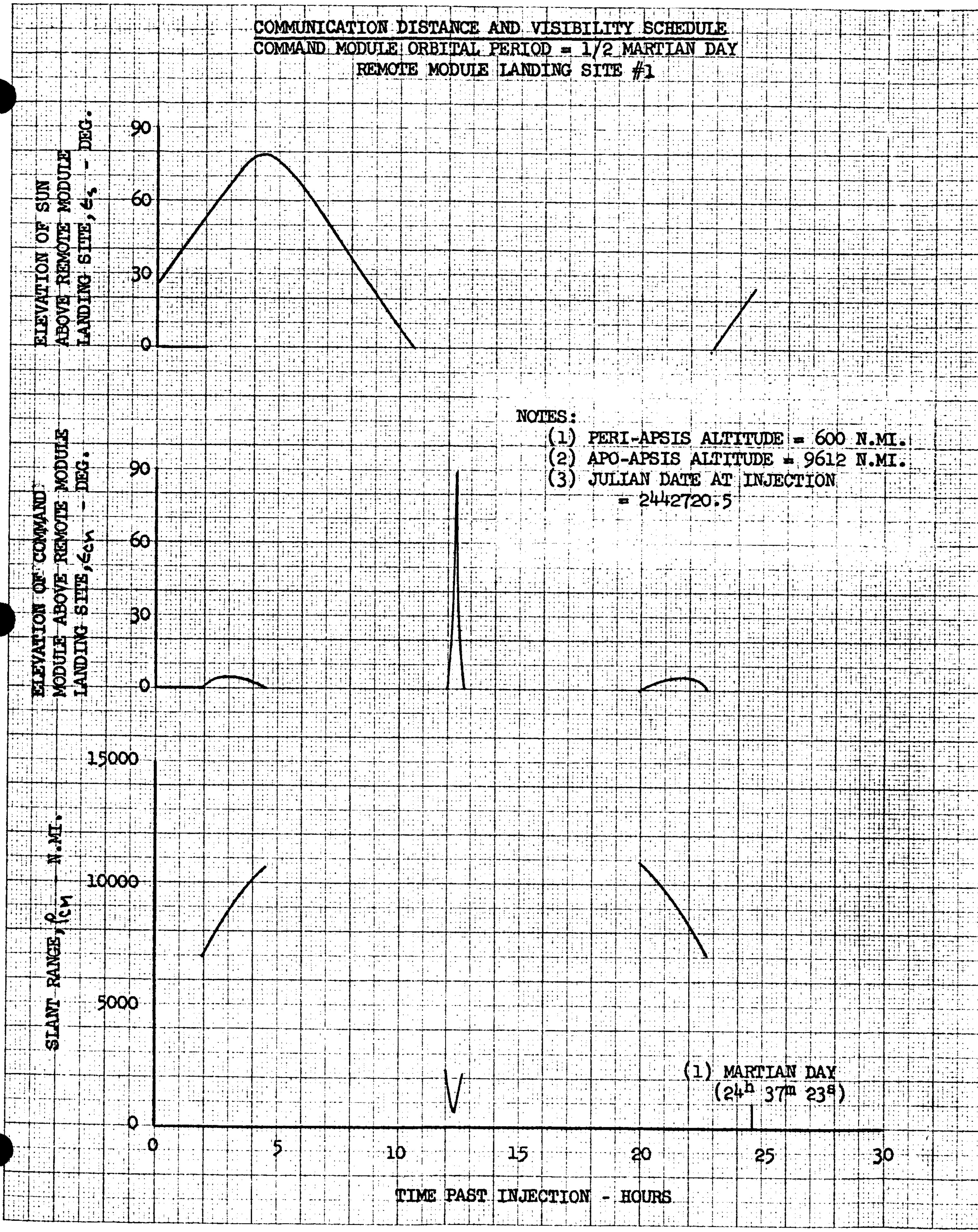
ρ_{CM}	SLANT RANGE FROM REMOTE MODULE TO COMMAND MODULE
ϵ_{CM}	ELEVATION OF COMMAND MODULE
ϵ_S	ELEVATION OF SUN

in the orbital elements are integrated with an interval size of one orbital revolution. To obtain illumination of the planet, the solar ephemeris elements relative to the planet are loaded into the program. Actual values of the solar ephemeris elements relative to Mars and the Julian date at which the zero meridian of Mars crosses the Martian vernal equinox are required inputs to the program and are derived in Appendix C.

Program output consists of epoch conditions, nodal conditions and tabular data defining the ground track, slant range (communication distance) from a tracking station (landing site), satellite elevation, and illumination of the landing site.

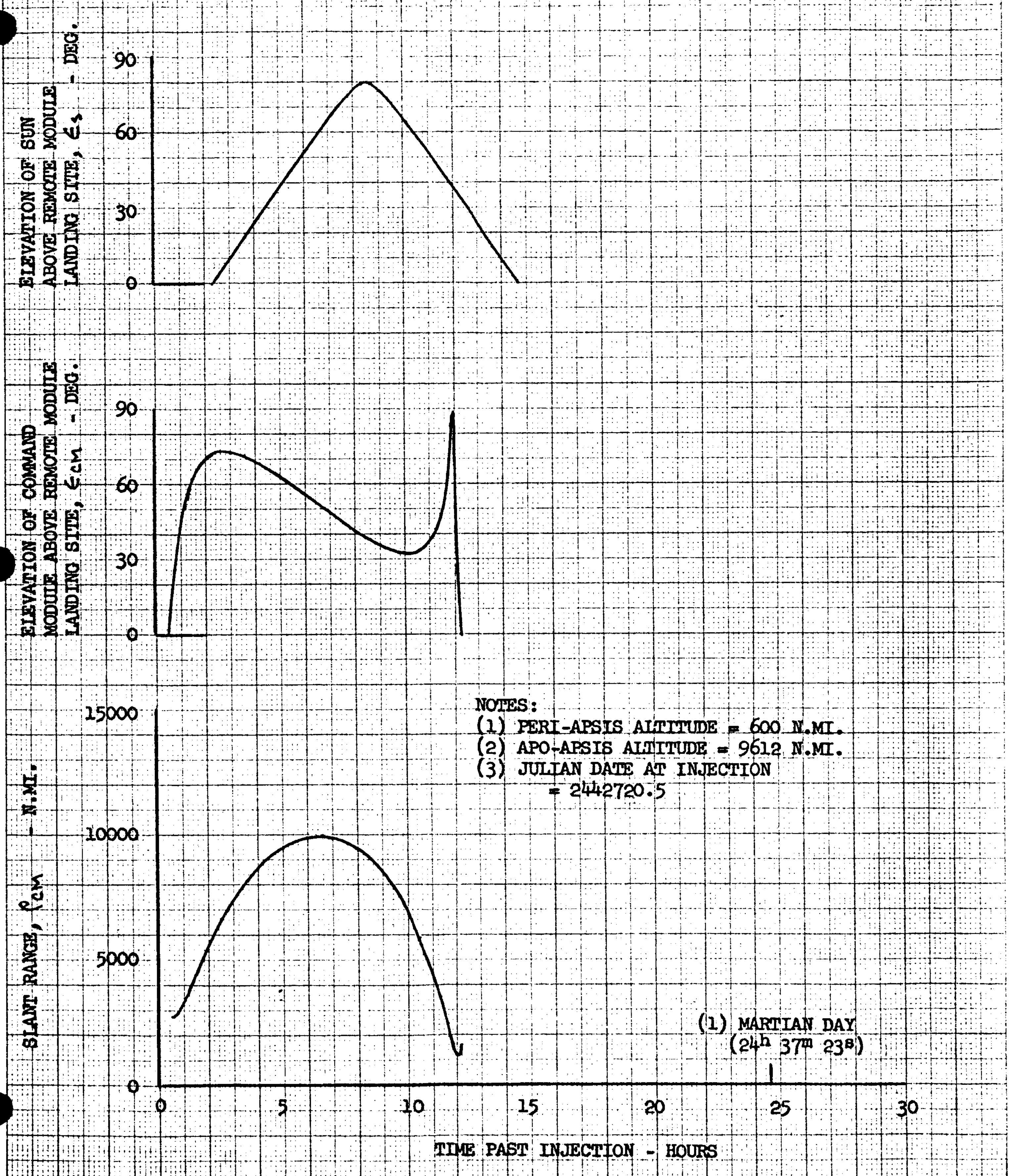
B.3.0 PARAMETRIC RESULTS

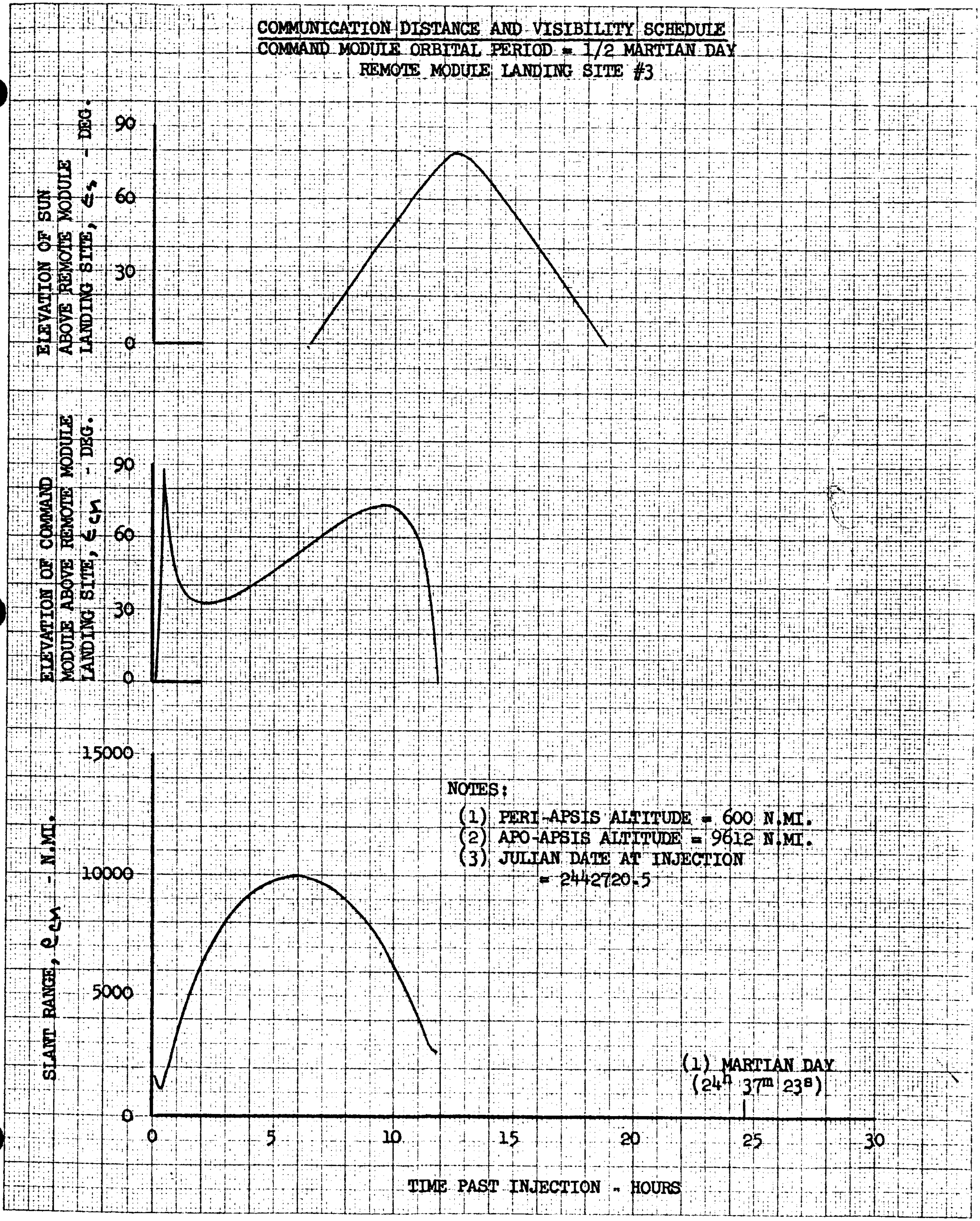
Communication distance information and visibility schedules for the orbits defined in Section B.2.2 and the landing sites selected in Section B.2.3 are presented in Figures B-5 through B-34. Data for the orbits of the first group are shown in Figures B-5 through B-29, while results for the second group are depicted in Figures B-30 through B-34. Data for the synchronous orbits are only presented for Site #4 because the command module always remains above the horizon. Shown in the figures are the slant range and elevation of the command module as well as the elevation of the Sun in terms of time past epoch. Results are shown only for a period of one Martian day since the data approximately repeat daily. Because Mars moves about the Sun at a rate of about 1/2 degree per day, the elevation of the Sun, shown in Figures B-5 through B-34, regresses about 2 minutes per day so that after the 50 day capture period the elevation curves will have shifted about 1.7 hours to the right. Results shown in Figures B-5 through B-29 indicate extended periods of communication up to 10 hours duration may be achieved for the highly eccentric orbits, while for the circular orbits communication time is reduced to less than one hour, however, there are up to nine periods of observation available per day. For the synchronized orbits of the second group, the command module can communicate with the remote module for the entire 50 day capture period. Furthermore, the remote module landing site is illuminated for over 12 hours per day. The minimum elevation angle for synchronous orbits is shown in Figure B-35 in terms of eccentricity of the orbit. Corresponding peri- and apo-apsis altitudes are also indicated. Note that for the circular synchronous orbit the command module remains directly



COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/2 MARTIAN DAY
REMOTE MODULE LANDING SITE #1
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 9612 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{cM} - DEG.
90
60
30
0
SLANT RANGE, ρ_{cM} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY
(24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

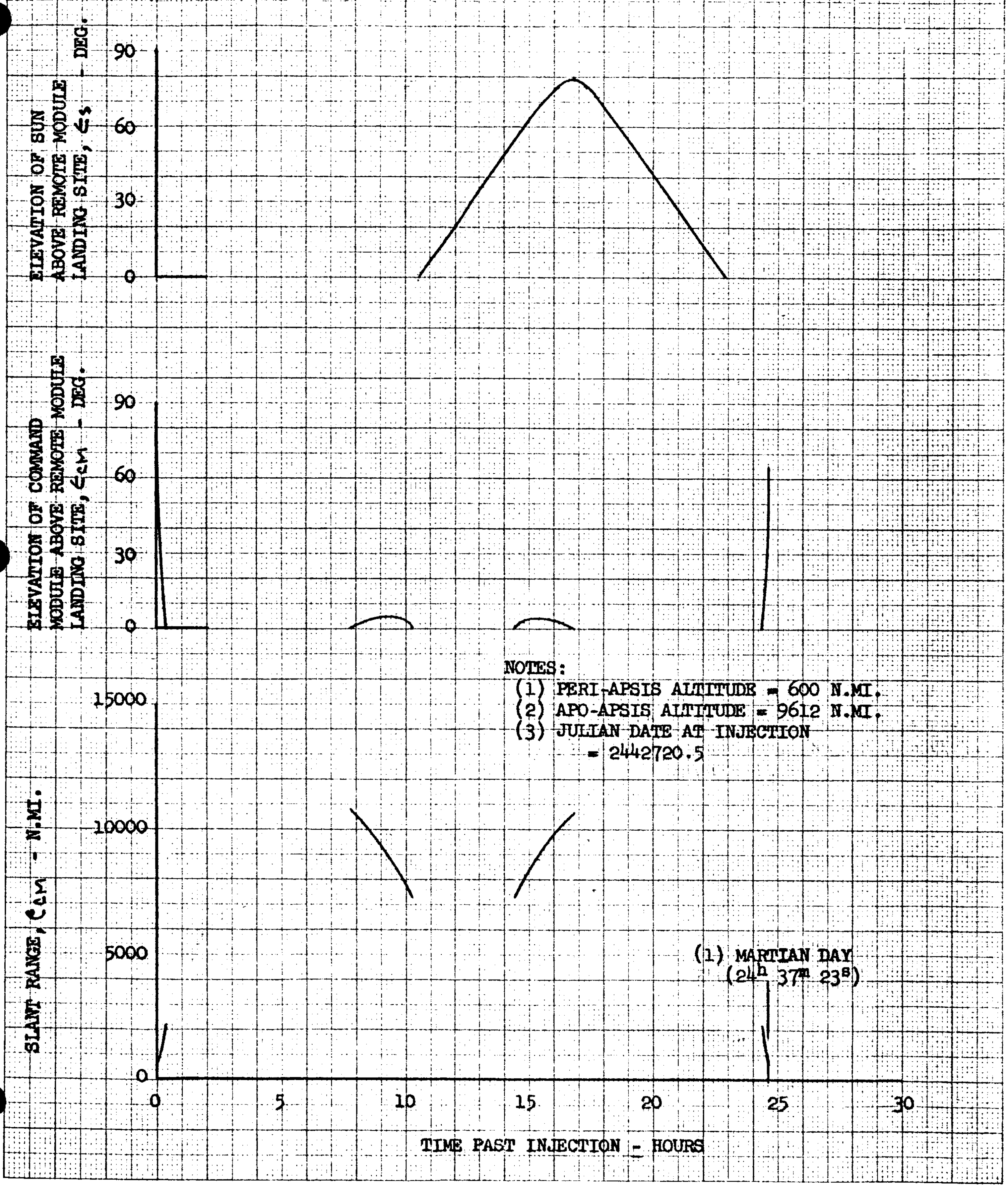
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/2 MARTIAN DAY
REMOTE MODULE LANDING SITE #2

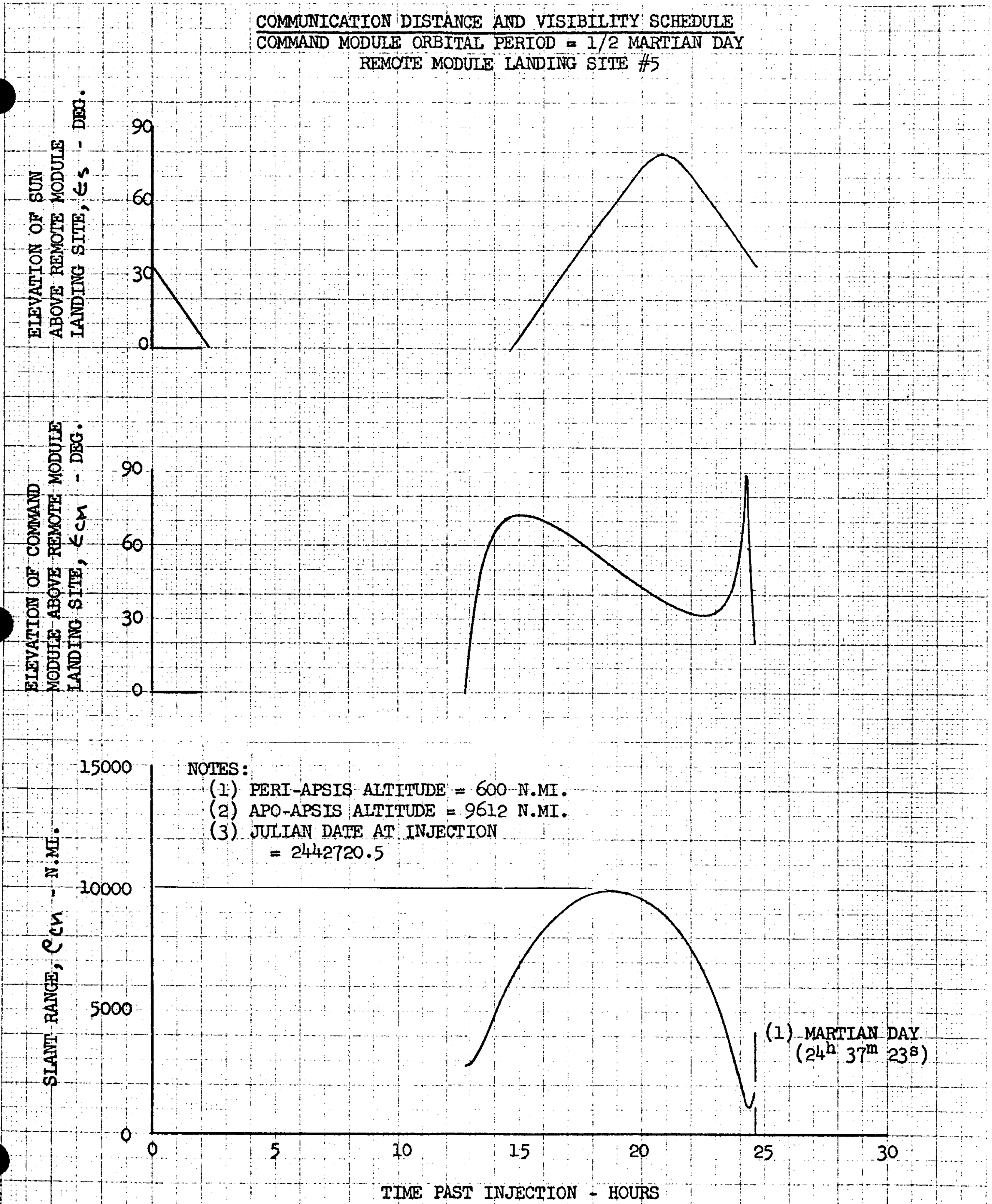




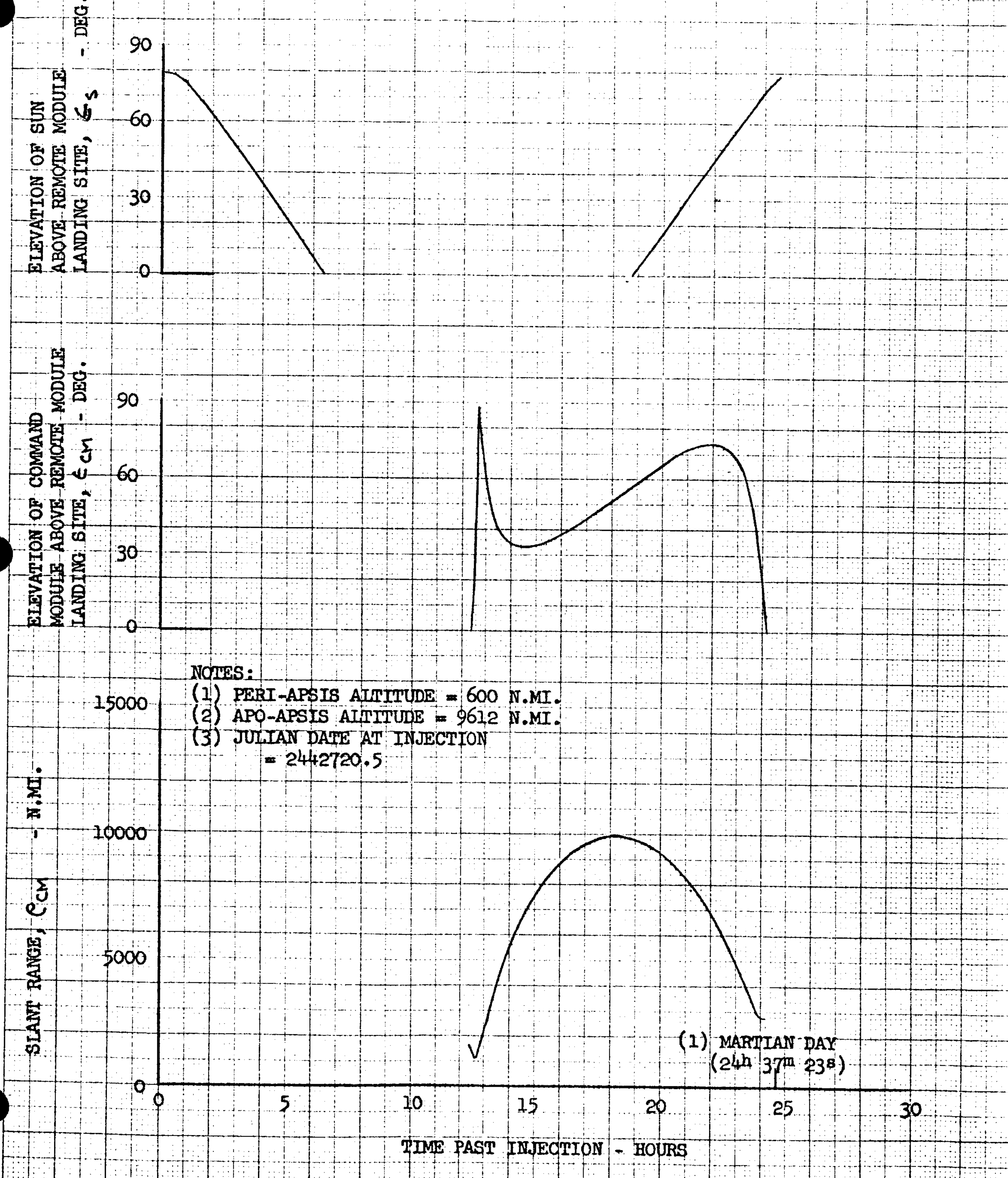
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/2 MARTIAN DAY
REMOTE MODULE LANDING SITE #3
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 9612 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

