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Jesse W. Moore

Supervisor, Advanced Navigation Group, Jet Propulsion Laboratory, Pasadena, California

Mel Swerdling

Member of Technical Staff, Jet Propulsion Laboratory, Pasadena, California

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CONCEPTUAL DESIGN OF A 1979 MARS ROVER

Jesse W. Moore
Supervisor, Advanced Navigation Group
Jet Propulsion Laboratory
Pasadena, California

Mel Swerdling
Member of Technical Staff
Jet Propulsion Laboratory
Pasadena, California

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ABSTRACT

The results of a conceptual design study of a Mars roving vehicle mission in 1979 are presented. Descriptions of the mission, science objectives, vehicle configuration and subsystems are included. Mission analysis parameters required to define a mission profile and sequence of events are presented. Science operations including the deployment of small, self-contained, long-lived meteorology and/or seismology stations are considered. The vehicle system is described by the functional requirements, vehicle configuration and weight and power allocations. Following the system description, seven subsystems on board the vehicle are considered. The characteristics and capabilities of each are described. Mission operations also were evaluated to the degree necessary to identify the areas of foremost concern.

INTRODUCTION

In future decades, the space science community will be provided with unique and challenging opportunities to explore the solar system by spacecraft of increased complexity, longer lifetime and more autonomy. A candidate mission is an automated traverse on Mars. Roving vehicles capable of extended operation on the surface, and sufficiently mobile to traverse regions remote from acceptable landing sites, would offer scientists the opportunity to explore large regions of the planetary surface.

The value of landed spacecraft in performing scientific explorations and surveying future landing sites for manned vehicles was demonstrated by the Surveyor lunar missions. Surveyor, a "fixed-point" surface spacecraft, collected composition and topographic data within local areas about the landing sites. In many cases, however, areas of scientific interest are likely to be in regions remote from acceptable spacecraft landing sites, since acceptable landing sites are chosen from topographic as well as scientific criteria. Furthermore, many scientifically interesting areas are likely to exist on the Martian surface and exploration of all of these areas by immobile surface spacecraft is clearly impractical.

Given the premise that long Martian surface distances are to be explored, the automated surface roving vehicle appears to be a prime means for achieving these exploration goals.

To focus and bound this conceptual design study, several assumptions were defined. These limited the depth of effort in certain areas and eliminated some of the tradeoffs that otherwise could have been performed. Throughout the study these assumptions were adhered to, and interpretation of the results should include the effect of these study assumptions.

The key assumptions made were:

(a) Six-wheeled vehicle concept

The six-wheeled vehicle concept has been shown by several previous studies(1, 2, 3) to provide the "best" mobility capability and the "best" overall design for operation on unknown surfaces.

(b) Direct-link communications with earth

A relay communications link with an orbiting vehicle was not considered, although relay communications may be practical and desirable in some instances.

(c) One routine science operation performed per day

Some science data should be collected during each day of the mission. This includes possibly imaging, meteorology, etc., but does not always include operation of the life-detection experiments.

(d) No locomotion during the Martian night

Since no communications with the earth can be effected with a direct link during the Martian night, the risk to the safety of the vehicle becomes quite high.

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

(e) No science during locomotion

All scientific observations were assumed to take place while the vehicle is stationary. This lowers the power consumption during motion.

(f) No TV during locomotion

This implies that the TV subsystem will not be used for near-real time driving of the vehicle. A picture might be taken during motion, but its transmissions to earth would be delayed until the vehicle is stopped.

Other assumptions made during the study are stated in this report as appropriate.

SCIENCE OBJECTIVES

From a scientific point of view, the rover under study may be considered as a lander with the flexibility to investigate a large number of different sites. The science objectives are, therefore, essentially identical to those of a lander with the recognition that the rover has the additional capability not only of studying many distinct sites, but also of escaping from the area altered by the landing maneuver and of deploying small, independent science packages for specialized investigations at one or more locations along the traverse route. The rover could deploy independent meteorology and seismic stations which would make possible the acquisition of simultaneous data from different locations, thus greatly enhancing the value of such investigations.

A listing of the major science objectives are given below:

(a) Search for evidence of living organisms over a large surface area.

(b) Visually characterize many scientific sites.

(c) Search for and characterize organic compounds over different types of surfaces.

(d) Determine atmospheric composition and its temporal, spatial and altitude variations.

(e) Determine meteorological characteristics.

(f) Determine seismological characteristics.

To achieve the above objectives, the basic science payload was assumed to consist of imaging, biology, molecular analysis, meteorology and seismometry experiments. It was further assumed that the total weight available for rover science was approximately 46 Kg.

In an earlier assumption it was stated that no science experiments are performed when the rover is in motion; therefore only a small amount of power for standby and for maintaining some previously acquired sample in proper incubation is required by science during the moving phase. When the rover stops at a science site, a large fraction of the power previously used to propel the vehicle becomes available for science. This power level is more than adequate to satisfy the needs of the science subsystem.

MISSION REQUIREMENTS AND ANALYSIS

The mission requirements and analysis is concerned mainly with parameters of the vehicle's surface operation; e.g., round-trip light time, earth elevation, and sun elevation. No effort was expended on the launch, cruise, entry and landing phases of the mission. Launch and arrival dates were determined and the rover was assumed to land in a 0.52 rad. latitude belt, centered around the equator. In addition, no effort was expended on specific scientific mission design. Considerable effort is required to determine a traverse route, including selection of the scientific sites to be investigated. This selection will significantly influence the design of the vehicle system (particularly affected will be mobility, lifetime requirements, and operational strategies).

The 1979 launch opportunity was considered, with arrival in 1980, and a vehicle operational lifetime of approximately one year. The minimum C_3 trajectory for this opportunity will be launched on November 3, 1979, arrive at Mars on August 5, 1980 and require a C_3 of 8.955 km^2/sec^2. Allowing for a reasonable spread of launch and arrival dates, launch could occur between late October and mid-November 1979, and arrival at Mars could be anytime in August 1980. Use of higher C_3 to shorten communication distance would somewhat modify these dates.

One of the most significant mission analysis parameters is the light time-delay between earth and Mars. This parameter influences the amount of operational autonomy desired for the on-board vehicle system. With large time delays, fly-by-wire control is not practical. Instead of travelling long distances, the mission lifetime is spent for the most part on transmitting and receiving commands. For an arrival date of August 5, 1980 and for a lifetime of 1 yr, the roundtrip light time between earth and Mars is shown in Figure 1. At arrival, the round-trip light time is approximately 28 min, as seen from the figure, increasing to a peak of 41 min and then decreasing slowly beginning in May 1981.

The Mars-earth communication visibility period is another parameter influencing the amount of autonomous control on-board the vehicle. Table 1 shows the number of hours per Martian day that the earth would be visible from various latitudes on Mars, and the various dates of interest. The altitude (elevation) angle of the earth is also given. For reliable communications with the vehicle, the earth must be at least 0.26 rad. above the local horizon.

To define the functional requirements of a Mars surface roving vehicle, it was necessary to establish a roving strategy. It was assumed that the

Table 1. Number of Hours Per Martian Day That Earth is Visible for Various Dates and Latitudes

JULIAN DATE, days	LATITUDE ON MARS, radian	VISIBILITY HRS OF EARTH	MAX ALTITUDE OF EARTH, radian	CALENDAR DATE
2444460	-0.52	8.96	0.63	AUG 9
	0	10.93	1.15	
	+0.52	12.90	1.44	
2444520	-0.52	10.64	0.84	OCT 8
	0	12.93	1.36	
	+0.52	13.97	1.25	
2444580	-0.52	13.12	1.17	DEC 7, 1980
	0	13.68	1.45	
	+0.52	10.25	0.92	
2444640	-0.52	15.00	1.41	FEB 5
	0	12.93	1.18	
	+0.52	10.86	0.65	
2444700	-0.52	13.68	1.41	APR 6
	0	11.68	1.15	
	+0.52	9.69	0.63	
2444760	-0.52	12.88	1.22	JUN 5
	0	11.68	1.38	
	+0.52	12.48	0.86	
2444820	-0.52	11.52	0.92	AUG 4, 1981
	0	12.93	1.44	
	+0.52	12.34	1.18	

intent of the rover was to move to an appropriate science site, perform prescribed scientific analysis of the area, transmit the appropriate findings to earth, and repeat the foregoing sequence for the duration of the mission.