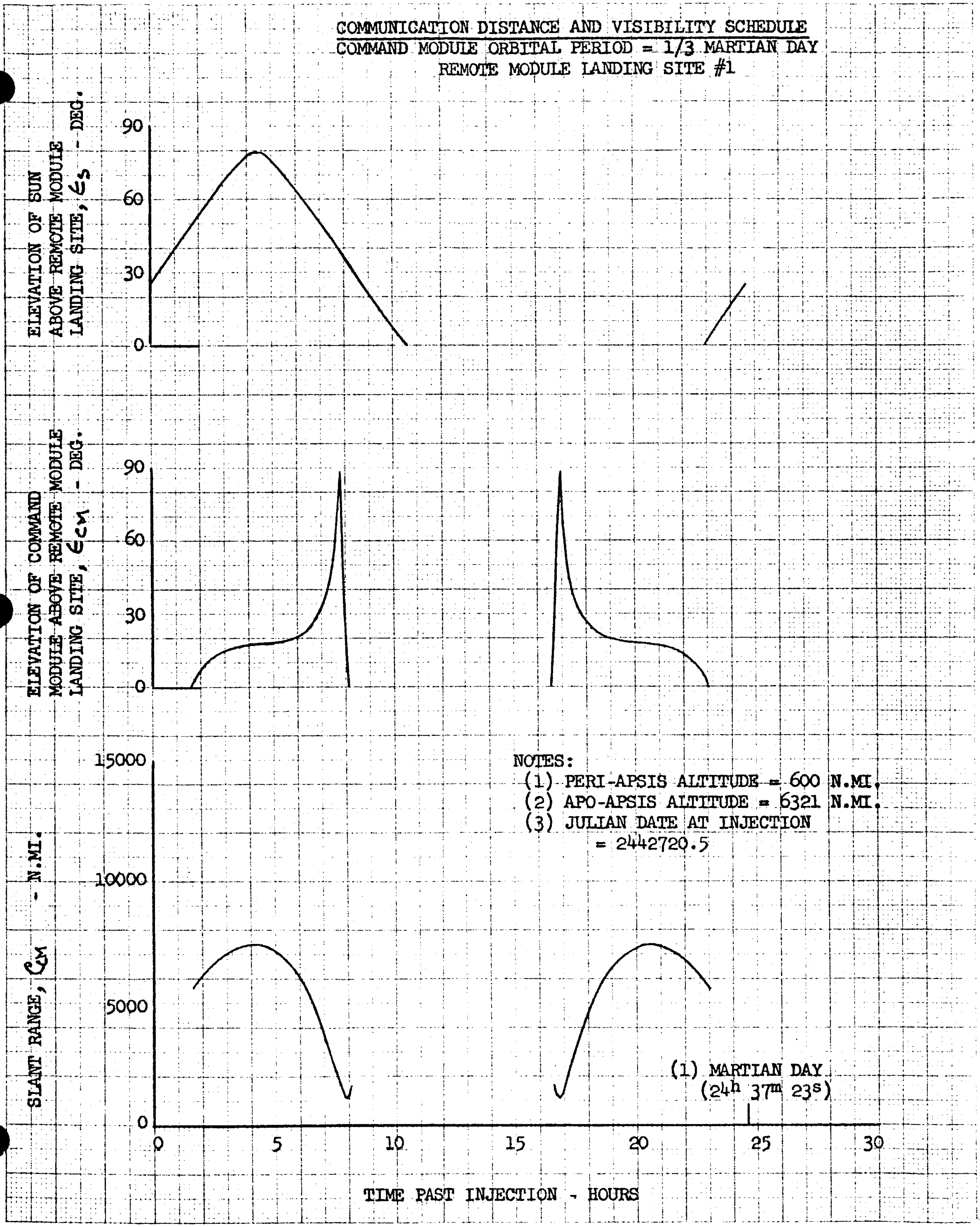
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/2 MARTIAN DAY
REMOTE MODULE LANDING SITE #4

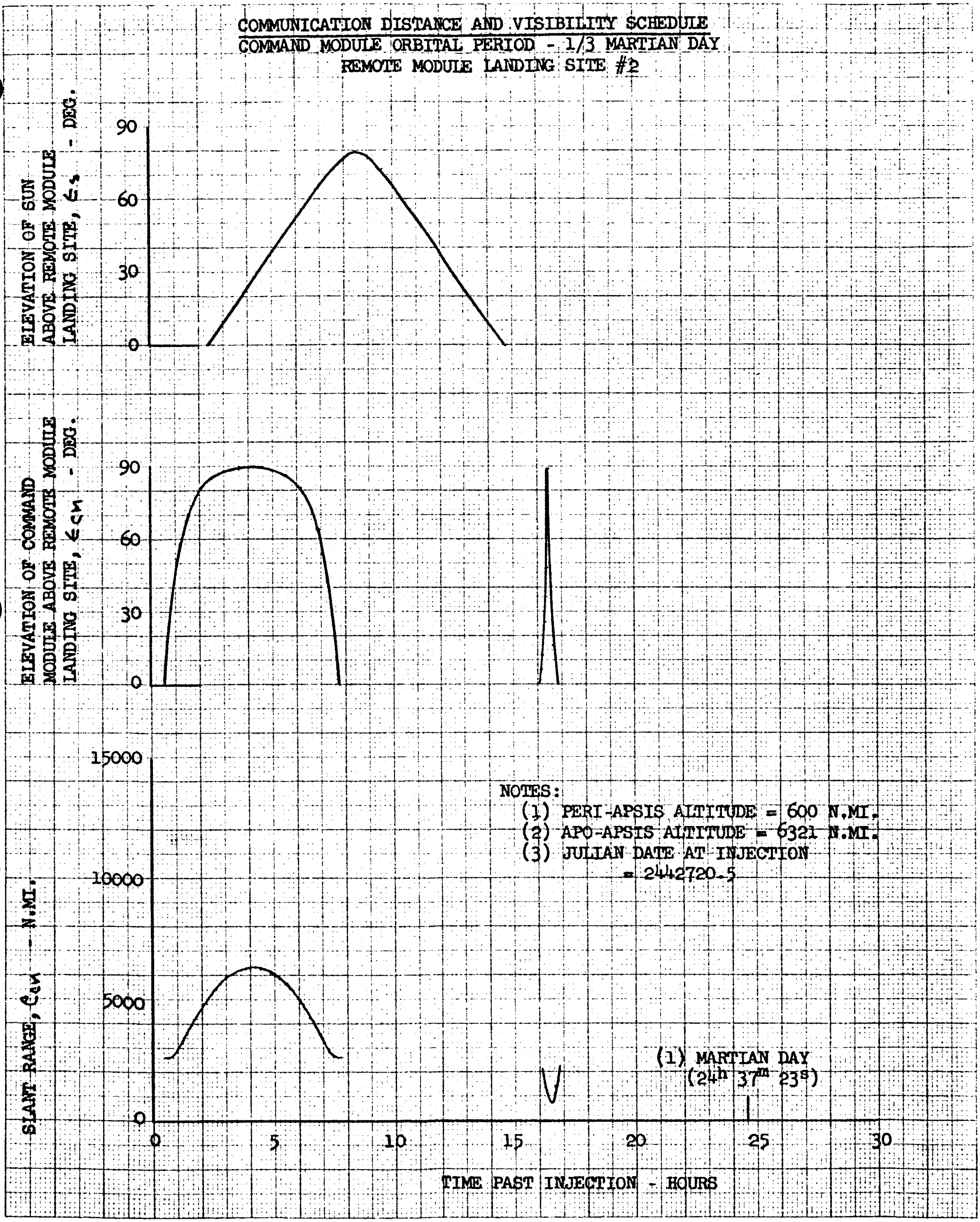



COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/2 MARTIAN DAY
REMOTE MODULE LANDING SITE #5
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 9612 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

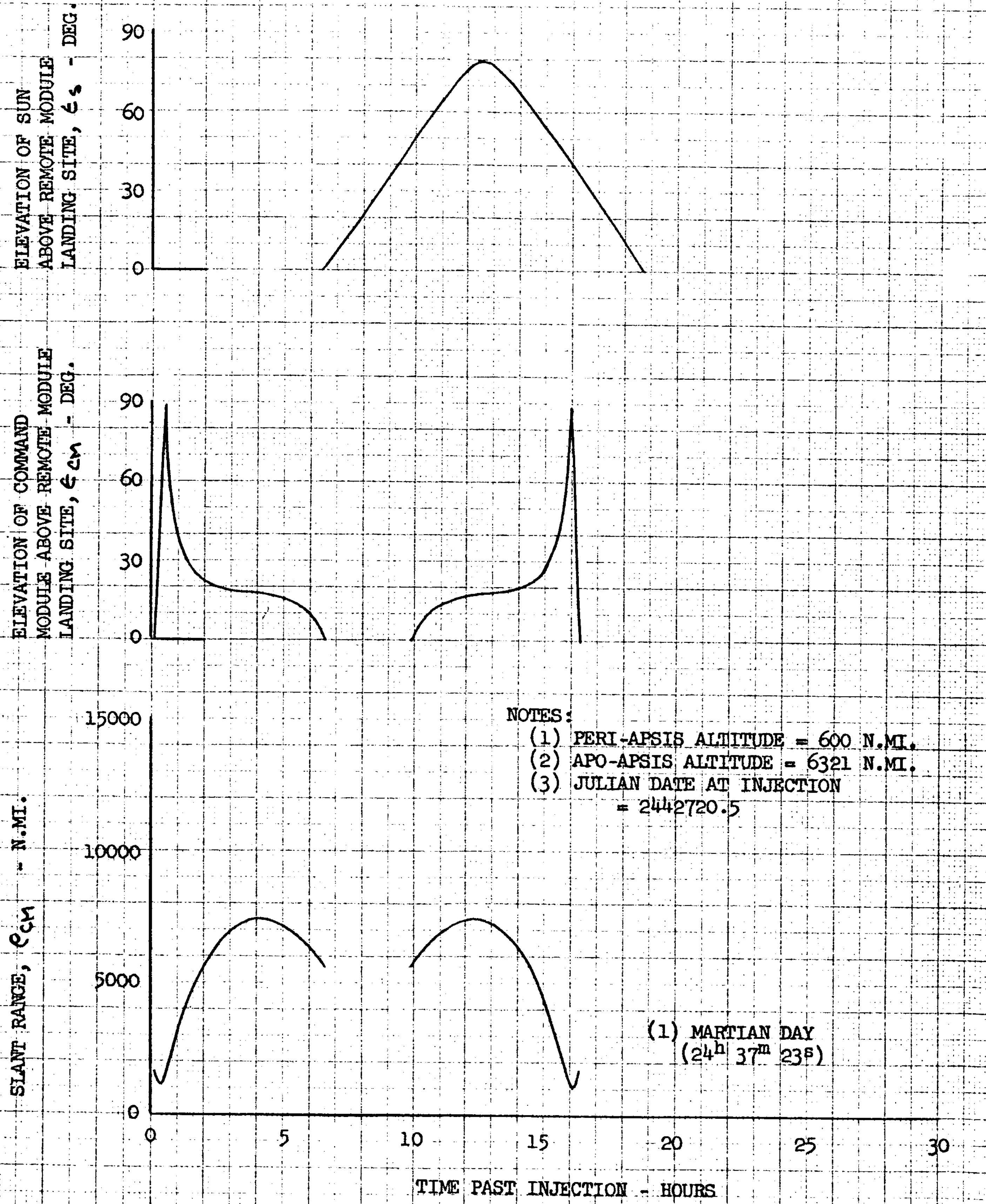
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/2 MARTIAN DAY
REMOTE MODULE LANDING SITE #6

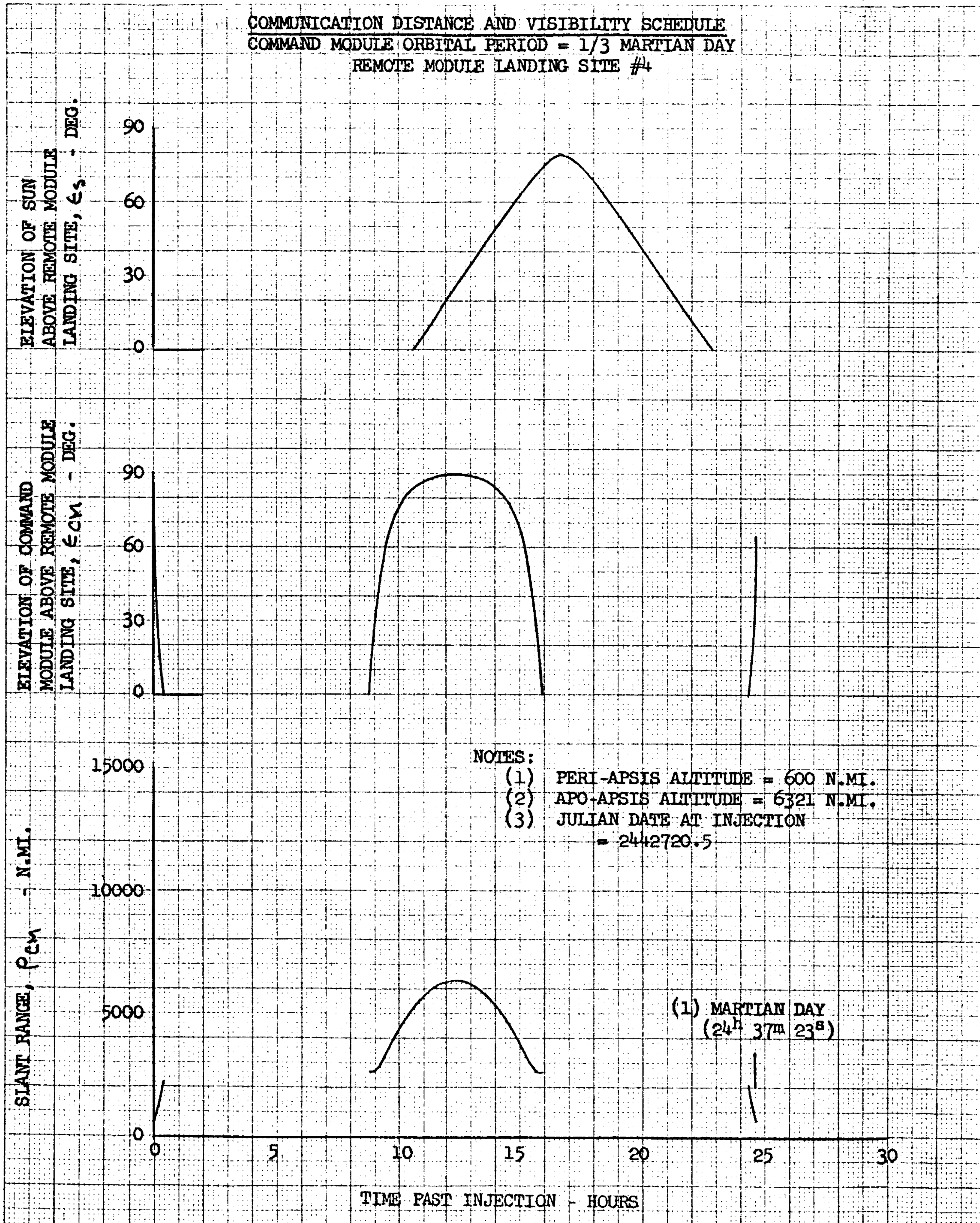


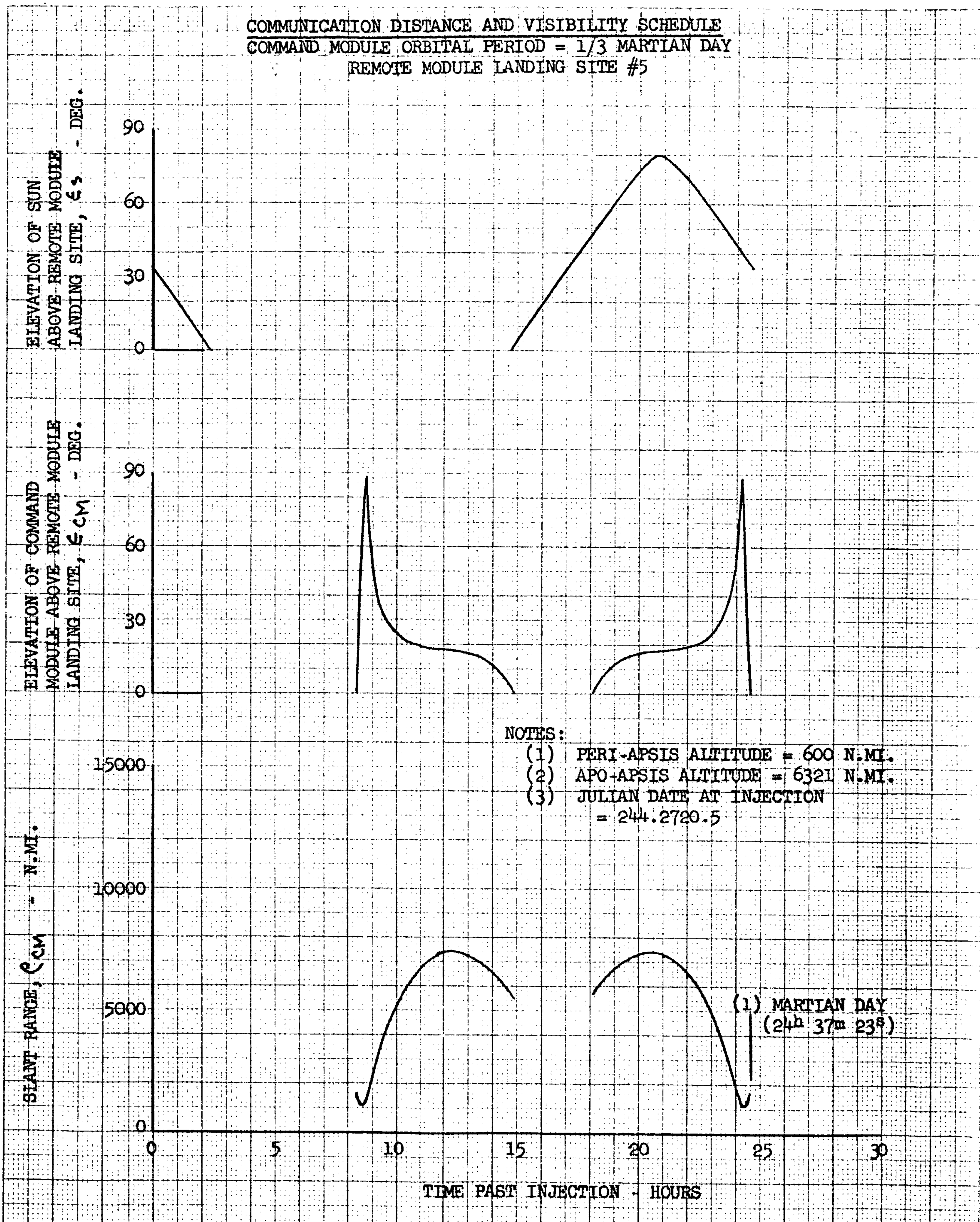

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/3 MARTIAN DAY
REMOTE MODULE LANDING SITE #1
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_S - DEG.
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
SLANT RANGE, ρ_{CM} - N.MI.
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 6321 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY (24^h 37^m 23^s)
TIME PAST INJECTION - HOURS

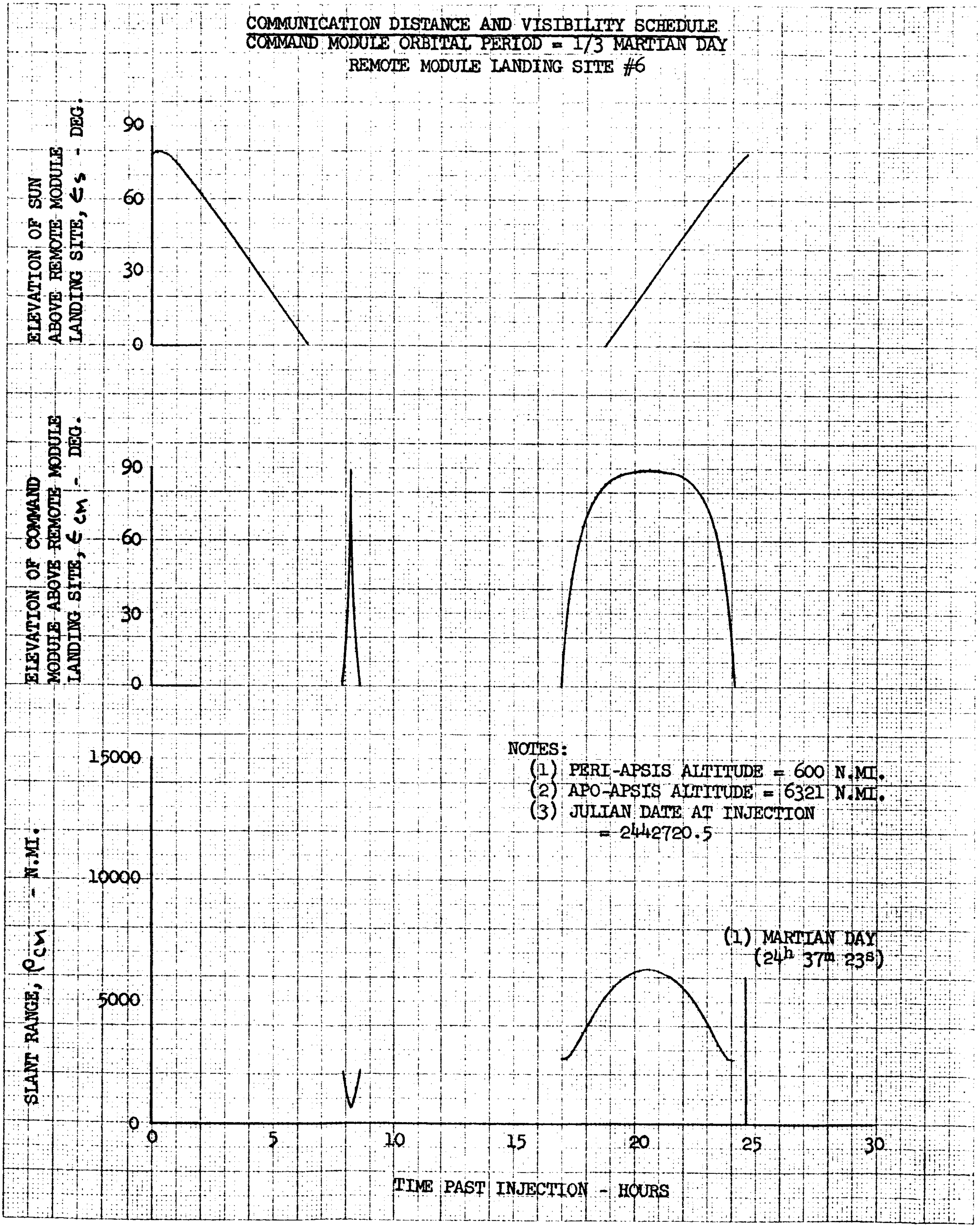

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD - 1/3 MARTIAN DAY
REMOTE MODULE LANDING SITE #2
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 6321 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY ($24^h\ 37^m\ 23^s$)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

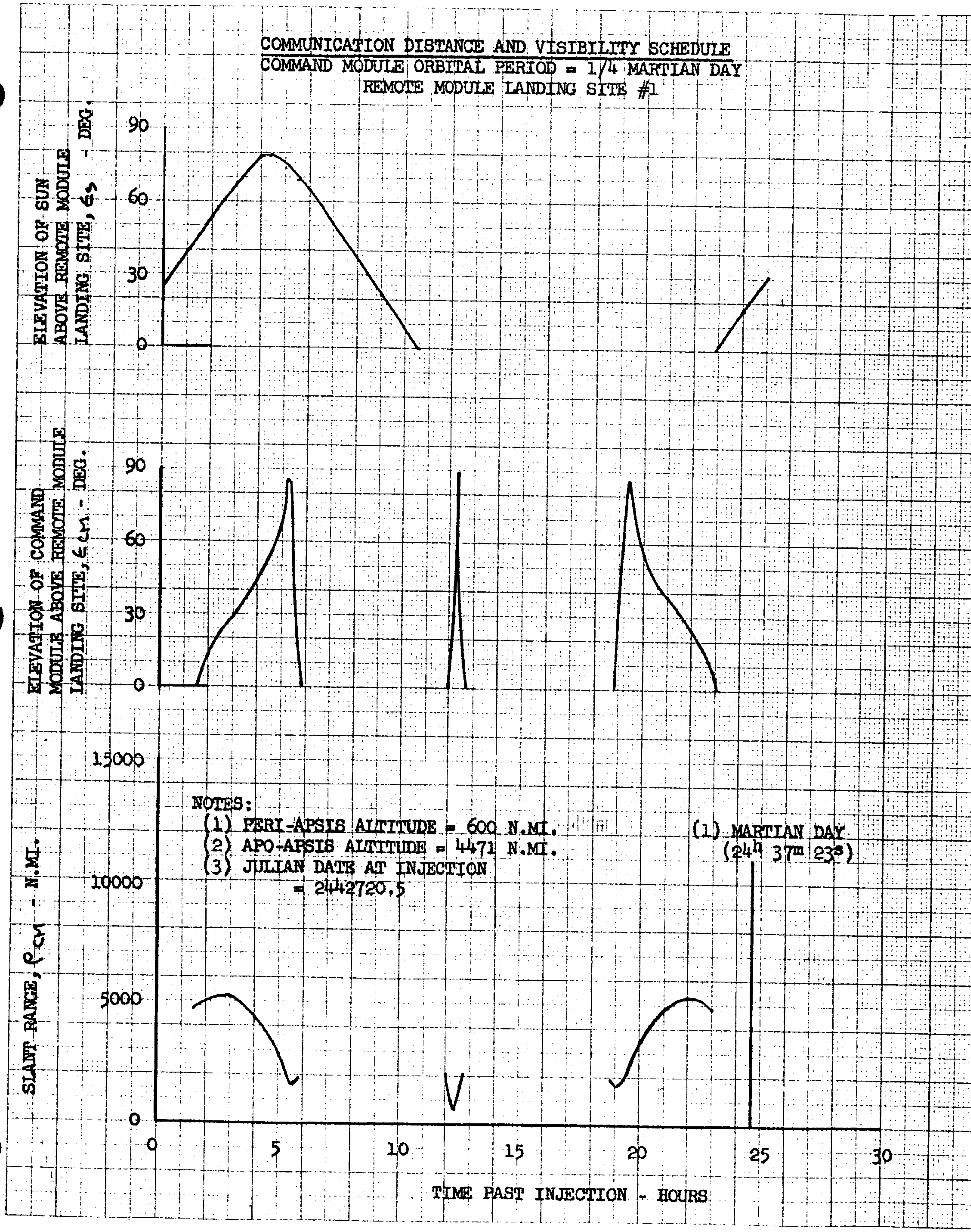
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/3 MARTIAN DAY
REMOTE MODULE LANDING SITE #3



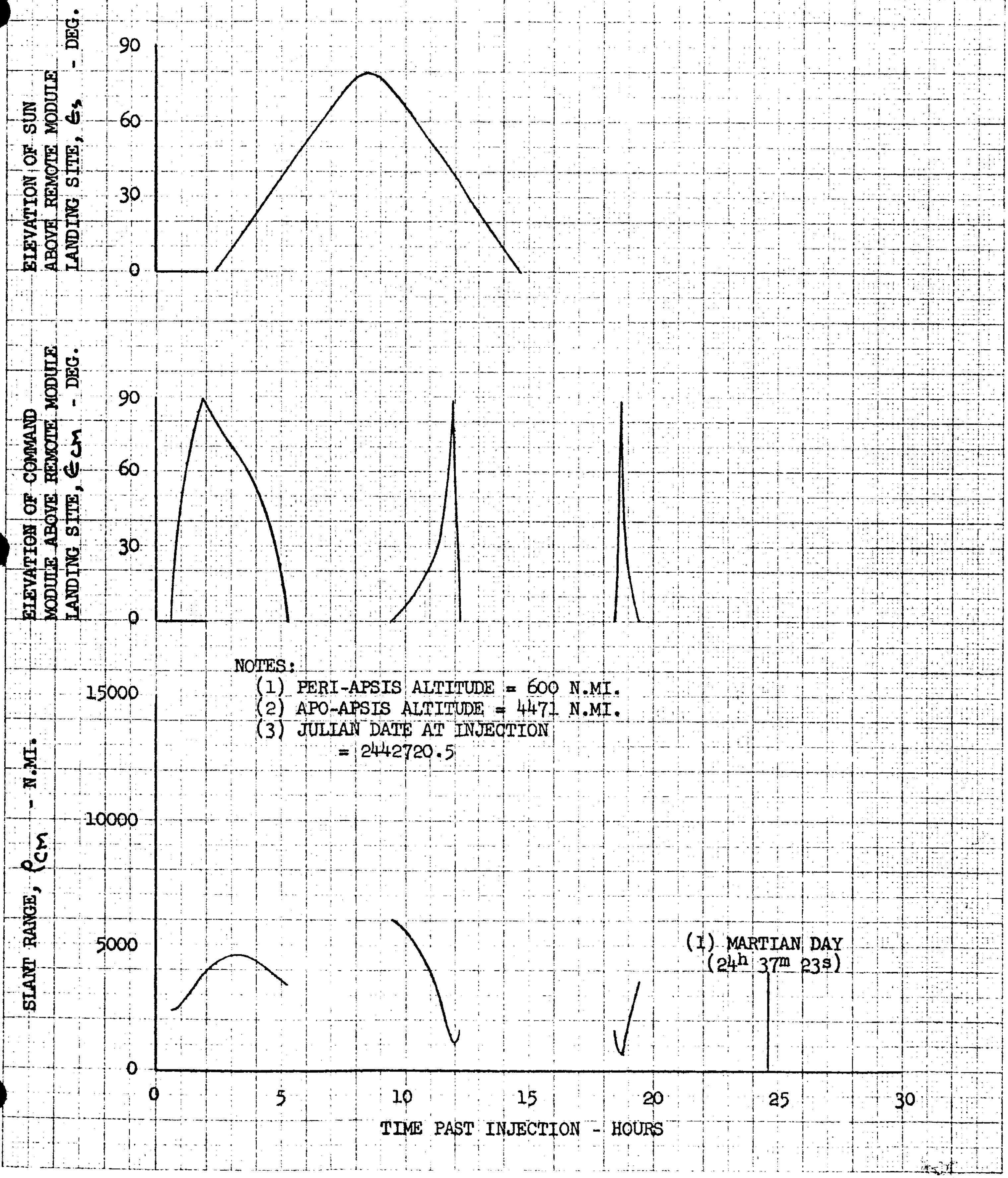

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/3 MARTIAN DAY
REMOTE MODULE LANDING SITE #4
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 6321 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

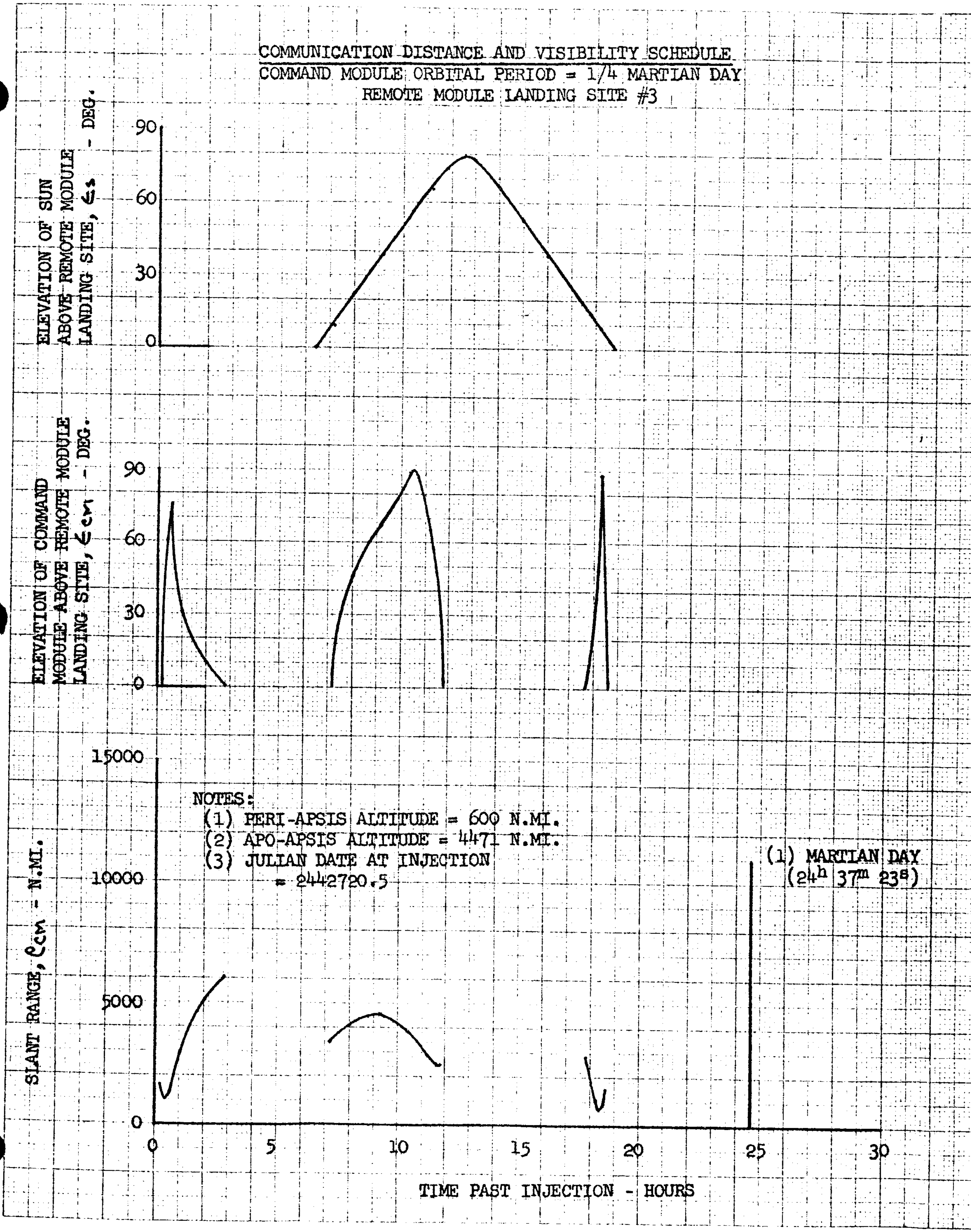

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/3 MARTIAN DAY
REMOTE MODULE LANDING SITE #5
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 6321 N.MI.
(3) JULIAN DATE AT INJECTION = 244.2720.5
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS


COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/3 MARTIAN DAY
REMOTE MODULE LANDING SITE #6
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 6321 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

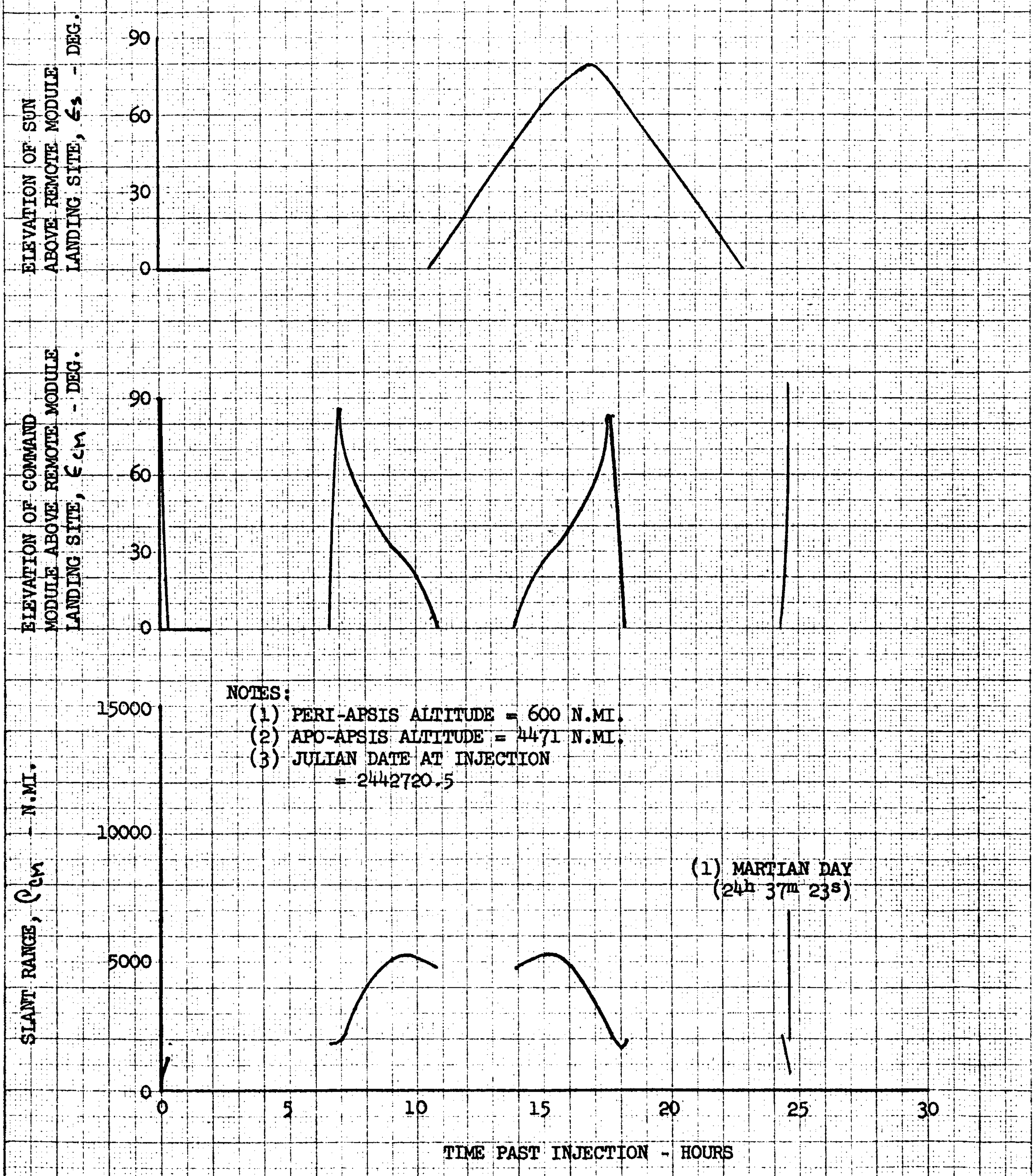

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/4 MARTIAN DAY
REMOTE MODULE LANDING SITE #1
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 4471 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

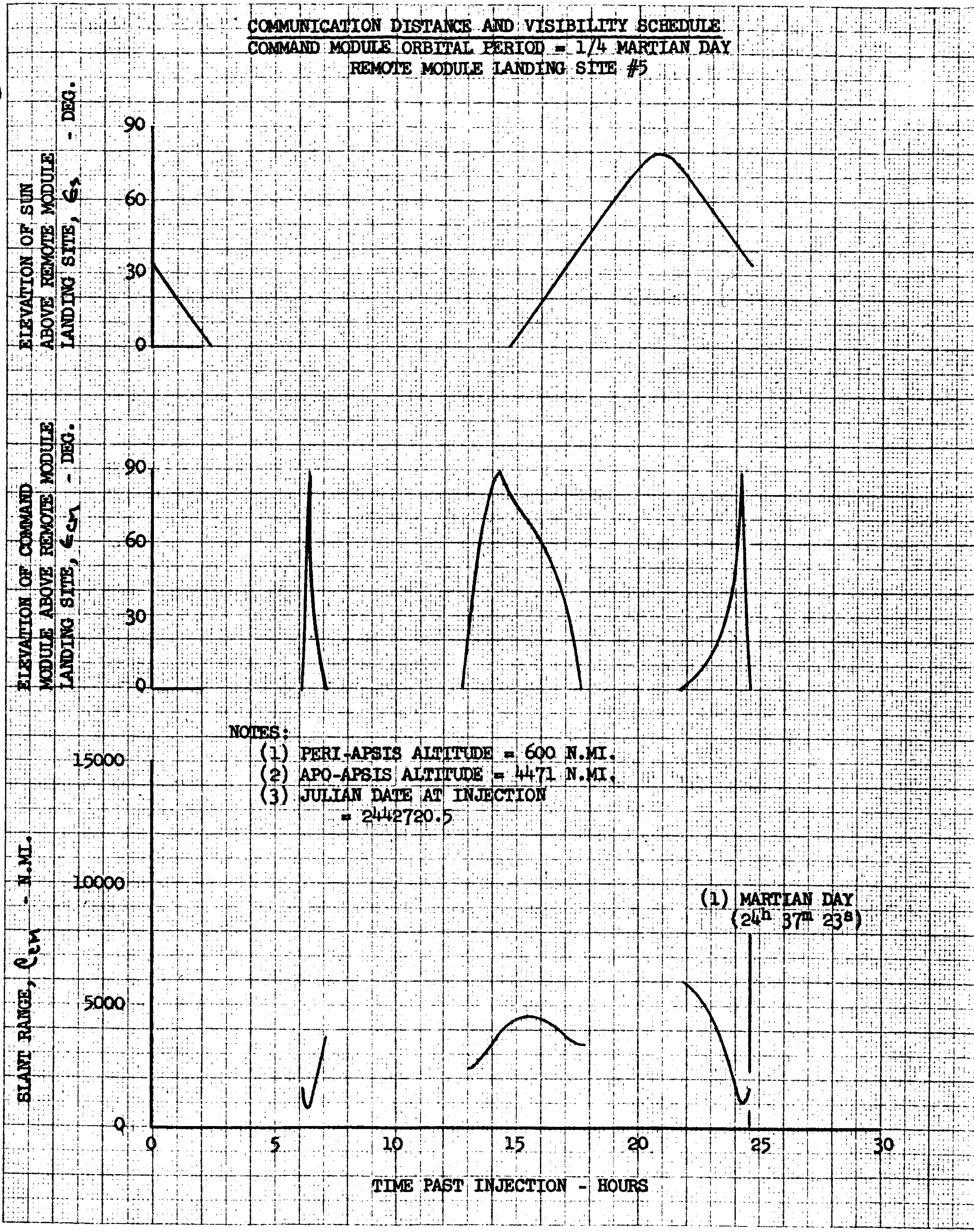
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/4 MARTIAN DAY
REMOTE MODULE LANDINGS SITE #2

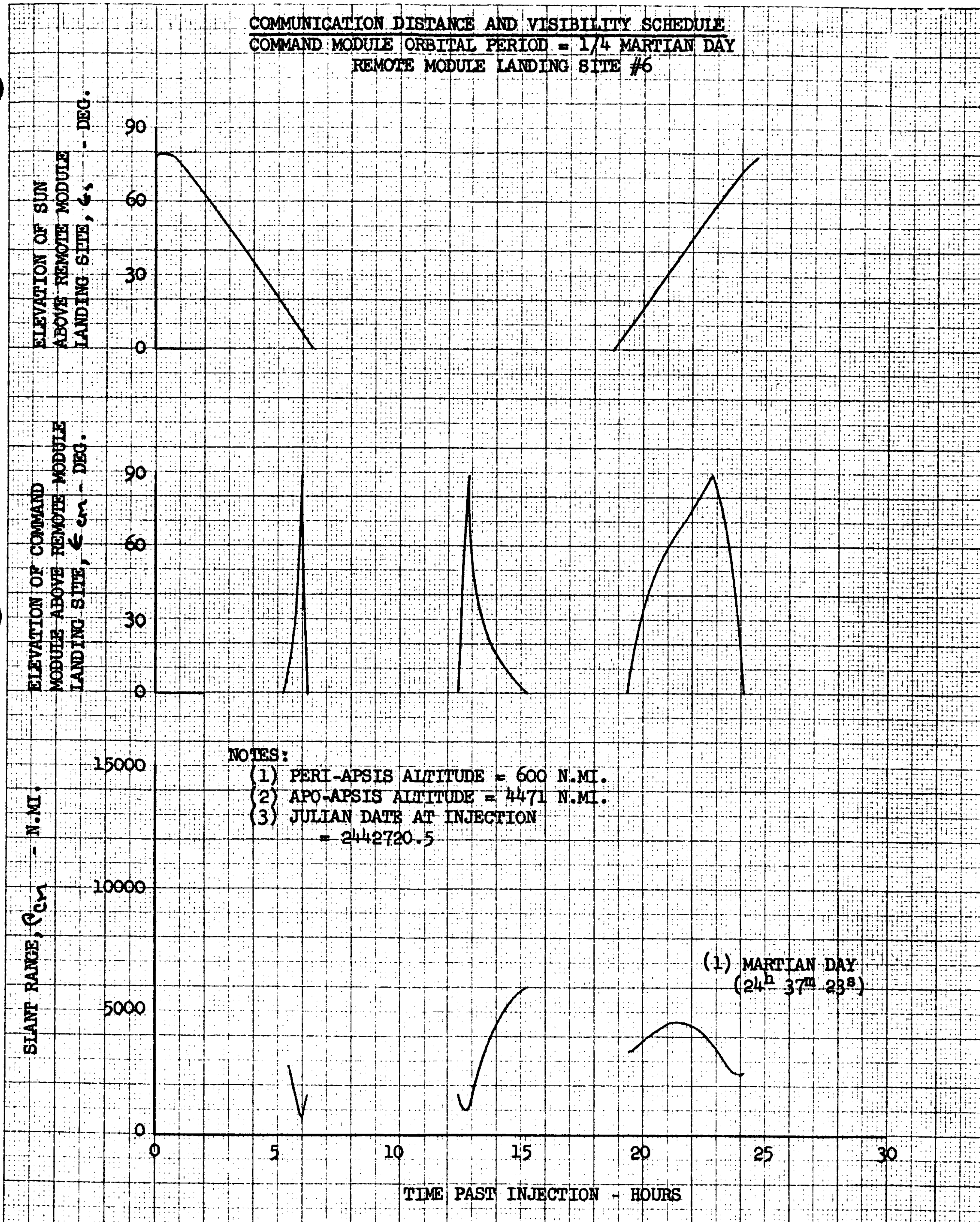


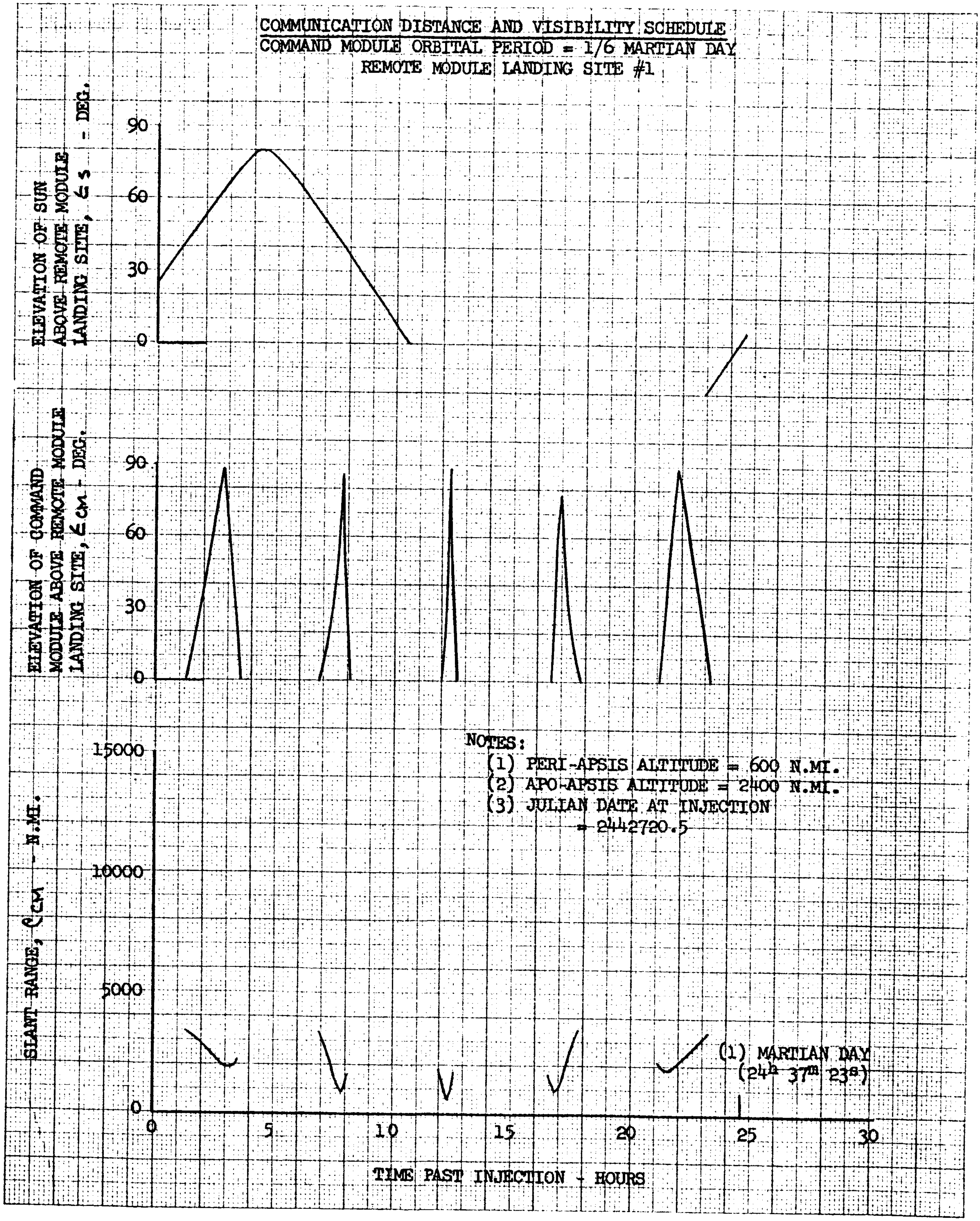

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/4 MARTIAN DAY
REMOTE MODULE LANDING SITE #3
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{cm} - DEG.
SLANT RANGE, ρ_{cm} - N.MI.
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 4471 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY (24^h 37^m 23^s)
TIME PAST INJECTION - HOURS
0
5
10
15
20
25
30
90
60
30
0
15000
10000
5000

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/4 MARTIAN DAY
REMOTE MODULE LANDING SITE #4



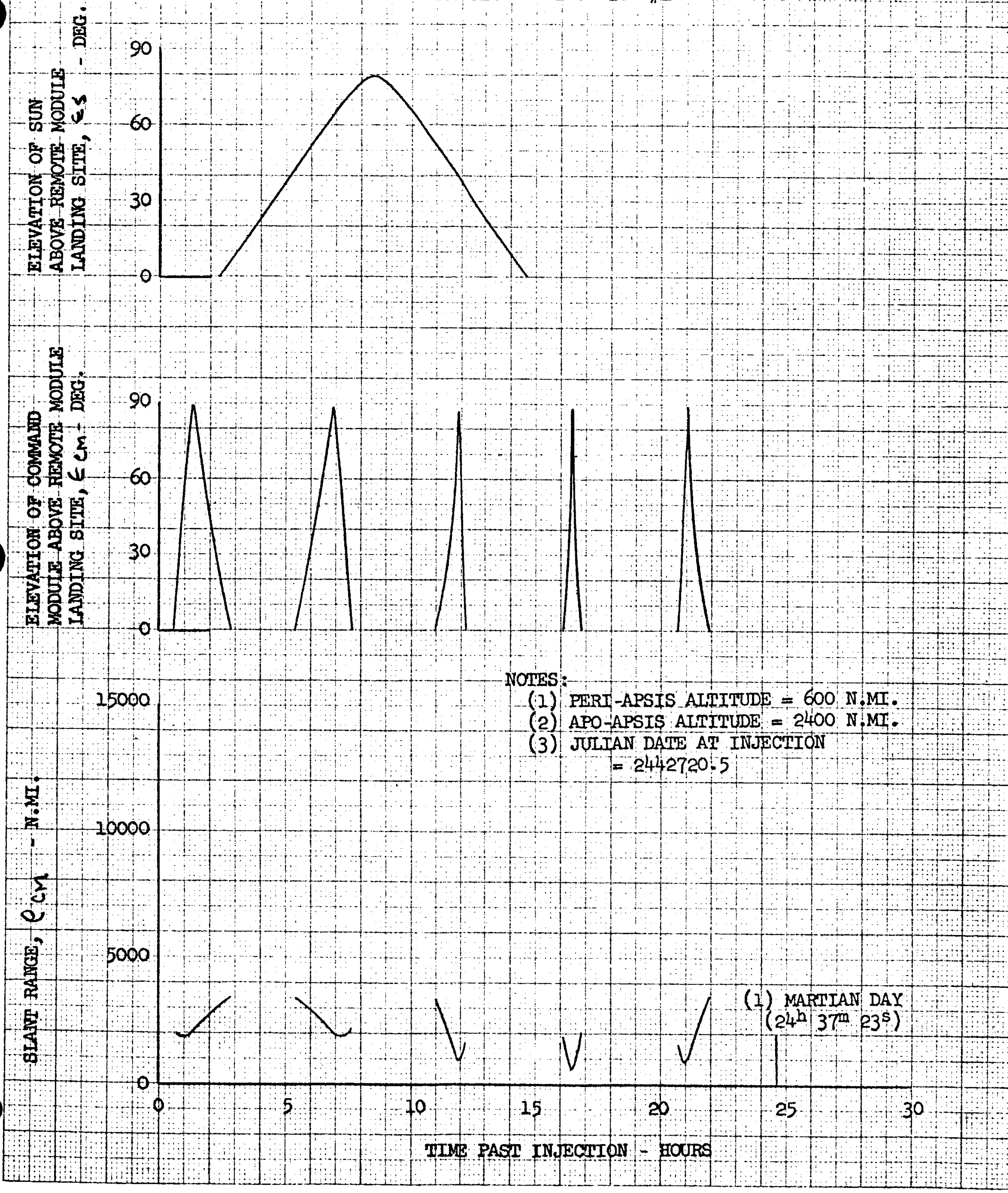

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/4 MARTIAN DAY
REMOTE MODULE LANDING SITE #5
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{cm} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 4471 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{cm} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