August 5, 1980 and a -0.52 rad latitude were chosen to graphically describe the profile of a single mission. The resulting single Martian day profile is shown in Figure 2. A reference time of zero is selected when the earth rises in the Martian sky on the above date. Vehicle motion is confined to the time when the earth is 0.26 rad. above the horizon, and on this date the time is confined to approximately 8-9 hr of operations. The cross-hatched areas indicate periods when data are transmitted to earth and commands from earth are received and verified. The solid areas represent 100-m traverse segments. For this day, three 100-m segments are possible. Beginning at sunset, the night science operations (meteorology, etc.) and battery recharge take place. This profile might be followed in the early phases of the mission; however, as time increases the traverse segments are likely to be lengthened to a kilometer or several kilometers. Assuming the individual traverse segments will be lengthened as a function of time, a range capability of the roving vehicle was estimated for a 1-yr mission. This range capability is shown plotted in Figure 3. To arrive at this plot, several additional assumptions are necessary. First, it was assumed that 9 major scientific sites would be investigated, each requiring up to 15-20 days for a complete investigation. Second, the number of kilometers per day was increased from 0.3 to 4.0 in increments. On later days the vehicle would have to travel during a large part of the visibility period and, in addition, the frequency of obstacles would have to be small. With these assumptions, it is possible to achieve a range of 400-500 km during a 1-yr surface mission.

VEHICLE SYSTEM DESCRIPTION

The basic functional elements of a Mars surface roving vehicle are centered around the on-board computer and sequencer (data handling subsystem) which performs the necessary computations, makes the decisions and executes the events in their proper sequence. The primary inputs to the computer are from the science, navigation, mobility and obstacle detection functional elements. The communication element, which includes the pointing of a directional antenna to earth, serves to telemeter data from the vehicle and receive commands from the earth. Power is required for all elements, and thermal and environmental control are needed to reduce the effect of variations in the Martian environment.

In order to make the exploratory design investigations as meaningful as possible, the initial configuration study considered a reference or baseline vehicle which:

(a) Is generally compatible with the Viking delivery and landing systems. (This imposes major weight and C. G. limitations, as well as some critical geometric constraints.)

(b) Provides sufficient mobility to a meaningful complement of science and communications to perform a major surface exploration mission.

The exploratory configuration developed for this vehicle adapts the major transport and descent systems of the Viking in order to soft land a six-wheeled roving vehicle onto the Martian surface. The entry and landing sequence is shown in Figure 4. The configuration uses the Viking descent capsule, the parachute system, and the soft-landing terminal propulsion system in combination with the radar systems for the descent requirements. However, it repackages the three-legged stationary landing spacecraft of Viking '75 (Surveyor-type) into a six-wheeled rover using a three-segment control compartment body.

The design configuration developed is shown in Figure 5. The body or chassis of the rover consists of three compartments, the first two of which contain the science, communications and electronics equipment in a thermally controlled environment. The rear compartment supports two multi-hundred watt RTG's (Radioisotope Thermoelectric Generator). Each compartment supports a pair of wheels with independent springing for landing on the wheels (in the interlocked condition), and surface roving (in the extended condition). The terminal descent propulsion modules are attached to the hubs of the science compartment wheels and the aft end of the rear RTG compartment. These are jettisoned after landing. Descent radar antennas attached to the hubs of the rear wheels are also jettisoned after landing. The mast attached to the central compartment is erected after landing. It supports the high- and low-gain antennas plus the facsimile (panoramic) camera, the local imaging and ranging sensors. Soil manipulation instruments are attached to the front compartment.