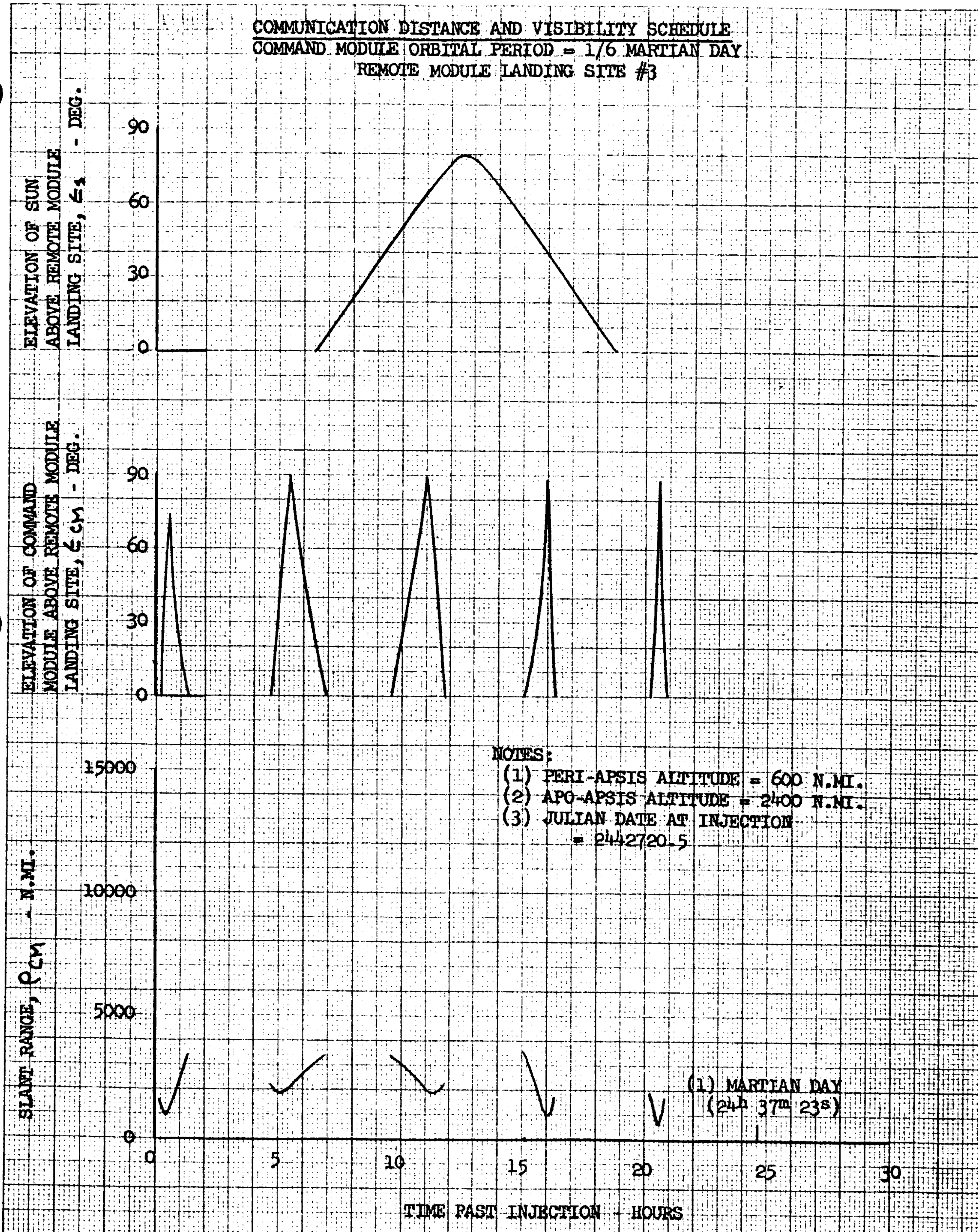

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/4 MARTIAN DAY
REMOTE MODULE LANDING SITE #6
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{cm} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 4471 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{cm} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS



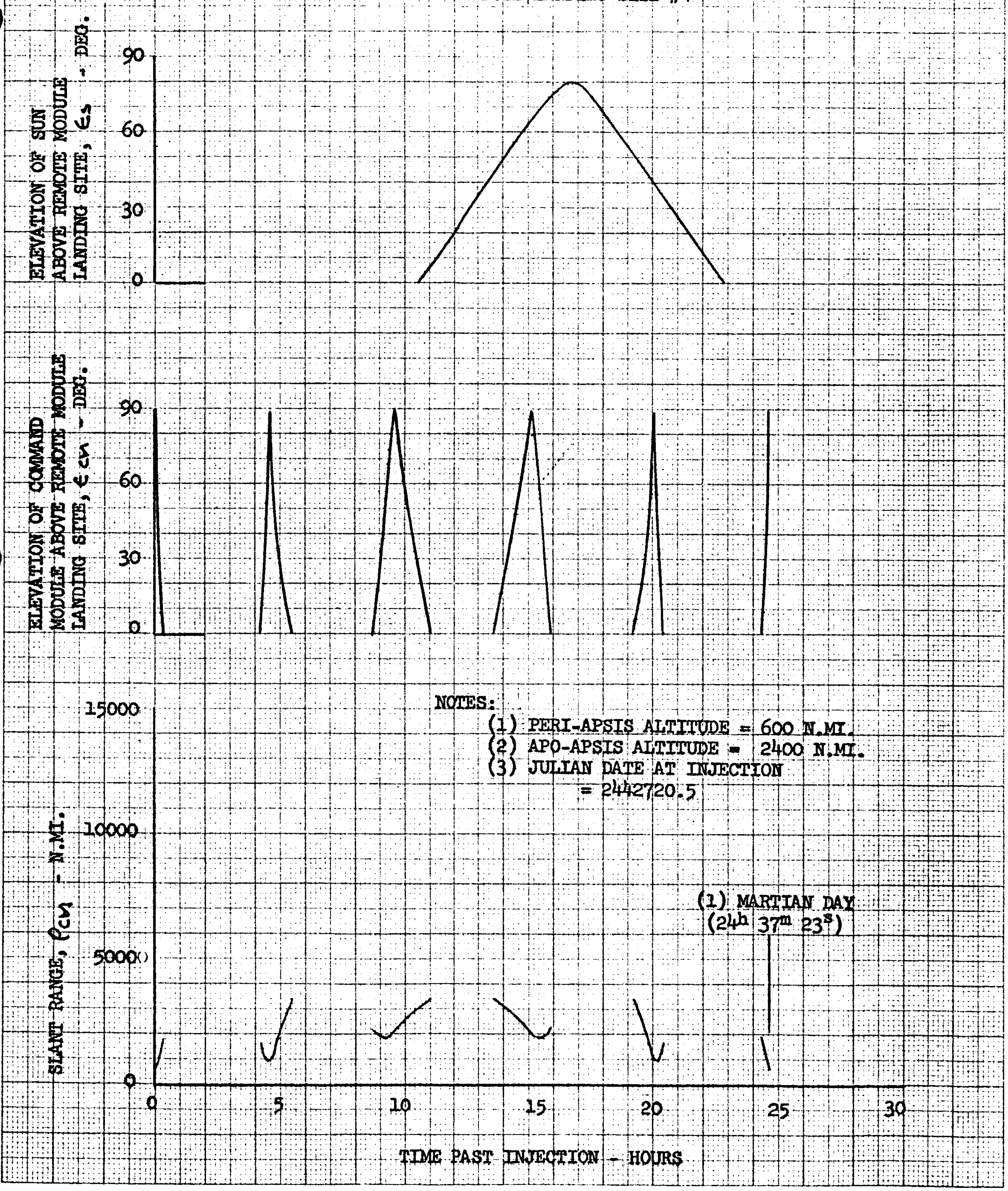
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/6 MARTIAN DAY
REMOTE MODULE LANDING SITE #1
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_S - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 2400 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

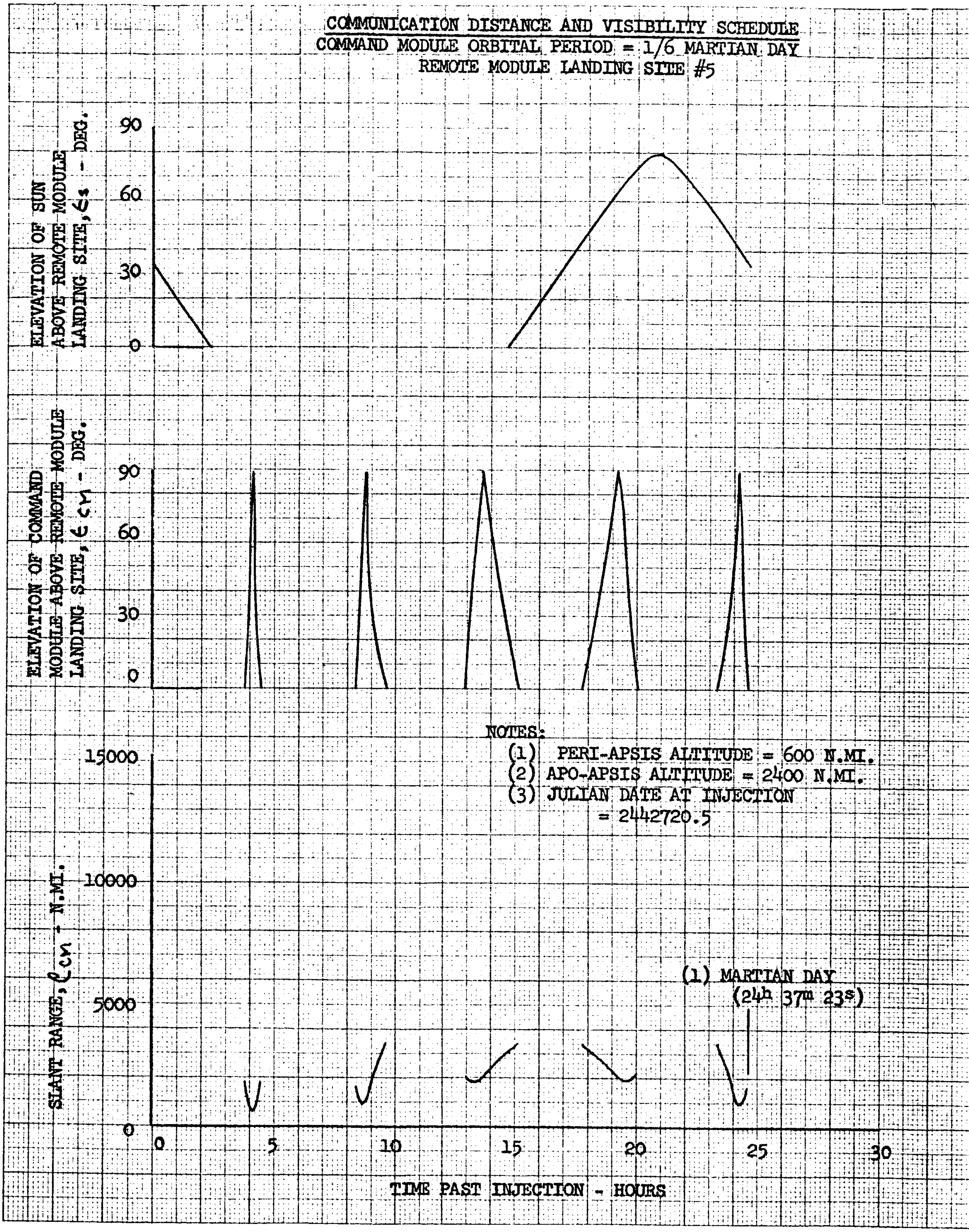
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/6 MARTIAN DAY
REMOTE MODULE LANDING SITE #2

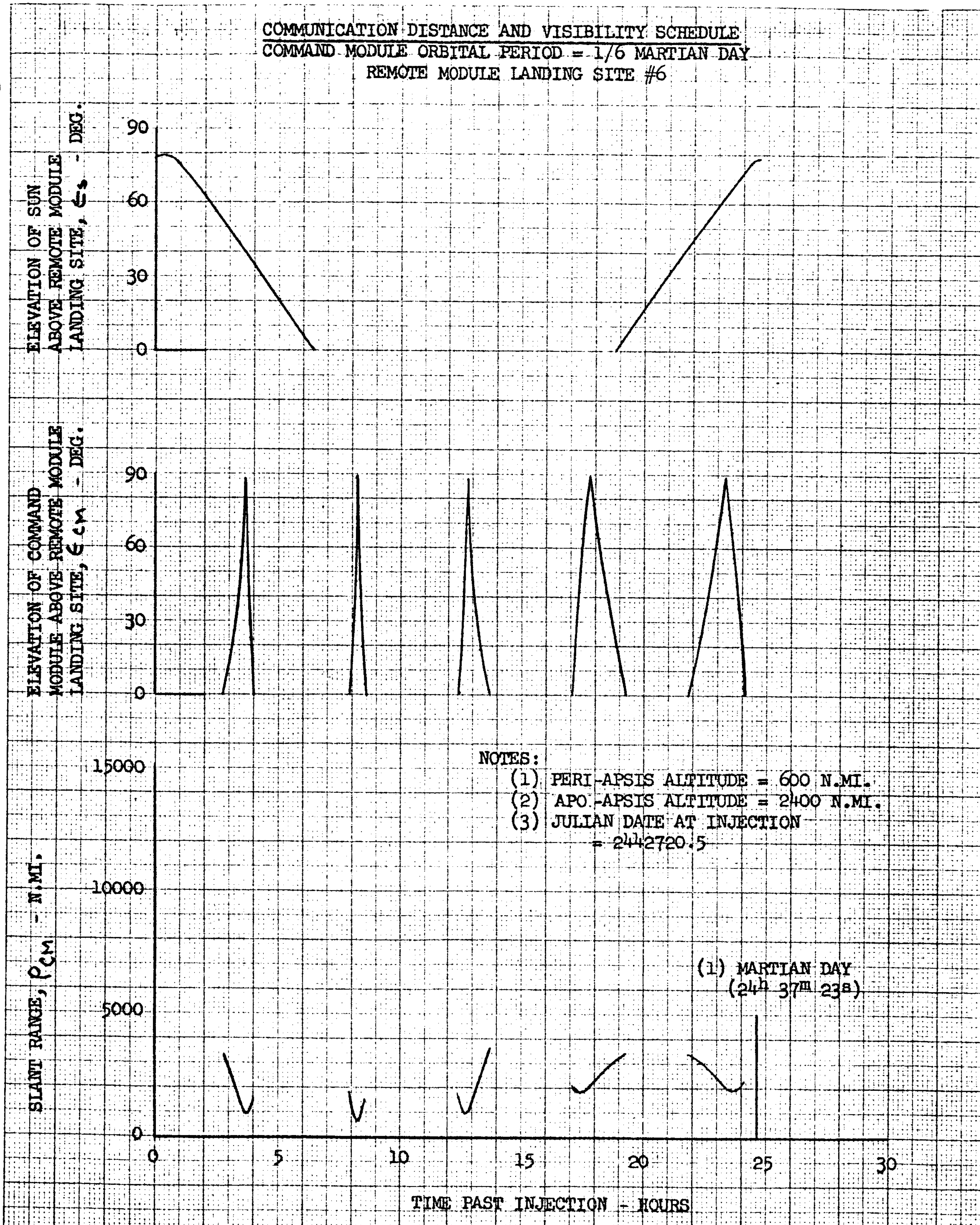



COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/6 MARTIAN DAY
REMOTE MODULE LANDING SITE #3
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 2400 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY
(24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

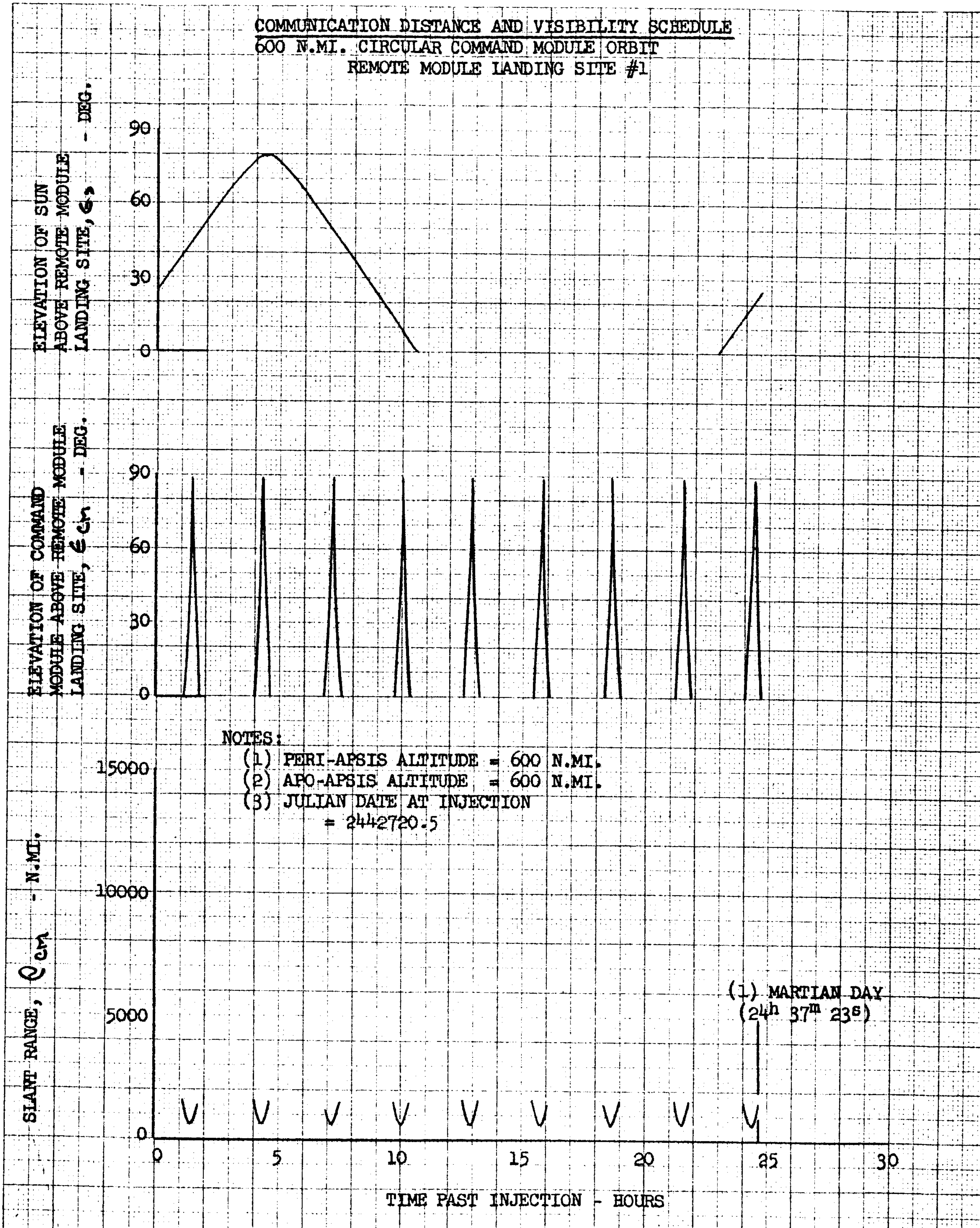
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/6 MARTIAN DAY
REMOTE MODULE LANDING SITE #4

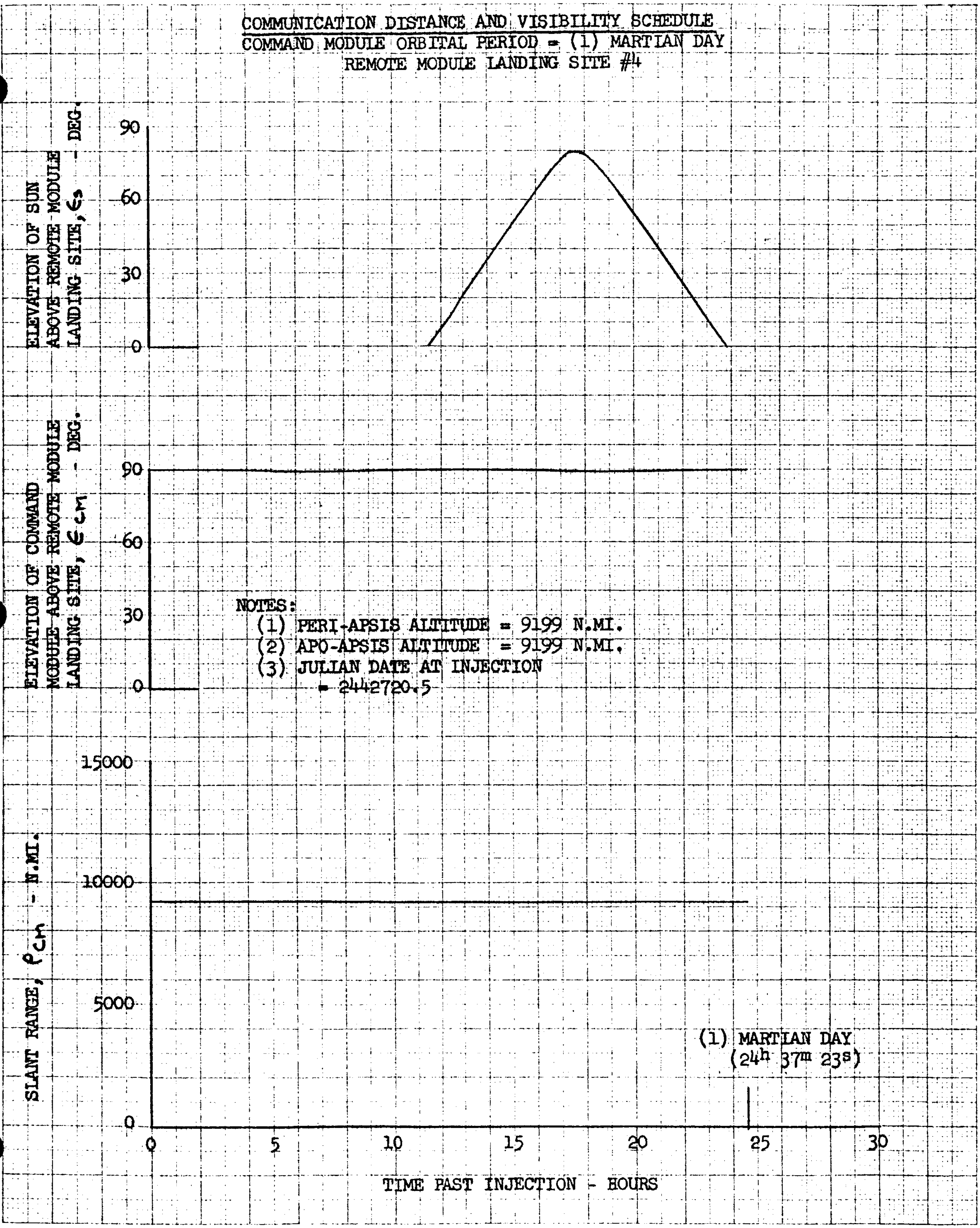


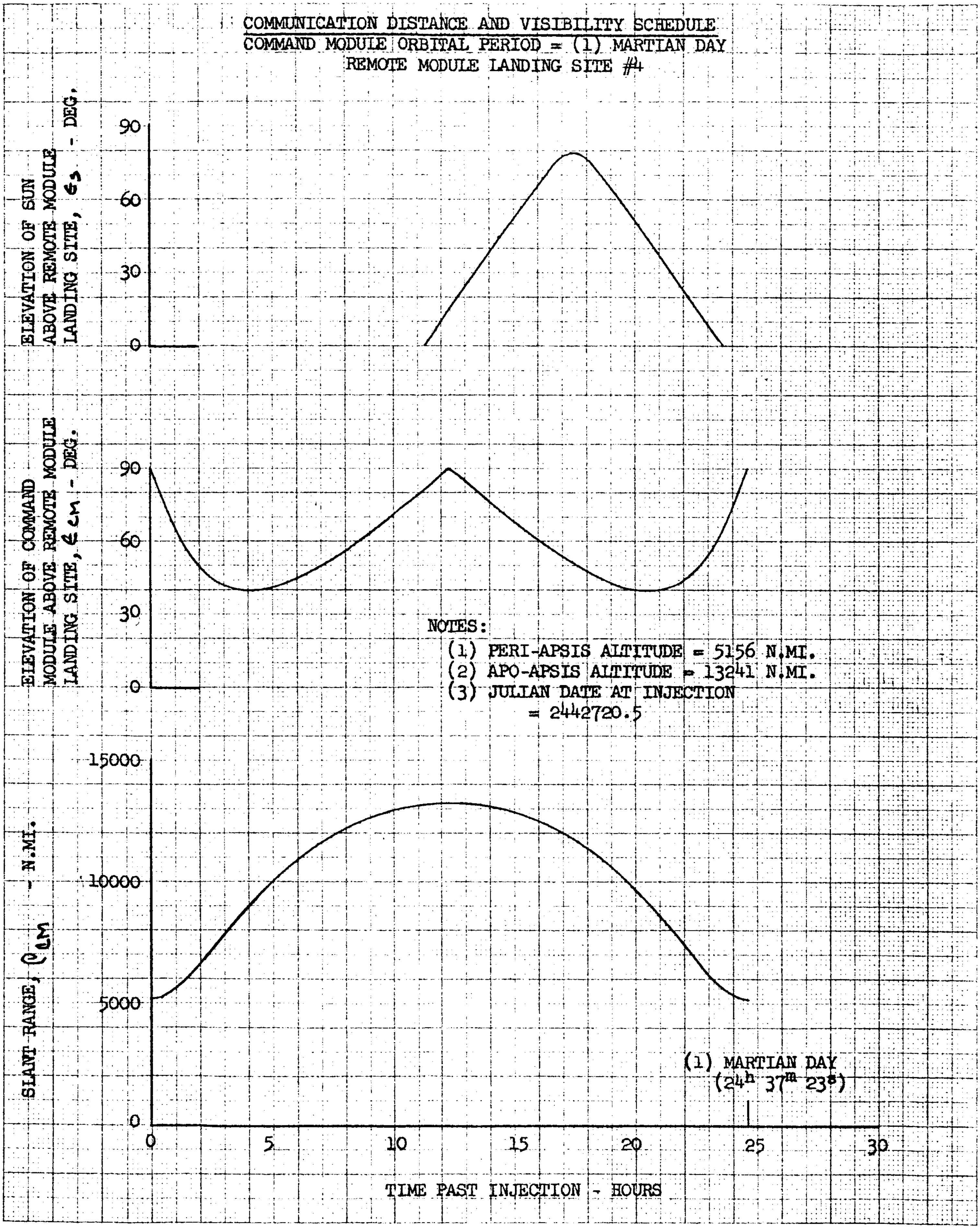

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/6 MARTIAN DAY
REMOTE MODULE LANDING SITE #5
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 2400 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY
(24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS



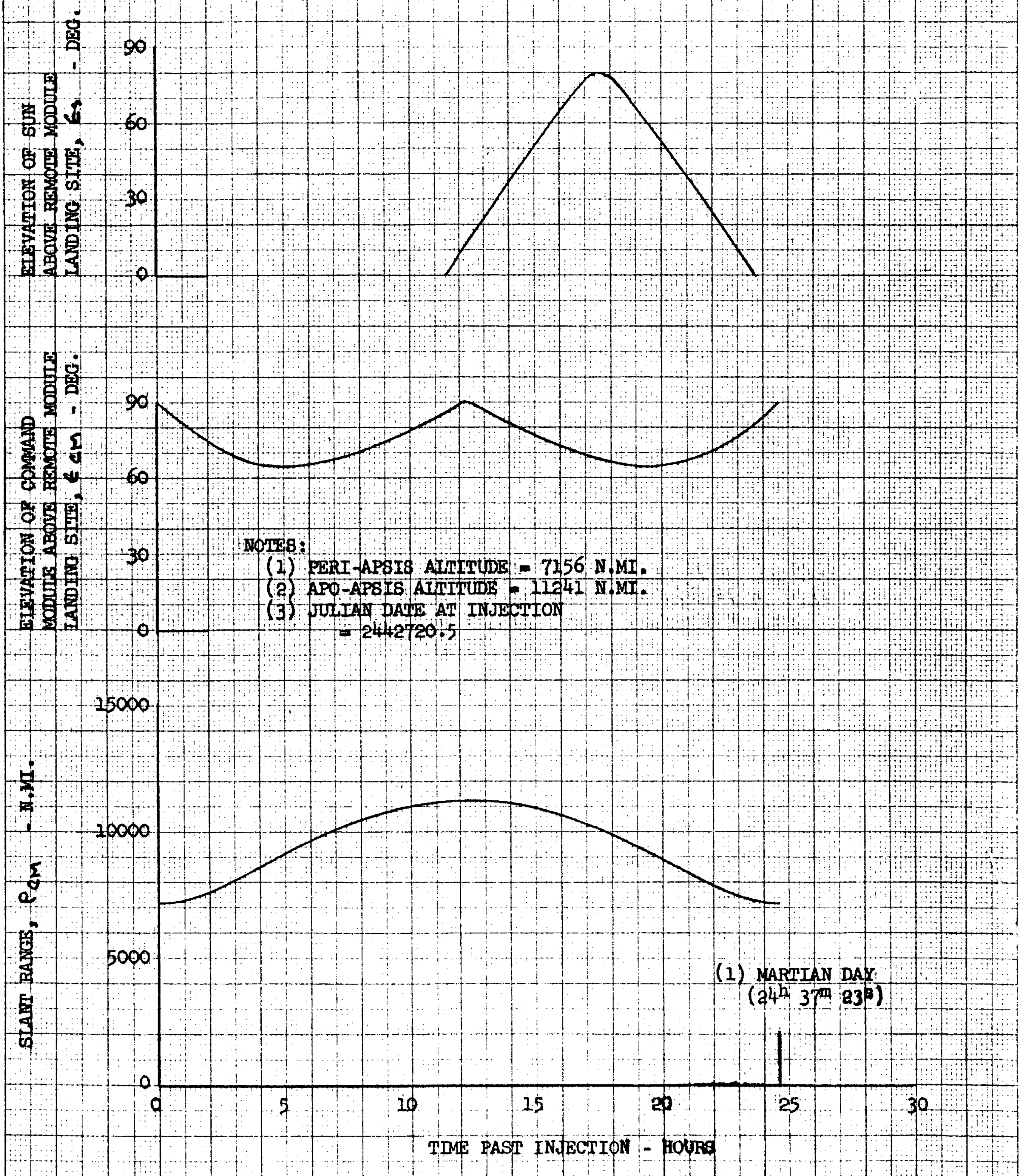
COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = 1/6 MARTIAN DAY
REMOTE MODULE LANDING SITE #6
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 2400 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY ($24^h\ 37^m\ 23^s$)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

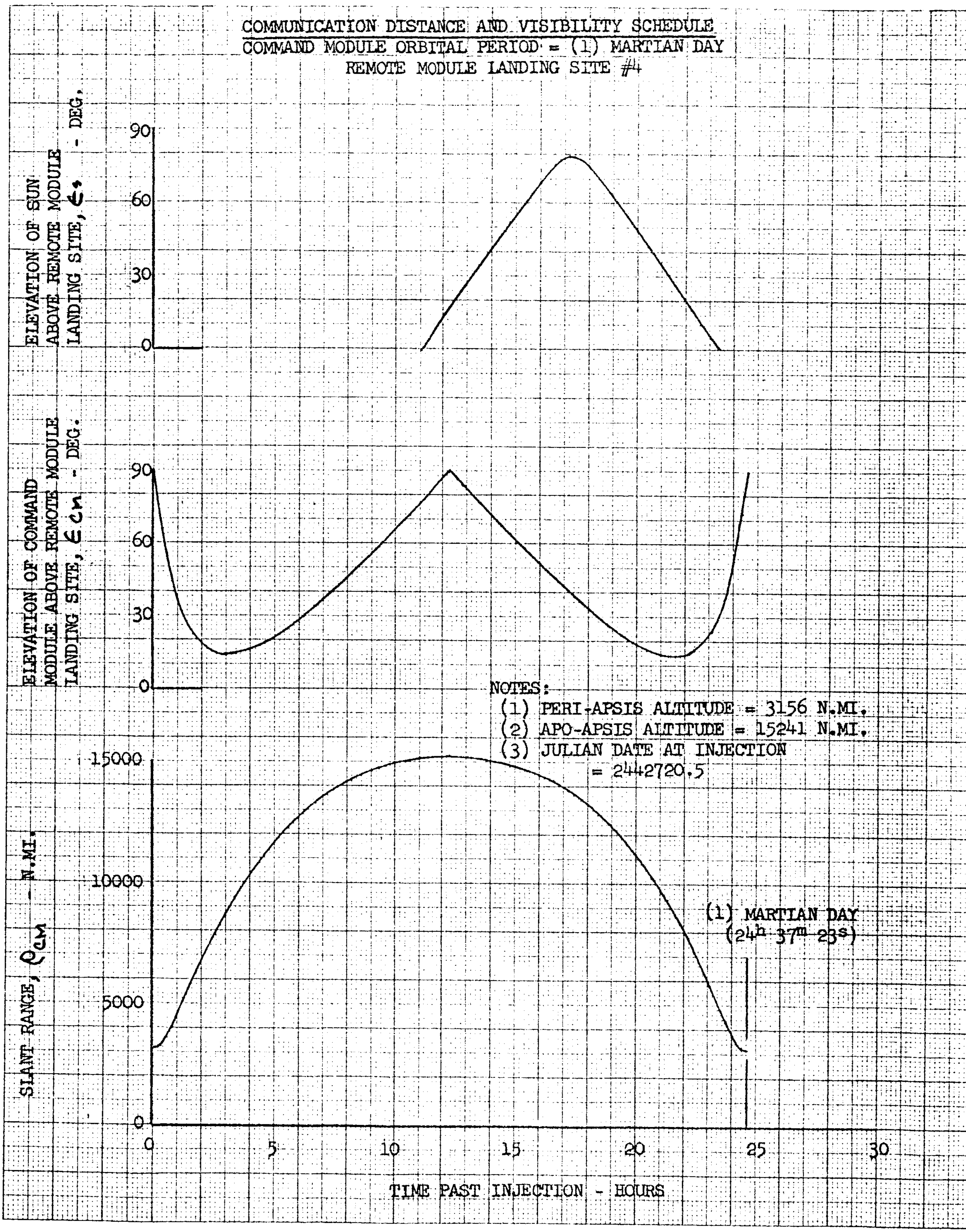

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
600 N.MI. CIRCULAR COMMAND MODULE ORBIT
REMOTE MODULE LANDING SITE #1
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{cm} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 600 N.MI.
(2) APO-APSIS ALTITUDE = 600 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{cm} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS


COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = (1) MARTIAN DAY
REMOTE MODULE LANDING SITE #4
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{cm} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 9199 N.MI.
(2) APO-APSIS ALTITUDE = 9199 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{cm} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY (24^h 37^m 23^s)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

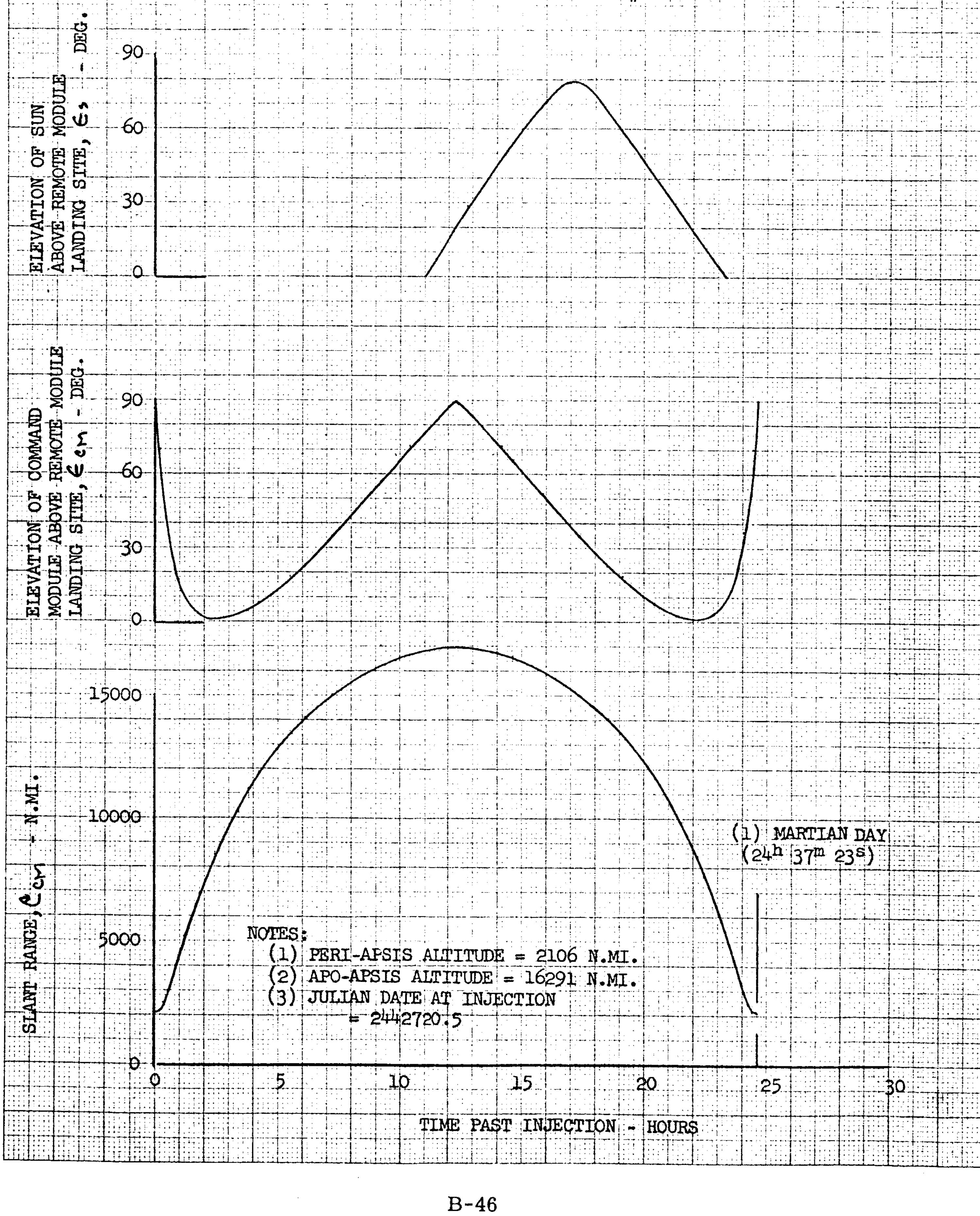

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = (1) MARTIAN DAY
REMOTE MODULE LANDING SITE #4
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_S - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 5156 N.MI.
(2) APO-APSIS ALTITUDE = 13241 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY
($24^h\ 37^m\ 23^s$)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = (1) MARTIAN DAY
REMOTE MODULE LANDING SITE #4

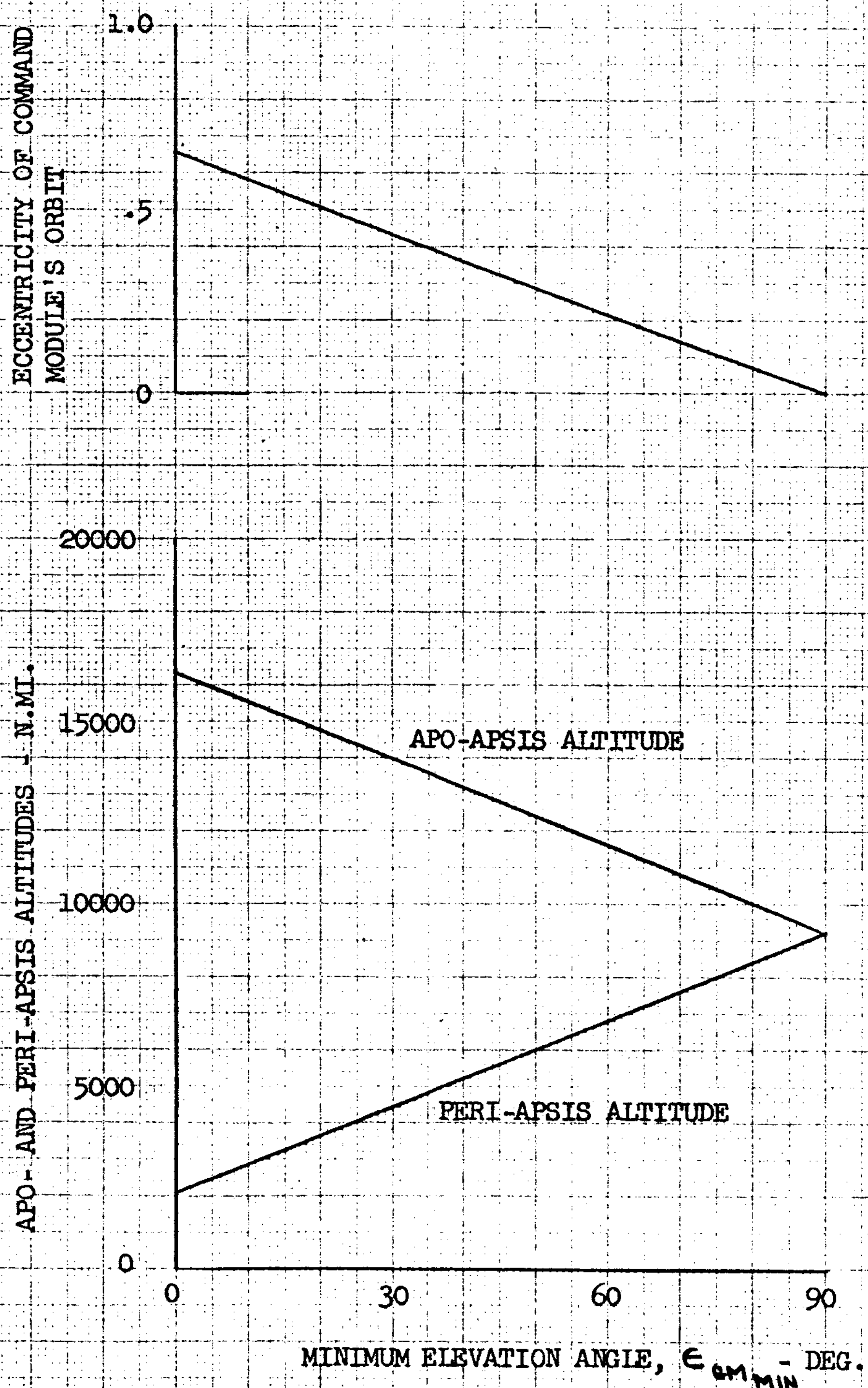



COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = (1) MARTIAN DAY
REMOTE MODULE LANDING SITE #4
ELEVATION OF SUN ABOVE REMOTE MODULE LANDING SITE, ϵ_s - DEG.
90
60
30
0
ELEVATION OF COMMAND MODULE ABOVE REMOTE MODULE LANDING SITE, ϵ_{CM} - DEG.
90
60
30
0
NOTES:
(1) PERI-APSIS ALTITUDE = 3156 N.MI.
(2) APO-APSIS ALTITUDE = 15241 N.MI.
(3) JULIAN DATE AT INJECTION = 2442720.5
SLANT RANGE, ρ_{CM} - N.MI.
15000
10000
5000
0
(1) MARTIAN DAY
($24^h\ 37^m\ 23^s$)
0
5
10
15
20
25
30
TIME PAST INJECTION - HOURS

COMMUNICATION DISTANCE AND VISIBILITY SCHEDULE
COMMAND MODULE ORBITAL PERIOD = (1) MARTIAN DAY
REMOTE MODULE LANDING SITE #4



MINIMUM ELEVATION FOR SYNCHRONOUS ORBITS OF VARIOUS ECCENTRICITIES



overhead the injection point.

In summary, the synchronous orbits provide continuous communication with the remote module for the entire 50 day capture period provided the communication system has sufficient range. Also, the remote module, when landed at Site #4, is illuminated by the sun for 1/2 Martian day each day. Retro velocity requirements for the orbits of the first group are smaller, however, thus allowing more weight for increasing the range of the communication system.

B.4.0 REFERENCES

B.1 "A Study of Early Manned Interplanetary Missions - Final Summary Report," Contract No. NA 8-5026, General Dynamics Astronautics, Rept. No. AOK 63-0001, 31 January 1963 (UNCLASSIFIED)

B.2 "Satellite Ephemeris Routine, LVVC-17," W. F. Dobson and H. U. Everett, LTV Astronautics, Rept. No. 00.343, 13 Feburary 1964 (UNCLASSIFIED)

APPENDIX C

DERIVATION OF A TECHNIQUE TO SIMULATE

COMMAND MODULE'S POSITION RELATIVE TO REMOTE MODULE

REMOTE MAN-MACHINE SYSTEMS

NASA CONTRACT NO. NASw-744 LTV ASTRONAUTICS

Prepared by:

J. W. Brice Jr.

J. W. Brice, Jr.

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LIST OF FIGURES

NOMENCLATURE

ENGLISH SYMBOLS

A_E	The right ascension of the Earth relative to the Martian planetocentric coordinate system.
A_S	The right ascension of the Sun relative to the Martian planetocentric coordinate system.
A.U.	Astronomical unit.
CENTRAL MERIDIAN	The meridian of Martian planetographic longitude which crosses the center of the Martian disc as seen from the Earth.
D_E	The declination of the Earth relative to the Martian planetocentric coordinate system.
declination	Celestial latitude measured positive north and negative south from a planet's equator in a planetocentric coordinate system.
D_S	The declination of the Sun relative to the Martian planetocentric coordinate system.
e	Eccentricity of the command module's approach hyperbola about Mars.
E	Specific energy of the command module's approach hyperbola about Mars.
Earth departure window	Permissable range of departure dates from the Earth's sphere of influence.
EQUATOR $\oplus$	The Earth's equator.
EQUATOR ♂	The Martian equator.

NOMENCLATURE (CONTINUED)

$e^2_{1♂}$	Eccentricity of the Martian spheroid squared.
$e_{\odot}$	Eccentricity of the Sun's orbit about Mars.
$e_{♂}$	Eccentricity of Mars' orbit about the Sun.
$f_{♂}$	Flattening of Mars.
G	Universal gravitational constant.
$g_{0♂}$	Acceleration due to gravity on the surface of Mars.
$\bar{i}$	A unit vector pointing in the direction of the Earth's vernal equinox.
i_v	Inclination of the command module's Martian orbit measured from the Martian equator.
$i_{\odot}$	Inclination of the Sun's orbit about Mars measured from the Martian equator.
$i_{♂}$	Inclination of Mars' orbit about the Sun measured from the Earth's equator.
$\bar{j}$	A unit vector lying in the Earth's equatorial plane and perpendicular to the Earth's vernal equinox direction.
J	The specific angular momentum of the command module's approach hyperbola about Mars.
J.D.	Julian date.
JD_i	Julian date at the time that the command module achieves its Martian orbit.
JD_{π}	Julian date of perihelion passage of Mars in its orbit about the Sun or of the Sun in its orbit about Mars.

NOMENCLATURE (CONTINUED)

$JD_{0/\Upsilon_{\male}}$	Julian date of passage of the Martian zero meridian across the Martian vernal equinox.
$J_{2_{\male}}$	Coefficient of the second gravitational harmonic of Mars.
$JD_{\oplus_s}$	Julian date at the time of departure from the Earth's sphere of influence.
$JD_{\male_s}$	Julian date at the time of arrival at the Martian sphere of influence.
$\bar{k}$	A unit vector pointing in the north pole direction of the Earth.
$K_{\male}$	Gravity-mass constant for Mars.
L_s	Position of the Sun - measured in the plane of the Sun's orbit about Mars, in the direction of the Sun's motion, from the Martian vernal equinox.
$M_{\male}$	Mass of Mars.
$N_{\oplus}$	North pole of the Earth.
$N_{\male}$	North pole of Mars.
P	Semilatus rectum of the command module's approach hyperbola about Mars.
peri-apsis	The point of closest approach of a trajectory to a planet.
perihelion	The point of closest approach of a planet to the Sun.

NOMENCLATURE (CONTINUED)

planetocentric coordinates	A planet-centered coordinate system where the x axis points in the direction of the planet's vernal equinox, the z axis points in the direction of the planet's north pole and the y axis lies in the planet's equatorial plane.
planetographic coordinates	A coordinate system fixed on the surface of a planet.
$p_{\odot}$	The semilatus rectum of the Sun's orbit about Mars.
$p_{♂}$	The semilatus rectum of Mars' orbit about the Sun.
right ascension	Celestial longitude measured positive in the direction of a planet's motion about the Sun and measured from the planet's vernal equinox direction in a planetocentric coordinate system.
R_P	Peri-apsis radius of the command module's approach hyperbola about Mars.
R_S	Radius of the Martian sphere of influence.
$R_{♂}$	Radius of Mars.
transmartian	Motion from the vicinity of the Earth to the vicinity of Mars.
$t_{\odot}$	Period of the Sun's orbit about Mars.
$t_{♂}$	Period of Mars' orbit about the Sun.
$\bar{U}_A$	A unit vector pointing in the direction of the vernal equinox direction of Mars (the x axis direction of the Martian planetocentric coordinate system).

$\bar{U}_B$	A unit vector pointing in the y axis direction of the Martian planetocentric coordinate system.
$\bar{U}_E$	A unit vector which points in the negative direction of the command module's hyperbolic excess velocity direction.
$\bar{U}_N$	A unit vector which points in the direction of the north pole of Mars (the z axis direction of the Martian planetocentric coordinate system).
$\bar{U}_R$	A unit vector lying in the plane of Mars' orbit about the Sun and perpendicular to the Martian vernal equinox direction.
$\bar{U}_S$	A unit vector pointing in the Mars-to-Sun direction.
$\bar{U}_T$	A unit vector lying in the plane of the Sun's orbit about Mars and perpendicular to the Mars-to-Sun line.
$\bar{U}_\pi$	A unit vector pointing in the Sun-to-Mars-perihelion direction.
$\bar{U}_O$	A unit vector normal to the plane of Mars' orbit about the Sun.
V_P	Peri-apsis velocity of the command module's approach hyperbola about Mars.
$\bar{V}_\infty$	The hyperbolic excess velocity vector of the command module's approach hyperbola about Mars.
ZERO MERIDIAN	The zero longitude meridian of the Martian planetographic coordinate system.

NOMENCLATURE (CONTINUED)

GREEK SYMBOLS

α_0	The Martian right ascension of the Martian zero meridian.
α_1	The right ascension of the Martian north pole measured relative to the Earth's planetocentric coordinate system.
α_2	Longitude of the $\overline{U}_E$ vector measured from the Mars-to-Sun line, in the plane of the Suns orbit about Mars, and positive in the direction of the Sun's motion.
α_3	The Martian right ascension of the $\overline{U}_E$ vector.
β	Martian planetographic latitude (positive north).
β_{RM}	Martian planetographic latitude of the remote module.
δ_1	The declination of the Martian north pole measured relative to the Earth's planetocentric coordinate system.
δ_2	Latitude of the $\overline{U}_E$ vector measured from the Sun's orbit about Mars.
δ_3	The Martian declination of the $\overline{U}_E$ vector.
ϵ	The angle between the $\overline{U}_E$ vector and the $\overline{R}_S$ vector (see Figure C-15).
ϵ_{CM}	Elevation of the command module above the local horizon of the remote module.
ϵ_S	Elevation of the Sun above the local horizon of the remote module.