The roving vehicle is powered by an electric motor in each wheel. Center point steering is also electrical; motion (forward or reverse) and steering is either ground-commanded or commanded on-board. Operation of the vehicle during roving is intermittent in that power is first provided to travel a short distance (approximately 50-100 m) and then stop. Power is then supplied to perform a new visual survey and, where appropriate, to make a series of experiments and transmit the results to the receiving station. This intermittent roving and decision, or experiment sequence, is then repeated. To limit the demands on the control system and earth-based operators, internal hazard-sensing devices (e. g. tilt obstacle detectors) are provided.

The Mars roving vehicle weight estimate summary is given in Table 2. Twelve subsystems are identified. The total weight of the vehicle, including a 46 kg contingency, is 512 kg. Mobility and power subsystems require the largest weight fractions. Power requirement estimates are provided for the worst case during locomotion, i. e., when the vehicle is in motion over an average +0. 09 rad. terrain slope. This will probably occur for a relatively small percentage of time. The mobility power estimate provides for a vehicle speed of 0. 35 km/hr while on the slope. The power estimates are shown in Table 3. A total of 283 W, of which 124 W are required for mobility, are required for locomotion.

VEHICLE SUBSYSTEMS

The on-board subsystems involved with vehicle motion and considered in this study are (a) mobility,

Table 2. Weight Estimate Summary

SUBSYSTEM		WEIGHT, Kg
Rover Structure		59
Mobility		127[a]
Science[c]		46
Communications		32
Data Handling		43
Power		110[b]
Navigation		9
Obstacle Detection		5
Antenna Pointing		5
Thermal Control		14
Cabling		11
Pyrotechnics		5
	Total	466 Kg
Contingency		46
		512 Kg

[a] Includes weight for landing survival

[b] Includes two batteries

[c] Does not include sampler weight

Table 3. Locomotion Mode Power Requirements (Worst Case)

SUBSYSTEM	POWER, W	VOLTAGE
Science	0	-
Communications	25	AC
Obstacle Detection	15	AC
Navigation	10	AC
Mobility	124[a]	DC
Controller	10	AC
Data Handling	70	AC
Thermal Control	10	AC
Conversion and Net Losses	19	-
Total	283 W	

[a] Provide for vehicle speed of 0.35 km/hr while operating on average 0.09 rad. slope

(b) power, (c) telecommunications, (d) navigation, (e) obstacle detection, (f) antenna pointing and (g) data handling. Omitted from consideration were the vehicle controller subsystem and the obstacle avoidance subsystem. The controller provides the commands to the drive motors for speed and heading changes. The obstacle avoidance subsystem makes use of the data from the obstacle detection subsystem to provide heading changes to the vehicle controller. Obstacle avoidance is a very necessary and complex subsystem for the Mars rover and its design must be compatible with the obstacle detection subsystem. Avoiding obstacles while minimizing some criterion function, such as time or distance to the destination, will require the development of path finding algorithms(4, 5) with significant flexibility and capability.

(a) Mobility

In considering the mobility approach for the Mars Roving Mission, a review was made of the various designs investigated for the lunar roving program(1, 2, 3). These included:

(1) Legged vehicles: single and multiple (articulated mechanical legs).

(2) Tracked vehicles: single and multiple tracks (with single and multiple chassis).

(3) Wheeled vehicles: single and multiple wheels (with single and multiple, rigid and flexible chassis/body configuration).

As in the lunar rover investigations, the choice from the above concepts for the Mars requirements, involved the evaluation of many competing factors. The most important of these factors were:

(1) Mission terrain characteristics. Surface characteristics along the routes of pertinent science objectives (roughness, slopes, hardness, obstacles, crevasses).

(2) Mobility system efficiency.

(3) Trade-off between obstacle traversing and obstacle avoidance subsystems.

(4) Mobility system reliability and redundancy.

(5) Adaptability of the concept to the delivery systems.