NOMENCLATURE (CONTINUED)

η_S	The negative of the true anomaly of the command module's approach hyperbola at the Martian sphere of influence.
$\eta_\odot$	The true anomaly of the Sun in its orbit about Mars at the time of the Martian sphere of influence crossing.
λ	Martian planetographic longitude (positive west).
λ_{RM}	Martian planetographic longitude of the remote module.
λ_o	Martian planetographic longitude of the central meridian.
π_V	Argument of the periapsis point of the command module's approach hyperbola about Mars.
$\pi_\odot$	Argument of perihelion of the Sun's orbit about Mars measured in the Martian planetocentric coordinate system.
$\pi_♂$	Argument of perihelion of Mars' orbit about the Sun measured in the Earth's planetocentric coordinate system.
$\pi_{♂_1}$	Argument of perihelion of Mars' orbit about the Sun measured in the Martian planetocentric coordinate system.
ρ_{CM}	Slant range from the remote module to the command module.
τ	Time in tropical years since the start of the Besselian year of 1950.
$\omega_♂$	The rotational rate of Mars on its axis.

NOMENCLATURE (CONTINUED)

ASTRONOMICAL SYMBOLS

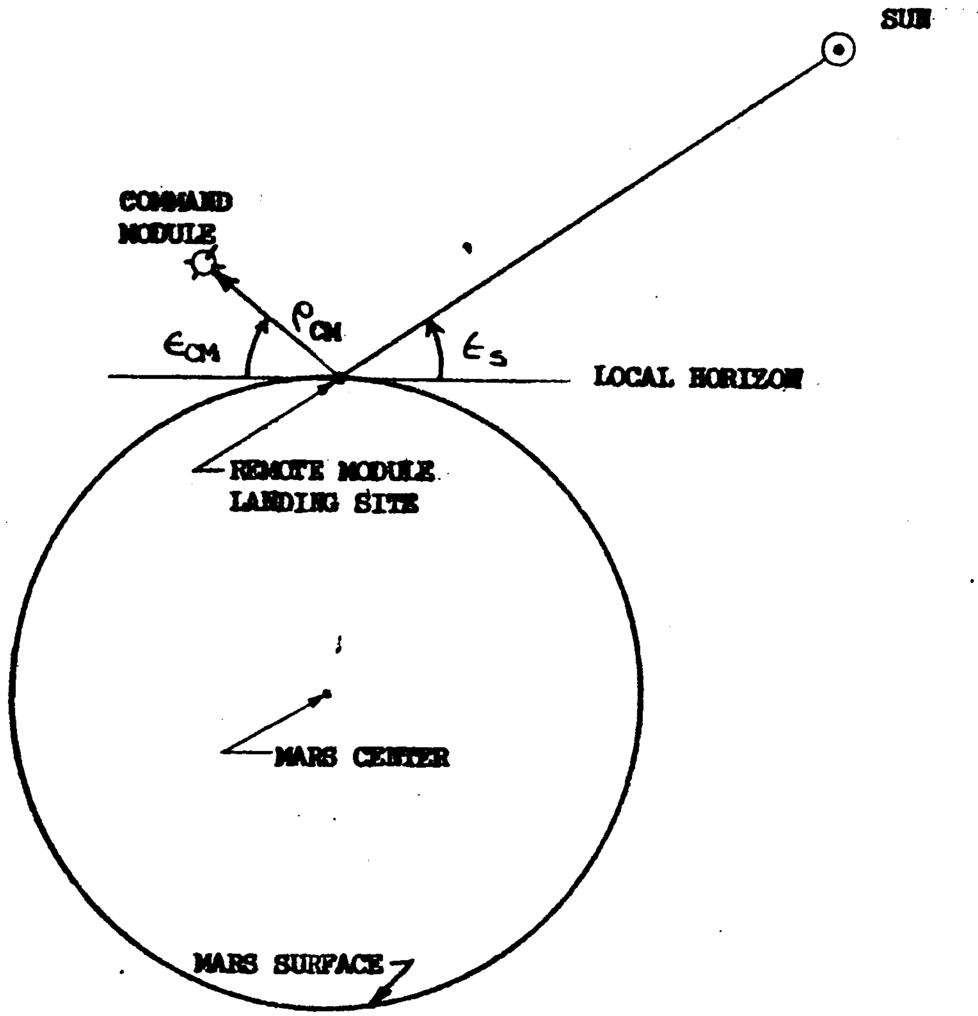
$\odot$	Sun.
$\oplus$	Earth.
♂	Mars.
$♈_{\oplus}$	The Earth's vernal equinox direction.
$♈_{♂}$	The Martian vernal equinox direction.
$☊_{v}$	The ascending node of the command module's Martian orbit (on the Martian equator).
$☋_{v}$	The descending node of the command module's Martian orbit (on the Martian equator).
$☊_{♂}$	The ascending node of Mars' orbit relative to the Sun (on the Earth's equator).

APPENDIX C

DERIVATION OF A TECHNIQUE TO SIMULATE COMMAND MODULE'S POSITION RELATIVE TO REMOTE MODULE

C.1 INTRODUCTION

Appendix B of this report presents data on the communication and illumination problems associated with remote control of a remote module (on the surface of Mars) from a command module in orbit about Mars. Figure C-1 illustrates the problem. In this figure the planet Mars, the Sun, the command module, and the remote module are shown. The elevation ϵ_{CM} of the command module above the remote module's horizon, the elevation ϵ_S of the Sun above the horizon, and the slant range ρ_{CM} of the command module are important parameters in determining the feasibility of remote control of the remote module. The data of Appendix B were calculated through the use of an IBM 7090 digital computer satellite ephemeris routine previously developed at LTV. Since this routine was originally developed to compute ephemerides of satellites in Earth orbits, several changes in gravitational and periodic constants and in coordinate systems were made to accommodate the problem at hand, namely, the generation of ephemeris data for objects in Martian orbits as seen from the Martian surface. It is the purpose of this Appendix to detail the derivation of the appropriate constants for this problem. Consideration is also given to the problem of establishing the orbital elements of a typical Martian orbit of the command module. Such a determination is made for an actual transmartian trajectory.



ρ_{CM}	SLANT RANGE FROM REMOTE MODULE TO COMMAND MODULE
ϵ_{CM}	ELEVATION OF COMMAND MODULE
ϵ_S	ELEVATION OF SUN

FIGURE C-1: COMMUNICATION AND ILLUMINATION GEOMETRY

C.2 DATA REQUIRED FOR SATELLITE EPHEMERIS ROUTINE

The satellite ephemeris routine used to calculate the ephemerides of the command module and the illumination of the remote module's landing site as a function of the location of this site on the Martian surface (shown in Appendix B) is described in reference 1. To obtain these data it was necessary to simulate the orbit of the command module and the orbit of the Sun relative to Mars in the computer routine. Figures C-2 and C-3 illustrate some of the geometrical variables that define the orbit of the Sun and the command module relative to a Mars centered coordinate system consisting of the Martian equator, the vernal equinox of Mars, and the Martian north polar axis. Figure C-4 illustrates how the location of the remote module on the surface of Mars is specified.

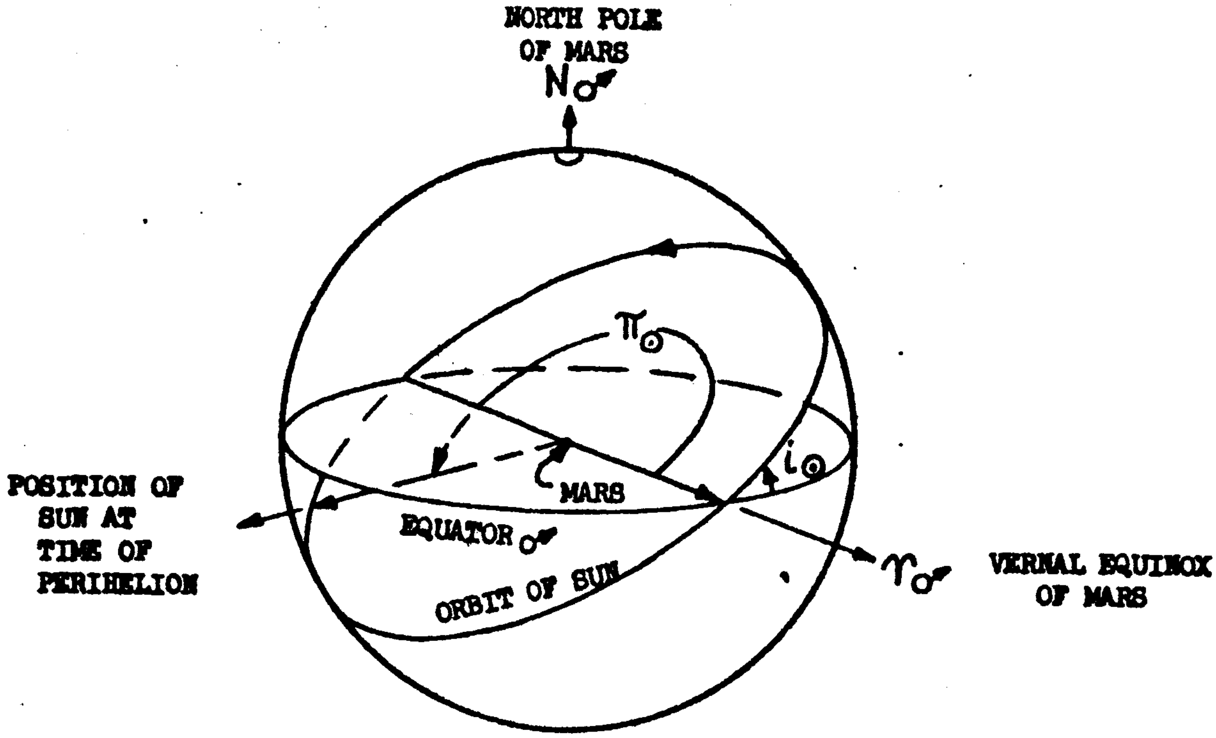


FIGURE C-2: INPUT DATA REQUIRED FOR ORBIT OF SUN

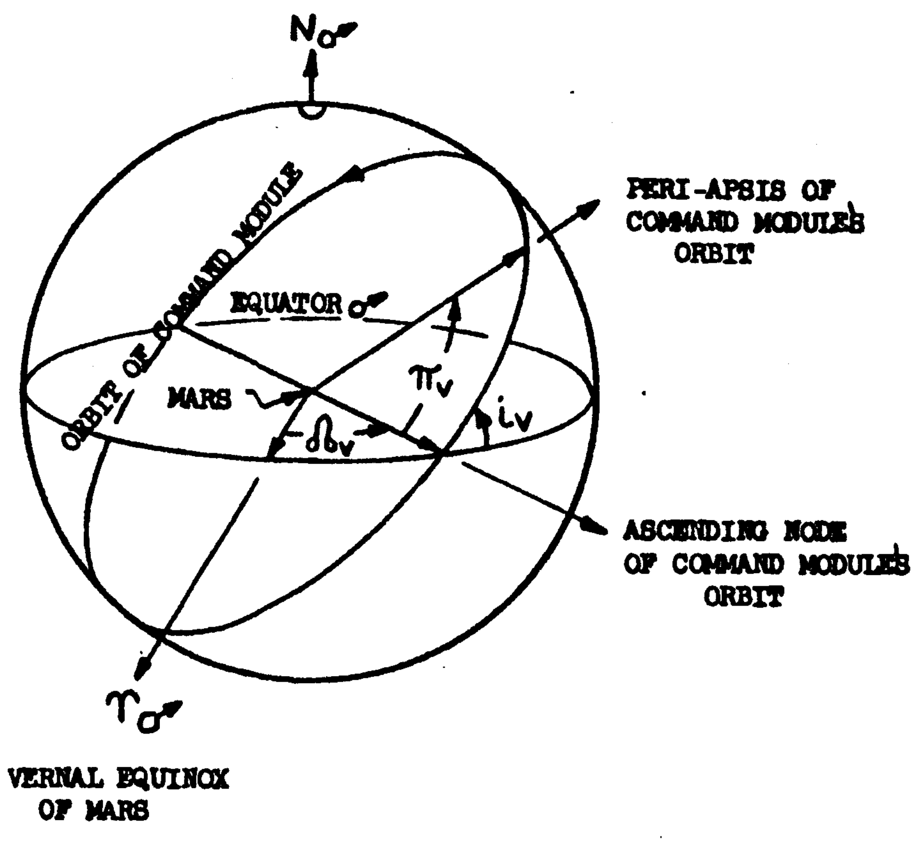


FIGURE C-3: INPUT DATA REQUIRED FOR ORBIT OF COMMAND MODULE

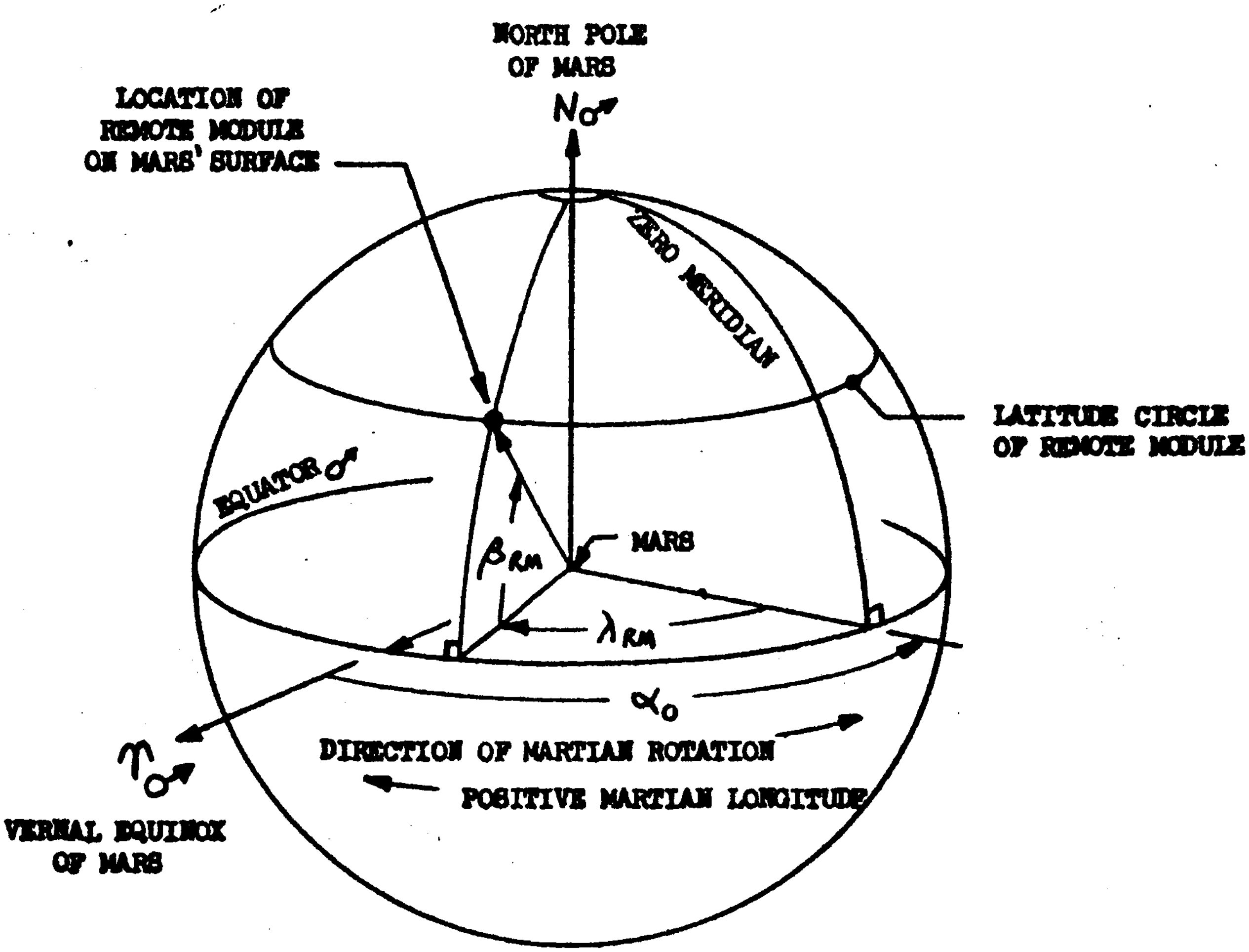


FIGURE C-4: INPUT DATA REQUIRED FOR LOCATING REMOTE MODULE ON THE SURFACE OF MARS

C.3 THE ORBIT OF THE SUN RELATIVE TO MARS

The elements of the orbit of the Sun relative to the Mars centered coordinate system of Figure C-2 were found by the following steps:

(1) The location of the Martian polar axis relative to the Earth's equator is given on page 521 of reference 2.

(2) The orbit of Mars relative to the Sun and the Earth's equator is given in Table I of reference 3.

(3) The Martian vernal equinox direction, $\Upsilon_{♂}$, is determined when the ascending node of the Martian orbit on the Martian equator is found.

(4) The orbit of Mars relative to the Sun, the Martian equator, and the Martian vernal equinox is then determined.

(5) Finally, the coordinate system is shifted from the Sun to Mars and the Martian orbit about the Sun becomes the Sun's orbit about Mars.

Page 521 of The American Ephemeris and Nautical Almanac (reference 2) gives the following relations for the right ascension, α_1, and declination, δ_1, of the north pole of Mars (See Figure C-5):

$$\alpha_1 = 21^h\ 11^m\ 10.42^s + 1.565^s\ \tau$$

$$\delta_1 = 54°\ 39'\ 27'' + 12.60''\ \tau$$

WHERE: τ = time in tropical years since the start of the Besselian year of 1950

$$\tau \approx \frac{\text{J.D.} - 2433282.5}{365.2422}$$

For the epoch 25.59531 May 1960 (JD = 2437081.09531), $\alpha_1 = 317.861°$, $\delta_1 = 54.694°$. In Figure C-6 the longitude of ascending node, $\Omega_{♂}$,

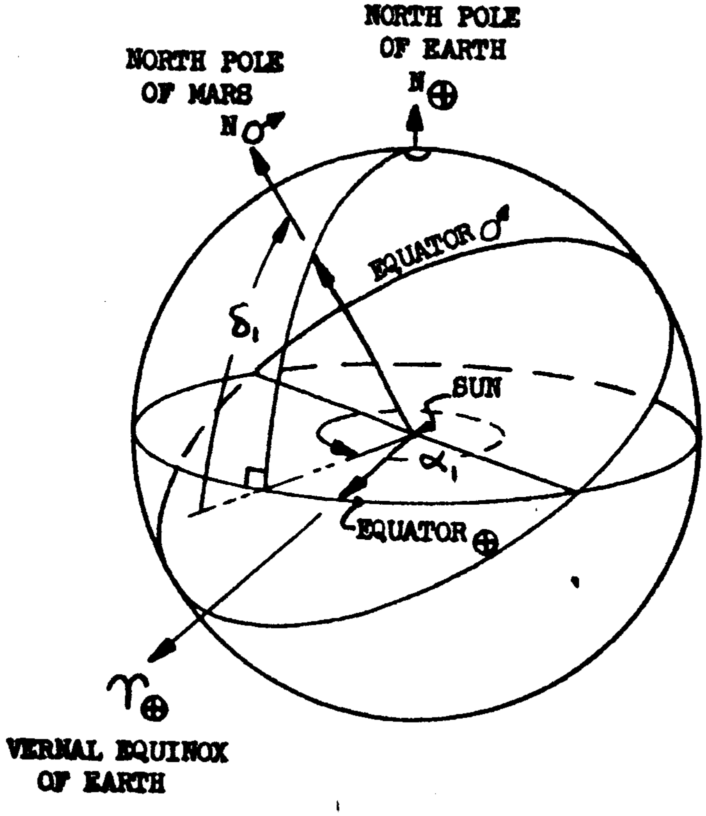


FIGURE C-5: LOCATION OF THE NORTH POLE OF MARS

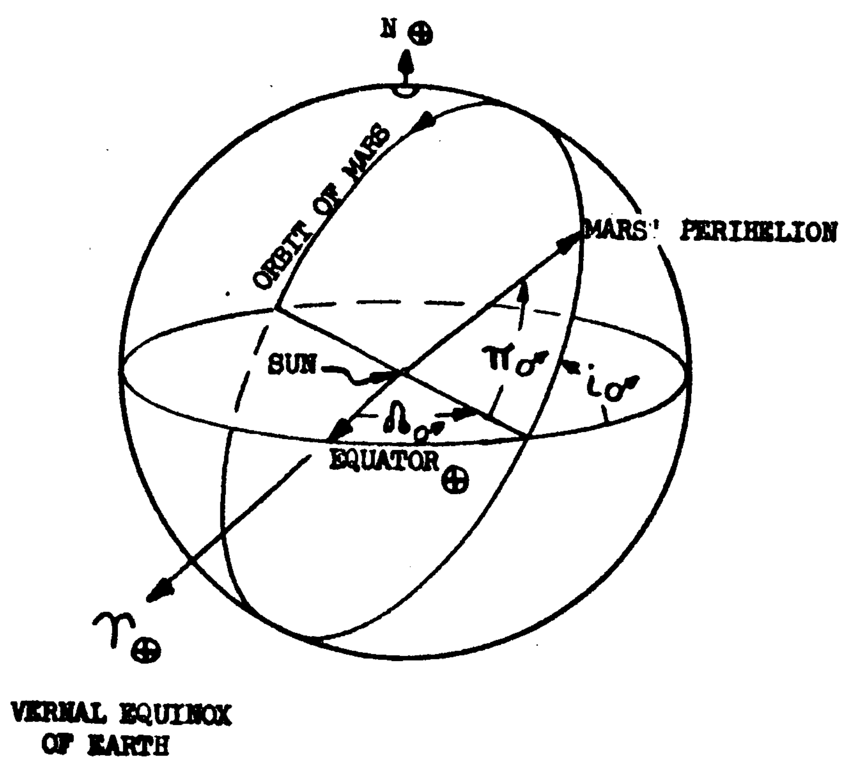


FIGURE C-6: SPATIAL ORIENTATION OF THE MARTIAN ORBIT RELATIVE TO THE EARTH'S EQUATOR inclination $i_{♂}$, and argument of perihelion, $\pi_{♂}$, of the Martian orbit relative to the Sun and the Earth's equator and vernal equinox are shown. These three variables define the spatial orientation of the Martian orbit. Table I of reference 3 gives the following values for these variables:

EPOCH = 23 SEPTEMBER 1960, J.D. = 2437200.5

MEAN EARTH'S EQUATOR AND MEAN EARTH'S VERNAL EQUINOX OF 1950

$☊_{♂}$ = .058500499 radians

$i_{♂}$ = .4310002 radians

$\pi_{♂}$ = 5.7966845 radinas

JD_{π} = 2437081.09531 days (Julian date of perihelion passage)

The Martian vernal equinox direction is determined from the preceding data as follows:

Referring to Figure C-7 a unit vector, $\bar{U}_N$, pointing in the direction of the Martian north pole is given by:

$$\bar{U}_N = U_{Nx}\,\bar{i} + U_{Ny}\,\bar{j} + U_{Nz}\,\bar{k}$$

$$U_{Nx} = \cos\delta_1 \cos\alpha_1$$

$$U_{Ny} = \cos\delta_1 \sin\alpha_1$$

$$U_{Nz} = \sin\delta_1$$

WHERE: $\bar{i}$ is a unit vector pointing in the Earth's vernal equinox direction, $♈_{\oplus}$:

$\bar{k}$ is a unit vector pointing in the Earth's north polar direction, $N_{\oplus}$.

$\bar{j}$ is a unit vector perpendicular to $\bar{i}$ and $\bar{k}$ and lying in the Earth's equatorial plane.

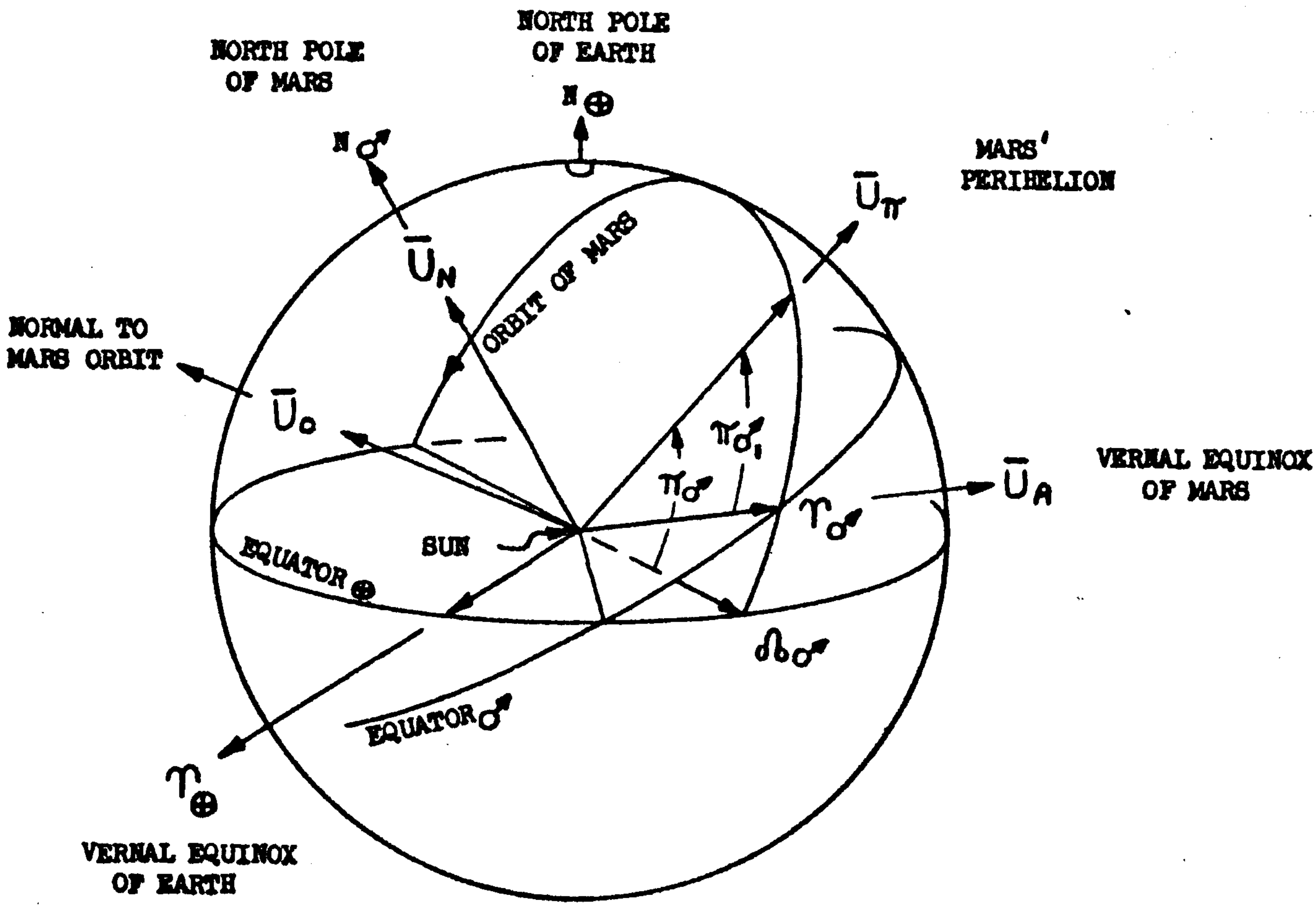


FIGURE C-7: DETERMINATION OF THE MARTIAN VERNAL EQUINOX

A unit vector, $\overline{U}_o$, perpendicular to the orbit of Mars is given by:

$$\overline{U}_o = U_{ox}\,\overline{i} + U_{oy}\,\overline{j} + U_{oz}\,\overline{k}$$

$$U_{ox} = \sin i_{♂} \sin \Omega_{♂}$$

$$U_{oy} = -\sin i_{♂} \cos \Omega_{♂}$$

$$U_{oz} = \cos i_{♂}$$

The ascending node of the Martian orbit on the Martian equator defines the Martian vernal equinox direction, $\Upsilon_{♂}$. A unit vector, $\overline{U}_A$, pointing in this direction is found by the cross product:

$$\overline{U}_A = \frac{\overline{U}_N \times \overline{U}_o}{|\overline{U}_N \times \overline{U}_o|} = U_{Ax}\,\overline{i} + U_{Ay}\,\overline{j} + U_{Az}\,\overline{k}$$

$$U_{Ax} = \frac{A_1}{\sqrt{A_1^2 + A_2^2 + A_3^2}}$$

$$U_{Ay} = \frac{A_2}{\sqrt{A_1^2 + A_2^2 + A_3^2}}$$

$$U_{Az} = \frac{A_3}{\sqrt{A_1^2 + A_2^2 + A_3^2}}$$

$$A_1 = U_{Ny} U_{oz} - U_{Nz} U_{oy}$$

$$A_2 = U_{Nz} U_{ox} - U_{Nx} U_{oz}$$

$$A_3 = U_{Nx} U_{oy} - U_{Ny} U_{ox}$$

The determination of the orbit of Mars relative to the Sun, the Martian equator, and the Martian vernal equinox follows: A unit vector, $\overline{U}_{\pi}$, in the direction of Mars' perihelion (See Figure C-7) is given by:

$$\bar{U}_\pi = U_{\pi x}\,\bar{i} + U_{\pi y}\,\bar{j} + U_{\pi z}\,\bar{k}$$

$$U_{\pi x} = \cos \pi_{o♂} \cos \Omega_{o♂} - \sin \pi_{o♂} \cos i_{o♂} \sin \Omega_{o♂}$$

$$U_{\pi y} = \cos \pi_{o♂} \sin \Omega_{o♂} + \sin \pi_{o♂} \cos i_{o♂} \cos \Omega_{o♂}$$

$$U_{\pi z} = \sin \pi_{o♂} \sin i_{o♂}$$

A unit vector, $\bar{U}_R$, lying in the plane of the Martian orbit and perpendicular to $\bar{U}_A$ and $\bar{U}_O$ (so as to form the second coordinate direction of a right hand coordinate system) is given by the cross product:

$$\bar{U}_R = \bar{U}_o \times \bar{U}_A = U_{Rx}\,\bar{i} + U_{Ry}\,\bar{j} + U_{Rz}\,\bar{k}$$

$$U_{Rx} = U_{oy} U_{Az} - U_{oz} U_{Ay}$$

$$U_{Ry} = U_{oz} U_{Ax} - U_{ox} U_{Az}$$

$$U_{Rz} = U_{ox} U_{Ay} - U_{oy} U_{Ax}$$

The vector, $\bar{U}_\pi$, pointing in the direction of Mars' perihelion may now be written in terms of the unit vectors, $\bar{U}_A$, $\bar{U}_R$, and $\bar{U}_O$ as follows:

$$\bar{U}_\pi = (\bar{U}_\pi \cdot \bar{U}_A)\bar{U}_A + (\bar{U}_\pi \cdot \bar{U}_R)\bar{U}_R + (\bar{U}_\pi \cdot \bar{U}_o)\bar{U}_o$$

From this relation the argument of perihelion, $\pi_{o♂_1}$, measured in the plane of the Martian orbit (See Figure C-8) from the Martian vernal equinox to the perihelion point is given by:

$$\sin \pi_{o♂_1} = \bar{U}_\pi \cdot \bar{U}_R = U_{\pi x} U_{Rx} + U_{\pi y} U_{Ry} + U_{\pi z} U_{Rz}$$

$$\cos \pi_{o♂_1} = \bar{U}_\pi \cdot \bar{U}_A = U_{\pi x} U_{Ax} + U_{\pi y} U_{Ay} + U_{\pi z} U_{Az}$$

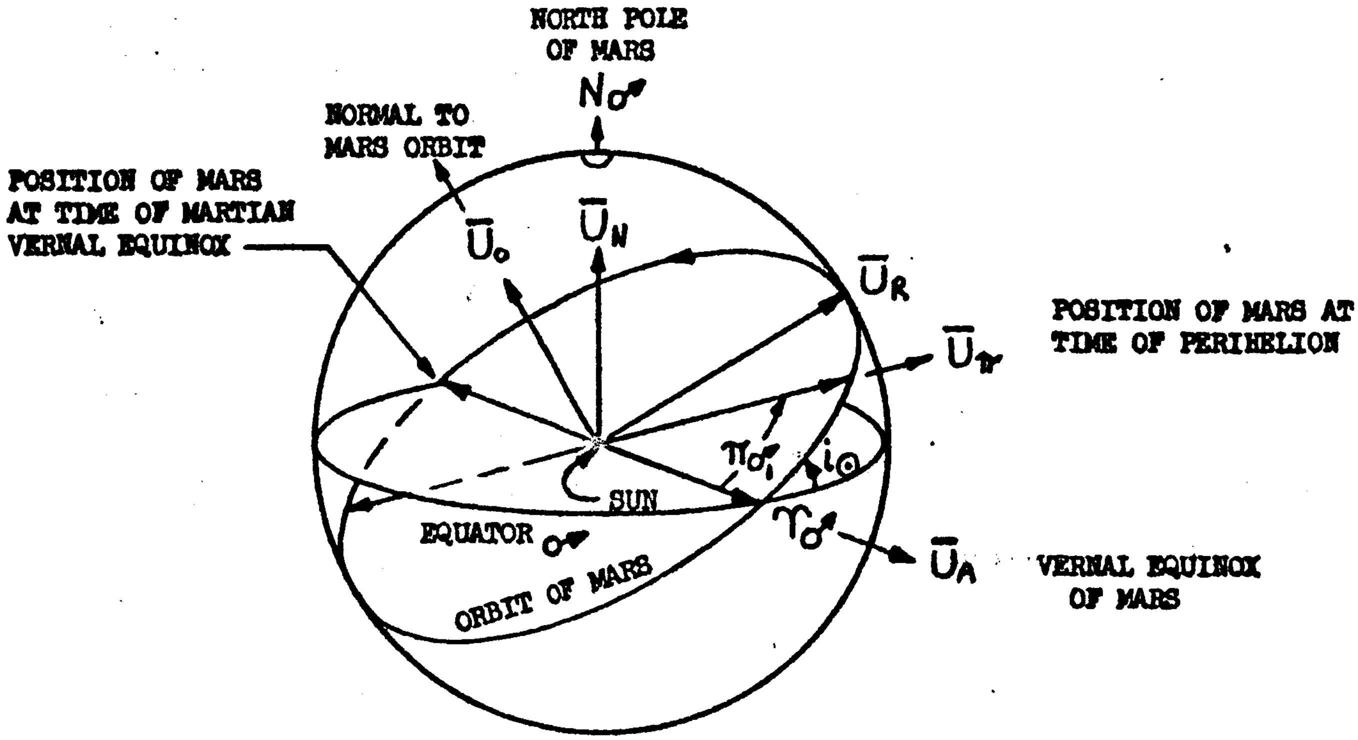


FIGURE C-8: SPATIAL ORIENTATION OF THE MARTIAN ORBIT RELATIVE TO MARS' EQUATOR

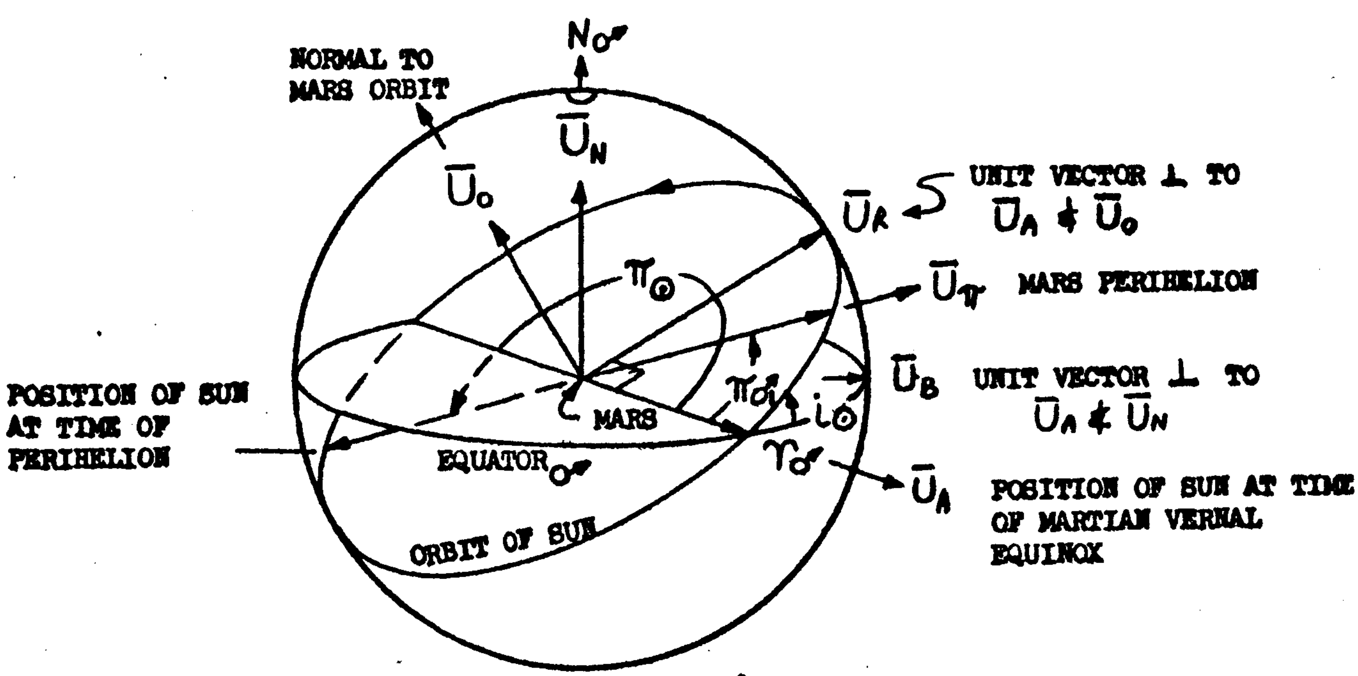


FIGURE C-9: SPATIAL ORIENTATION OF THE SUN'S ORBIT RELATIVE TO MARS' EQUATOR

The inclination $i_\odot$, of the Martian orbit to the Martian equator (See Figure C-8) is equal to the angle between the $\bar{U}_O$ and the $\bar{U}_N$ vectors and is given by:

$$\cos i_\odot = U_{Ox} U_{Nx} + U_{Oy} U_{Ny} + U_{Oz} U_{Nz}$$

IF $\cos i_\odot > 0$; $i_\odot$ IS IN QUADRANT I

IF $\cos i_\odot = 0$; $i_\odot = 90°$

IF $\cos i_\odot < 0$; $i_\odot$ IS IN QUADRANT II

Thus far the spatial orientation elements, $i_\odot$ and $\pi_{♂_1}$ of the Martian orbit relative to the Martian equator and Martian vernal equinox have been determined. These elements are shown in Figure C-8. It will be noted in this figure that the Martian vernal equinox direction, $\Upsilon_{♂}$, is defined as the direction of the Mars-to-Sun-line at the time of the Martian vernal equinox. Also, the angle $\pi_{♂_1}$, defines the position of Mars in its orbit at the time of perihelion.

In Figure C-9 the origin of coordinates has been shifted from the Sun to Mars. Thus, the Martian orbit of Figure C-8 becomes the Sun's orbit relative to Mars in Figure C-9. Additionally, in Figure C-9, the Sun is at the Martian vernal equinox position, $\Upsilon_{♂}$, at the time of the Martian vernal equinox. The Sun is at the position defined by the angle $\pi_\odot$ (180° beyond the Mars perihelion position) at the time of perihelion passage. The angle $\pi_\odot$ is given by:

$$\sin \pi_\odot = -\left[U_{\pi x} U_{Rx} + U_{\pi y} U_{Ry} + U_{\pi z} U_{Rz}\right]$$

$$\cos \pi_\odot = -\left[U_{\pi x} U_{Ax} + U_{\pi y} U_{Ay} + U_{\pi z} U_{Az}\right]$$

The angle, $i_{\odot}$, between the Sun's orbit and the Martian equator has been determined above.

The remaining elements of the Sun's orbit about Mars are identical to the elements of Mars' orbit about the Sun and are given in Section C.6.1.

C.4 LOCATION OF PLANETOGRAPHIC COORDINATE SYSTEM RELATIVE TO PLANETOCENTRIC COORDINATE SYSTEM

Thus far the Sun's orbit has been defined with respect to the planetocentric (Mars centered) coordinate system consisting of the Martian equator and the Martian vernal equinox. Since it is desired to locate points on the Martian surface (planetographic coordinate system) relative to the planetocentric coordinate system, the relationship between the two coordinate systems must be found. Page 521 of reference 2 defines the sidereal rotational period of Mars to be $24^h\ 37^m\ 22.6689^s$. Referring to Figure C-4 it will be seen that once a date of passage of the Martian zero longitude meridian across the Martian vernal equinox direction is found (i.e., a date when $\alpha_o = 0°$), then the location, α_o, of the zero longitude meridian may be ascertained for any other date.

The data of the table beginning on page 328 of reference 2 (ephemeris for physical observations of Mars) may be used to obtain the desired date of passage of the zero longitude meridian across the Martian vernal equinox. On page 329 of reference 2 the planetographic longitude of the central meridian is given for daily time increments. Referring to Figure C-10, it will be noted that the central meridian is that meridian of longitude on the Martian surface which passes through the center of the disc, as seen from the Earth, at a given instant. The planetographic longitude of the central meridian is the angle λ_o measured from the zero meridian on the Martian surface.

Figure C-11 defines the variables given on page 328 of reference 2. The instantaneous planetocentric position of the Earth is defined by the

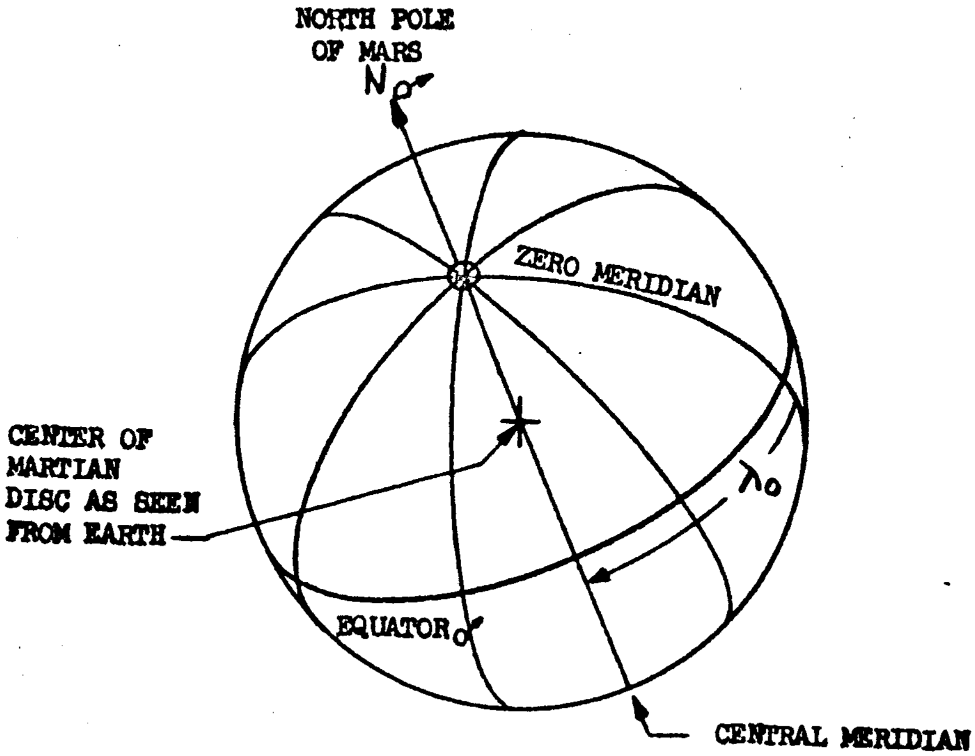


FIGURE C-10: DEFINITION OF MARTIAN CENTRAL MERIDIAN

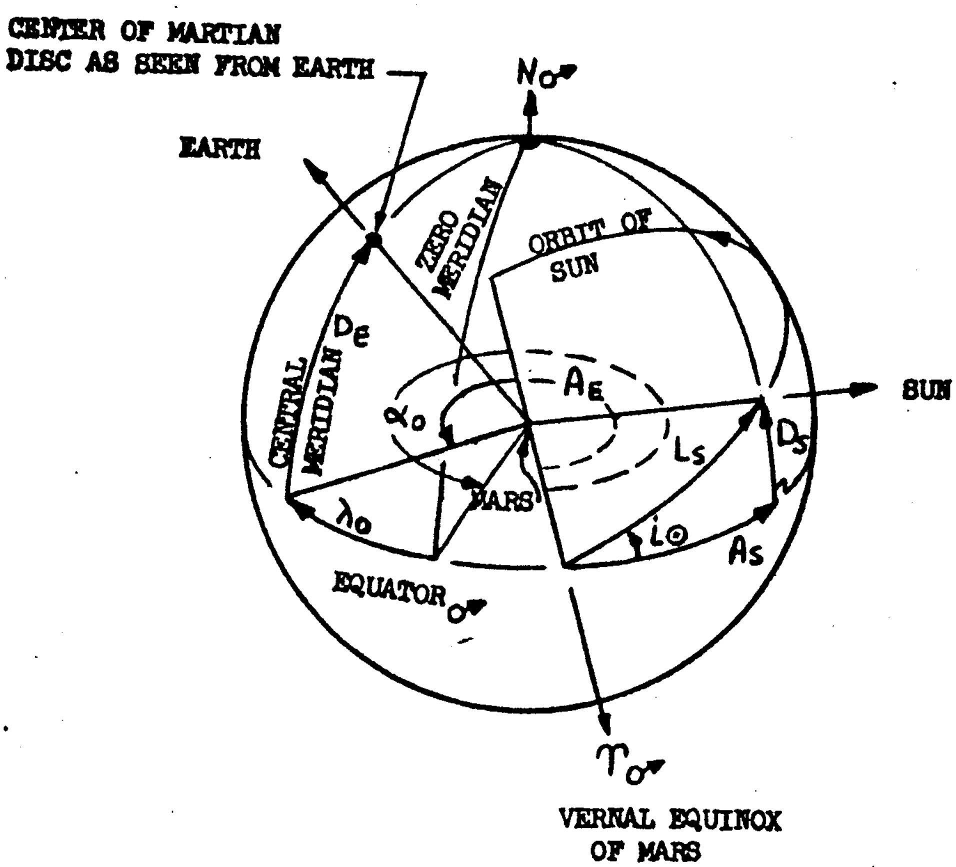


FIGURE C-11: DEFINITION OF VARIABLES LISTED IN EPHEMERIS OF PHYSICAL OBSERVATIONS OF MARS right ascension, A_E , (measured in the Martian equatorial plane, in the direction of Martian rotation, from the Martian vernal equinox) and the declination, D_E , (from the Martian equator) of the Mars-to-Earth line. The point at which the Mars-to-Earth line pierces the Martian surface is the center of the Martian disc as seen from the Earth. Thus, the angle A_E defines the inertial (planetocentric) location of the central meridian. Since the planetographic position of the central meridian relative to the Martian zero meridian is given by λ_o, the planetocentric position of the zero meridian may be found from the formula:

$$\alpha_o = A_E + \lambda_o$$

Having thus found the Martian right ascension of the zero meridian for a given date, the date of passage of the zero meridian across the Martian vernal equinox may be found from the relation:

$$JD_{o/\Upsilon_{♂}} = JD_i + \frac{(360^\circ - \alpha_o)}{\omega_{♂}}$$

WHERE:

$JD_{o/\Upsilon_{♂}}$ = The Julian Date of passage of the Martian zero meridian across the Martian vernal equinox

JD_i = The Julian Date for which the A_E & λ_o data were given

$\omega_{♂}$ = The rotational rate of Mars

= 350.891962 degrees/day (reference 2, page 521)

The satellite ephemeris routine used to calculate the data presented in Appendix B takes to quantities $JD_{o/\Upsilon_{♂}}$ and $\omega_{♂}$ as inputs and computes the right ascension, α_o , of the zero meridian for any subsequent Julian date from the relationship:

$$\alpha_{o\,(DATE)} = \left[JD_{(DATE)} - JD_{o/\Upsilon_{\male}} \right] \omega_{\male}$$

Figure C-4 defines the planetographic coordinate system by which points on the Martian surface are located. Planetographic longitude, λ, is measured westward from the zero meridian and planetographic latitude, β, is positive north from the Martian equator.

C.5 ORBITAL ELEMENTS OF THE COMMAND MODULE'S MARTIAN ORBIT

Referring to Figure C-1 it will be noted that the variables ρ_{CM}, ϵ_{CM}, and ϵ_S (the slant range from the remote module to the command module, the elevation of the command module above the remote module's horizon, and the elevation of the Sun above the remote module's horizon, respectively) may be computed only after the Sun's orbit relative to Mars, the location of the remote module on the Martian surface, and the command module's Martian orbit have been defined. Section C.3 defined the orbit of the Sun relative to the planetocentric coordinate system and Section C.4 defined the relation between the planetocentric and planetographic coordinate system. This section describes how the elements of the command module's Martian orbit were determined from data on an actual, typical transmartian trajectory. Appendix B describes the choice of actual remote module landing sites on the surface of Mars.

Section 4 of Final Report, Advanced Orbital Launch Operations, Volume VII, Space Mechanics (reference 4) contains a detailed description of a twenty day Earth departure window for a 1975 manned Mars capture mission. (The transmartian trajectories for this mission were originally selected by General Dynamics Astronautics Division during the course of their "Early Manned Interplanetary Missions," study.) A transmartian trajectory from this particular manned Mars mission was chosen as a basis for establishing a Martian orbit for the command module because of the availability of the required trajectory data. Referring to Figure C-14, it will be seen that any specific transmartian trajectory arrives in the vicinity of Mars with a definite approach direction as defined by $\overline{V}_\infty$, the hyperbolic approach asymptote. The importance of this fact is that the angle that the approach asymptote makes with the Martian equator, δ_3, is equal to the minimum possible inclination of the command module's orbit to the Martian equator. For the particular transmartian trajectory used in this study, the inclination of the resulting Martian orbit of the command module was 0.55°. A study of how this minimum inclination varies from one transmartian trajectory to another is beyond the scope of the present effort.

The interplanetary trajectory routine used to compute the transmartian trajectory employed in this analysis was developed by the authors of reference 5 and is described briefly therein. A more detailed description is given in reference 6. Departure from the Earth's sphere of influence occurs on Julian date 2442482.0 (10.5 March 1975). Arrival at the Martian sphere of influence occurs on Julian date 2442720.0 (3.5 November 1975).

The trajectory routine utilized supplies longitude, α_Z, and latitude, δ_Z, of the hyperbolic approach asymptote relative to the Sun's orbital plane about Mars and the Mars-to-Sun line, as shown in Figure C-12. In the particular case at hand, the routine defined for the selected trajectory the following characteristics:

$$\alpha_Z = 13.275°$$

$$\delta_Z = 6.912°$$

$$V_\infty = 2.9946377 \text{ statute miles/second}$$

Orbital elements of the command module's Martian orbit are obtained from these data by the following procedure. In Figure C-12 a unit vector $\bar{U}_E$ which points in the negative direction of the hyperbolic approach asymptote $\bar{V}_\infty$ is shown. This vector has the components:

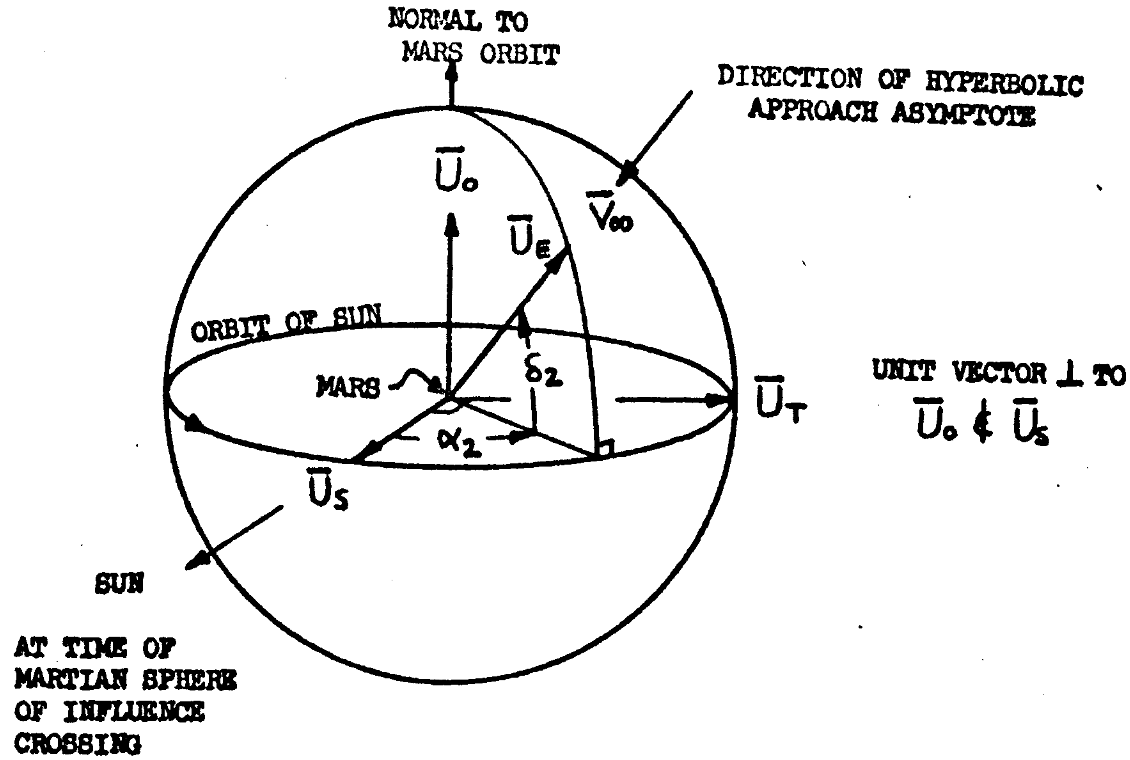


FIGURE C-12: HYPERBOLIC APPROACH ASYMPTOTE COORDINATES

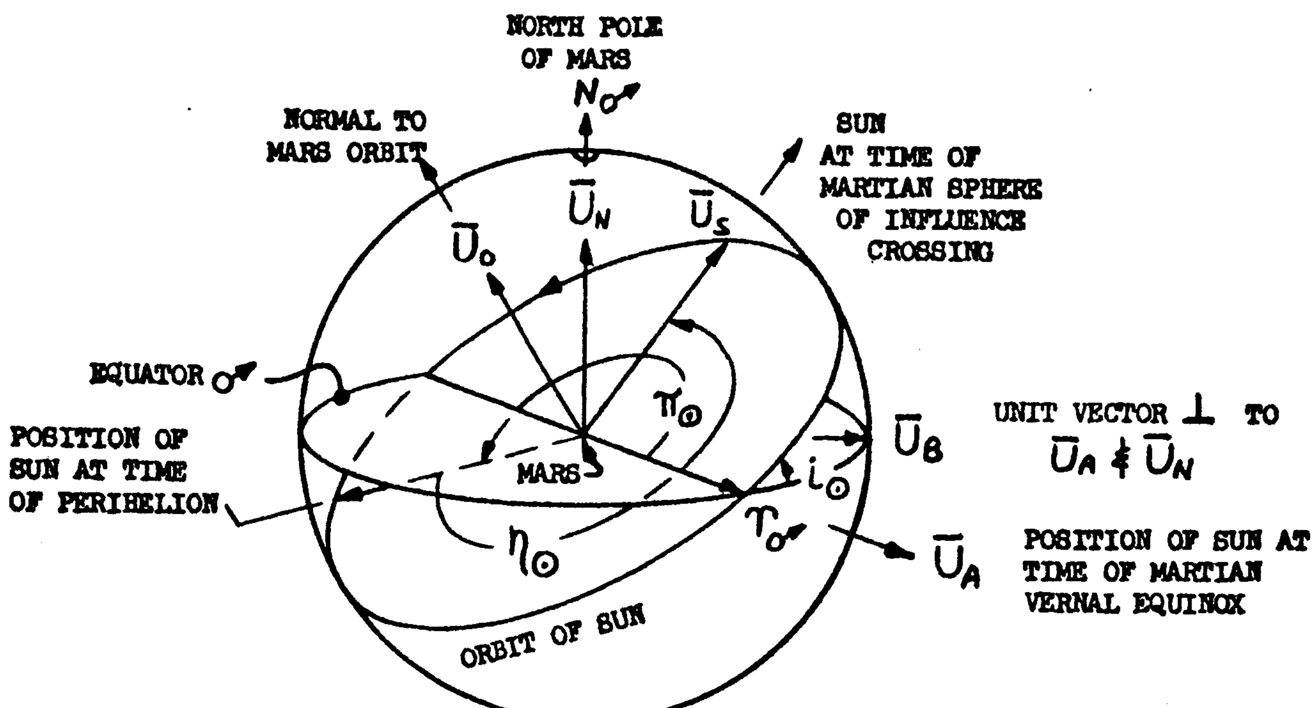


FIGURE C-13: LOCATION OF MARS-TO-SUN VECTOR RELATIVE TO PLANETOCENTRIC COORDINATE SYSTEM

$$\bar{U}_E = U_{E_{11}} \bar{U}_S + U_{E_{22}} \bar{U}_T + U_{E_{33}} \bar{U}_O$$

$$U_{E_{11}} = \cos \delta_2 \cos \alpha_2$$

$$U_{E_{22}} = \cos \delta_2 \sin \alpha_2$$

$$U_{E_{33}} = \sin \delta_2$$

where $\bar{U}_S$, $\bar{U}_T$, and $\bar{U}_O$ are orthogonal unit vectors forming a right hand coordinate system.

It is now desired to express $\bar{U}_E$ in terms of the planetocentric coordinate system mentioned in Section C.3 and C.4. To accomplish this coordinate transformation it is necessary to express $\bar{U}_S$, $\bar{U}_T$, and $\bar{U}_O$ in terms of the unit vectors $\bar{U}_A$, $\bar{U}_B$, and $\bar{U}_N$ shown in Figure C-13. (First it will be necessary to write $\bar{U}_B$ in terms of the unit vectors, $\bar{i}$, $\bar{j}$, and $\bar{k}$ discussed in Section C.3).

$$\bar{U}_B = U_{B_1} \bar{i} + U_{B_2} \bar{j} + U_{B_3} \bar{k} = \bar{U}_N \times \bar{U}_A$$

$$U_{B_1} = U_{Ny} U_{Az} - U_{Nz} U_{Ay}$$

$$U_{B_2} = U_{Nz} U_{Ax} - U_{Nx} U_{Az}$$

$$U_{B_3} = U_{Nx} U_{Ay} - U_{Ny} U_{Ax}$$

$\bar{U}_S$ may now be expressed in terms of $\bar{U}_A$, $\bar{U}_B$, and $\bar{U}_N$ as follows:

$$\bar{U}_S = U_{S_1} \bar{U}_A + U_{S_2} \bar{U}_B + U_{S_3} \bar{U}_N$$

$$U_{S_1} = \cos (\pi_\odot + \eta_\odot)$$

$$U_{S_2} = \sin (\pi_\odot + \eta_\odot) \cos i_\odot$$

$$U_{S_3} = \sin (\pi_\odot + \eta_\odot) \sin i_\odot$$

(The value of $\eta_\odot$ used in the expression for $\overline{U}_S$ above was given by the transmartian trajectory run as 85.56° and was checked by consulting reference 7.)

$\overline{U}_O$ is found through the use of the relation:

$$\overline{U}_O = (\overline{U}_O \bullet \overline{U}_A)\overline{U}_A + (\overline{U}_O \bullet \overline{U}_B)\overline{U}_B + (\overline{U}_O \bullet \overline{U}_N)\overline{U}_N$$

$$\overline{U}_O = U_{11}\overline{U}_A + U_{22}\overline{U}_B + U_{33}\overline{U}_N$$

$$U_{11} = U_{Ox}U_{Ax} + U_{Oy}U_{Ay} + U_{Oz}U_{Az}$$

$$U_{22} = U_{Ox}U_{B1} + U_{Oy}U_{B2} + U_{Oz}U_{B3}$$

$$U_{33} = \cos i_\odot$$

The cross product of $\overline{U}_O$ and $\overline{U}_S$ yields $\overline{U}_T$:

$$\overline{U}_T = \overline{U}_O \times \overline{U}_S = U_{T_1}\overline{U}_A + U_{T_2}\overline{U}_B + U_{T_3}\overline{U}_N$$

$$U_{T_1} = U_{22}U_{S_3} - U_{33}U_{S_2}$$

$$U_{T_2} = U_{33}U_{S_1} - U_{11}U_{S_3}$$

$$U_{T_3} = U_{11}U_{S_2} - U_{22}U_{S_1}$$

Using the expressions developed above for $\overline{U}_S$, $\overline{U}_T$, and $\overline{U}_O$ in terms of $\overline{U}_A$, $\overline{U}_B$, and $\overline{U}_N$; vector $\overline{U}_E$ becomes:

$$\begin{aligned}\overline{U}_E = {} & U_{E_{11}}\left[U_{S_1}\overline{U}_A + U_{S_2}\overline{U}_B + U_{S_3}\overline{U}_N\right] \\ & + U_{E_{22}}\left[U_{T_1}\overline{U}_A + U_{T_2}\overline{U}_B + U_{T_3}\overline{U}_N\right] \\ & + U_{E_{33}}\left[U_{11}\overline{U}_A + U_{22}\overline{U}_B + U_{33}\overline{U}_N\right]\end{aligned}$$

WHENCE:

$$\bar{U}_E = U_{E_1}\bar{U}_A + U_{E_2}\bar{U}_B + U_{E_3}\bar{U}_N$$

$$U_{E_1} = U_{E_{11}}U_{S_1} + U_{E_{22}}U_{T_1} + U_{E_{33}}U_{11}$$

$$U_{E_2} = U_{E_{11}}U_{S_2} + U_{E_{22}}U_{T_2} + U_{E_{33}}U_{22}$$

$$U_{E_3} = U_{E_{11}}U_{S_3} + U_{E_{22}}U_{T_3} + U_{E_{33}}U_{33}$$

$\bar{U}_E$ is now expressed in terms of the unit vectors of the planetocentric coordinate system. Figure C-14 shows how the spatial orientation of the command module's orbit is determined from $\bar{U}_E$. The direction of $\bar{U}_E$ is given by its right ascension, α_3, and declination, δ_3:

$$\sin\alpha_3 = \frac{U_{E_2}}{\sqrt{U_{E_1}^2 + U_{E_2}^2}}$$

$$\cos\alpha_3 = \frac{U_{E_1}}{\sqrt{U_{E_1}^2 + U_{E_2}^2}}$$

$$\sin\delta_3 = U_{E_3}$$

IF: $U_{E_3} > 0$; δ_3 IS IN QUADRANT I

IF: $U_{E_3} = 0$; $\delta_3 = 0°$

IF: $U_{E_3} < 0$; δ_3 IS IN QUADRANT IV

As discussed in Appendix A of reference 4, there are many different approach hyperbolas (of different inclinations and longitudes of ascending nodes) that are defined by $\bar{U}_E$. For this particular problem it was desired to keep inclination, i_V, as low as possible, so the minimum value of i_V was used:

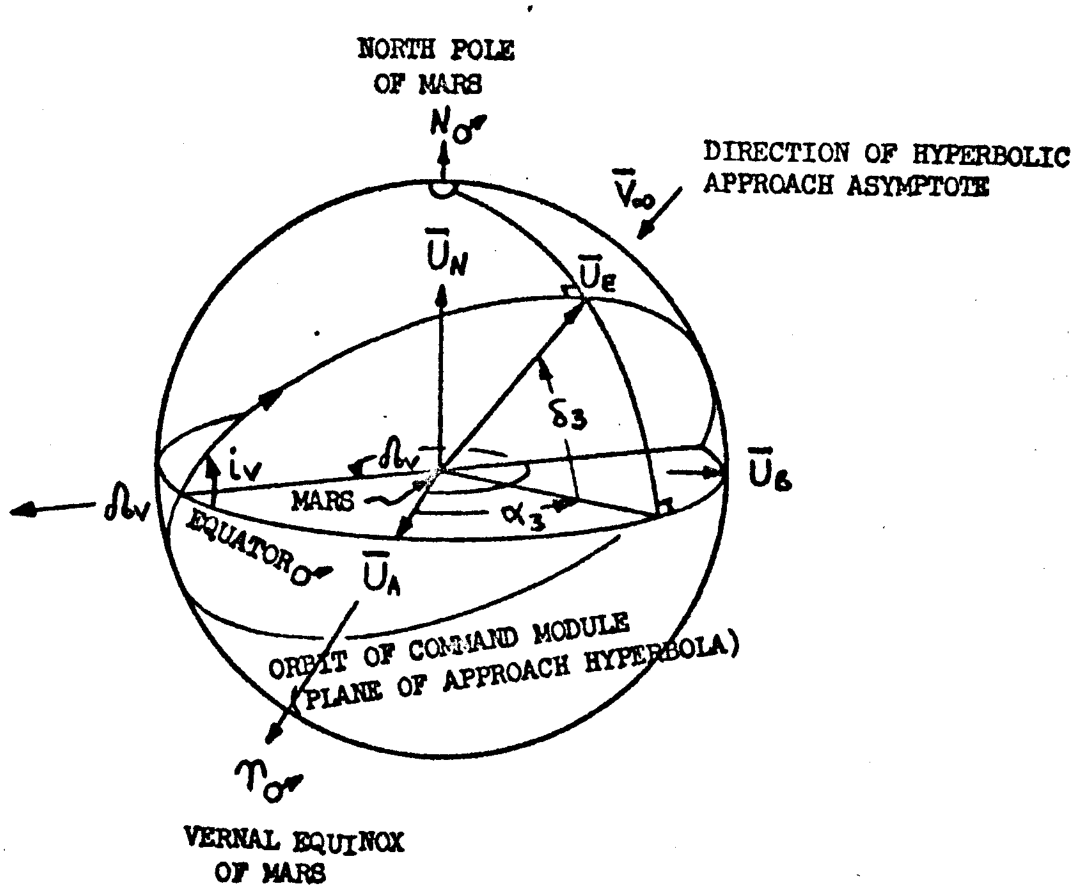


FIGURE C-14: DETERMINATION OF SPATIAL ORIENTATION OF COMMAND MODULE'S ORBIT

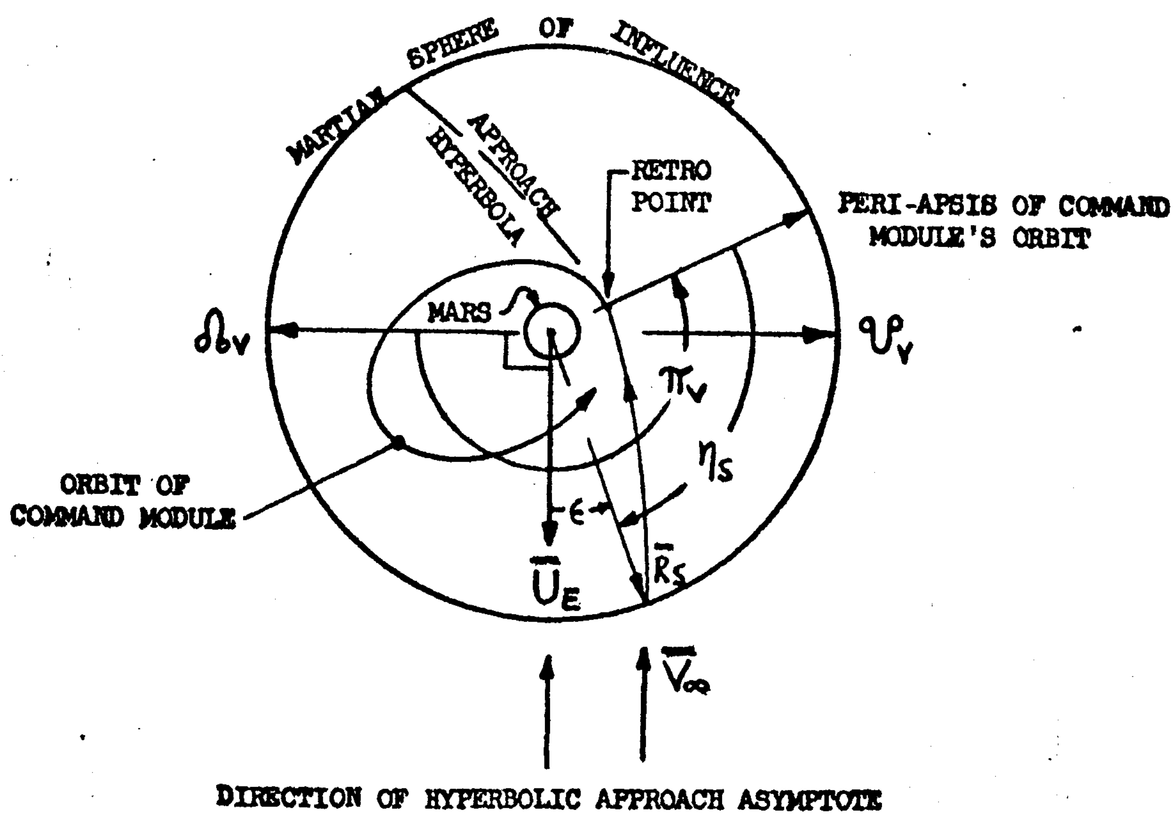


FIGURE C-15: IN-PLANE DETAILS OF COMMAND MODULE'S ORBIT

$$i_V = |\delta_3|$$

$$\delta b_V = \alpha_3 + 270^\circ$$

The remaining elements of the approach hyperbola are given by the following expressions and are depicted in Figure C 15 (it should be noted that the angle ϵ is so small it was set equal to zero):

$$\pi_V = 90^\circ + \eta_S$$

WHERE:

$$\cos \eta_S = \frac{1}{e}\left(\frac{P}{R_S} - 1\right)$$

IF $\cos \eta_S > 0$; η_S IS IN QUADRANT I

IF $\cos \eta_S = 0$; $\eta_S = 90^\circ$

IF $\cos \eta_S < 0$; η_S IS IN QUADRANT II

(Actually η_S is in either quadrants III or IV but the above definition provides the correct value for π_V).

$$P = J^2/K_{♂} \qquad J = R_P V_P$$

$$V_P = \sqrt{2\left(\frac{1}{2}V_\infty^2 + \frac{K_{♂}}{R_P} - \frac{K_{♂}}{R_S}\right)}$$

$$e = \sqrt{1 + \frac{2PE}{K_{♂}}} \qquad E = \frac{1}{2}V_\infty^2 - \frac{K_{♂}}{R_S}$$

The variables δb_V, i_V, and π_V define the spatial orientation of both the approach hyperbola and the command module's Martian orbit. The other orbital elements apply only to the approach hyperbola. For a definition of the corresponding elements of the command module's orbit see Appendix B.

C.6 SUMMARY OF INPUT DATA AND SOURCES

This section lists the numerical values of the various satellite ephemeris routine input quantities calculated from the equations of the previous sections. Also listed are the constants and factors used to obtain the final data. All final data (used by the ephemeris routine) are denoted by underlining. It will be observed that no special attempt was made to get a completely consistent set of data or to obtain extreme accuracy.

C.6.1 ORBIT OF THE SUN RELATIVE TO MARS

From reference 3, page 85, the elements of the Martian orbit relative to the Earth's equator and the Earth's vernal equinox are:

EPOCH = 23 SEPTEMBER 1960, J.D. = 2437200.5

MEAN EARTH'S EQUATOR AND MEAN EARTH'S VERNAL EQUINOX OF 1950

$\Omega_{♂}$ = .058500499 radians

= longitude of ascending node - see Figure C-6

$i_{♂}$ = .4310002 radians

= inclination - see Figure C-6

$\pi_{♂}$ = 5.7966845 radians

= argument of perihelion - see Figure C-6

Other elements of the Martian orbit listed in reference 3 that apply without change to the Sun's orbit about Mars are:

$e_{♂} = e_{\odot} = \underline{.093369}$

= eccentricity of the Martian orbit

= eccentricity of the Sun's orbit

$p_{♂} = p_{\odot} = \underline{1.5104078 \text{ A.U.}}$

= semilatus rectum of the Martian orbit

= semilatus rectum of the Sun's orbit

JD_{π} = <u>2437081.09531 days</u>

= Julian date of perihelion passage

$t_{♂} = t_{\odot}$ = <u>686.97964 days</u>

= period of Martian orbit

= period of Sun's orbit

Using the variables $\Omega_{♂}$, $i_{♂}$, and $\pi_{♂}$ given above and the equations of Section C.3, the remaining elements of the Sun's orbit relative to Mars are found to be:

$i_{\odot}$ = <u>.42089 radians</u>

= inclination of the Sun's orbit to the Martian equator - see Figure C-9

$\pi_{\odot}$ = <u>4.309497 radians</u>

= argument of perihelion - see Figure C-9

Other data used in computing $i_{\odot}$ and $\pi_{\odot}$ include:

EPOCH = 25.59531 May 1960, J.D. = 2437081.09531

α_1 = 317.861 degrees

= right ascension of Martian north pole relative to Earth's equator and Earth's vernal equinox - see Figure C-5

δ_1 = 54.694 degrees

= declination of Martian north pole relative to Earth's equator and Earth's vernal equinox - see Figure C-5

C.6.2 RELATION BETWEEN PLANETOGRAPHIC AND PLANETOCENTRIC COORDINATES

The relationship between the Martian planetographic and planetocentric coordinate systems is defined when a date of passage of the Martian zero meridian across the Martian vernal equinox is found. From pages 328 and 329 of reference 2:

EPOCH: 4 April 1960

λ_o = 341.76 degrees

= longitude of central meridian - see Figure C-10

A_E = 240.76 degrees

= right ascension of Earth - see Figure C-11

From these data and the equations of Section C.4:

α_o = 222.52 degrees

= right ascension of zero meridian - see Figure C-11

JD_i = 2437028.5

= Julian date of epoch 4 April 1960

$\omega_{♂}$ = 350.891962 degrees/day = 7.0881911 x 10^{-5} radians/second

= rotational rate of Mars

$JD_{o/\Upsilon_{♂}}$ = 2437028.8918051

= Julian date of passage of the Martian zero meridian across the Martian vernal equinox

An interesting check on the data and concepts listed above is afforded by additional information given on page 329 of reference 2. For 4 April 1960 the time of transit of the zero meridian across the central meridian is listed as 1 hour and 15 minutes past midnight. From Figure C-11 it may be seen that the zero meridian must rotate through an angle of:

$$A_E - \alpha_o = 18.24 \text{ degrees}$$

to get to the center of the Martian disc as seen from the Earth. Applying the rotational rate of Mars on its axis, it would take the zero meridian

$$\frac{18.24}{350.891962} = .051982102 \text{ day or 1 hour 14.86 minutes}$$

to reach the Center of the Martian disc - which checks with the 1 hour 15 minutes noted.

C.6.3 MARTIAN PLANETARY CONSTANTS

The constants which define the shape and gravitational potential of Mars are:

$$K_{♂} = G\,M_{♂} = g_{o♂} R_{♂}^{2} = \underline{1.5177467 \times 10^{15}} \text{ feet}^3/\text{second}^2 = 4.297780 \times 10^4 \text{ kilometers}^3/\text{seconds}^2$$

= gravity-mass constant for Mars (Reference 8, page 11)

$J_{2♂}$ = $\underline{.002011}$

= coefficient of second gravitational harmonic of Mars (Reference 9)

$R_{♂}$ = $\underline{11204068}$ feet = 3415 kilometers

= radius of Mars (Reference 9)

$f_{♂}$ = 1/150

= flattening of Mars (Reference 9)

$e_{1♂}^{2}$ = $\underline{.0132888889} = 2 f_{♂} - f_{♂}^{2}$

= eccentricity of the spheroid squared

C.6.4 SPATIAL ORIENTATION OF COMMAND MODULE'S ORBIT

The spatial oreintation parameters of the command module's Martian orbit (Ω_V, i_V and Π_V - shown in Figures C-14 and C-15) were calculated from the following transmartian trajectory as explained in Section C.5:

$JD_{\oplus S}$ = 2442482.0 (10.5 March 1975)

= Julian date of departure from the Earth's sphere of influence

$JD_{♂S}$ = 2442720.0 (3.5 November 1975)

= Julian date of arrival at the Martian sphere of influence

α_2 = 13.275 degrees

= longitude of $\bar{U}_E$ vector - see Figure C-12

δ_2 = 6.912 degrees

= latitude of $\bar{U}_E$ vector - see Figure C-12

V_∞ = 2.9946377 statute miles/second

= hyperbolic excess approach velocity relative to Mars

$\eta_\odot$ = 85.56 degrees

= true anomaly of Sun at time of Martian sphere of influence crossing - see Figure C-13

From the above data the coordinates of the $\bar{U}_E$ vector relative to the planetocentric coordinate system were found to be:

α_3 = 344.222 degrees

= right ascension of $\bar{U}_E$ vector - see Figure C-14

δ_3 = 0.550 degrees

= declination of $\bar{U}_E$ vector - see Figure C-14

From the above data and the equations of Section C.5 were calculated:

η_S = 106.345 degrees

= negative of the true anomaly of the Martian sphere of influence crossing point - see Figure C-15

P = $.657915438 \times 10^8$ feet

= semilatus rectum of approach hyperbola

J = $.315998257 \times 10^{12}$ feet^2/second

= angular momentum of approach hyperbola

V_P = 21279.72 feet/second

= peri-apsis velocity of approach hyperbola

e = 3.430485

= eccentricity of approach hyperbola

E = $.124206245 \times 10^9$ feet^2/second^2

= energy of approach hyperbola

R_P = 14849737.55 feet = 2443.95248 n.mi.

= peri-apsis radius of approach hyperbola

R_S = 1.90080×10^9 feet = 360,000 statute miles

= Martian sphere of influence radius (Reference 6)

Using the above data and the equations of Section C.5 the spatial orientation parameters of the command module's Martian orbit become:

Ω_V = <u>254.222 degrees</u>

= longitude of ascending node - see Figure C-14

i_V = <u>0.550 degrees</u>

= inclination to the Martian equator - see Figure C-14

π_V = <u>196.345 degrees</u>

= argument of peri-apsis - see Figure C-15

APPENDIX C

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