Since the accurate evaluation of these factors for the different roving concepts on Mars was beyond the scope of this initial study, a gross review was made of the difference in the Martian and lunar environments as they affected these competing factors. It was found that although there were considerable environmental differences between Moon and Mars (gravity, temperature range, atmosphere, communication distance, etc.) none of these seemed of sufficient influence to appreciably change the comparative merits of the various mobility concepts, as made for lunar roving studies.

In view of these results the choice of mobility concepts for the reference vehicle was narrowed to four- or six-wheeled vehicles as considered for the moon. Since investigations of the four-wheeled rovers indicated quite limited mobility (approximately half that of the six-wheeled version in obstacle and crevasse capability) as well as reduced redundancy, the six-wheeled concept was adopted for the initial reference vehicle. However, it should be pointed out that a four-wheeled concept might present advantages for missions limited to comparatively smooth areas. Mobility characteristics of the referenced vehicle is given in Table 4.

In attempting to achieve the 0.52-0.61 rad. goal established for this vehicle, special effort was made to reduce soil pressures as much as possible. Such design takes advantage of soil cohesion that is available on the moon and is perhaps available on Mars. Soil pressure on the lunar rover, which uses 82 x 23 cm wheels, is approximately 4800 N/m^2. The concept presented here is expected to have about half to two-thirds of that soil pressure, which may provide for the 0.52-0.61 rad. slopes.

(b) Power

Radioisotope thermoelectric generators and hermetically sealed nickel cadmium batteries are the primary and secondary power sources selected for the Mars Rover application. This combination can provide the dependability and high reliability required throughout the approximate 2-yr mission.

A power profile depicting three key modes of operation, such as mobility/locomotion, science, and a typical "night time" period is shown in Table 5.

Table 4. Mobility Characteristics

CRITERIA	ESTIMATES
1. Maximum slope capability	0.52-0.61 rad. soft soil
2. Ground clearance	(A) Straddle a 0.61 rad.-wedge formed by two intersecting crater walls (B) Undercarriage clearance 0.4 m (approx). (Within central compartment area)
3. Maneuverability	(A) Turning radius 3-4 m (approx) (B) Front and rear steering (C) Reverse drive
4. Stability	Approximately 0.70-0.79 rad. for traversing crater walls of soft soil and providing for some wheel sinkage
5. Obstacle capability	0.9 m (approx)
6. Crevasse capability	0.6 to 0.9 m (approx)

Table 5. Mars Rover Power Profile Continuous (watts)

SUBSYSTEM	VOLTAGE	MOBILITY	SCIENCE OPERATION	NIGHT OPERATION
Computer	AC	40	40	40
Centralized data storage	AC	18	18	18
Communications (TWT)	DC	0	55	0
Radio frequency	AC	25	25	25
Navigation	AC	10	0	0
Controller (mobility)	AC	10	0	0
Data handling	AC	12	12	12
Thermal control	AC	10	0	10
Mobility (locomotion)	DC	124[a]	0	0
Obstacle detection	AC	15	0	0
Science		0	96[b]	81
Battery charging	DC	2	2	48
Conversion and distribution losses		17	25	23
TOTAL:		283	273	257

[a] Provides for an initial vehicle speed of 0.36 km/hr while operating with 2 RTGs only on an average 0.09 rad. slope. Battery supplemented for greater speed or steeper local slopes.

[b] Continuous average shown. Peaks may not be on simultaneously unless battery fully charged.

The power requirements are based on what can be expected from technology development through 1975 - 1976, as well as that which can be expected from the Viking '75 program. Voltages shown were assumed for conversion losses, required raw power, and weight.

The mobility power demand of 124 W (see Table 5) is based on that available from 2 RTGs after providing for supporting subsystems. The 124 W available will provide for a speed of 0.36 km/hr on an average 0.09 rad. slope. A functional block diagram of the Mars Rover power subsystem is shown on Figure 6.

Operating the RTG on the Martian surface may affect performance, since this design is for the deep space environment. For this study, it was estimated that each RTG will provide approximately 140 W at arrival on the surface, approximately 136 W at the end of 1 yr, and 134 W at the end of mission.

A shunt regulator is provided with each RTG to maintain the RTG at its maximum power capability when subsystem power demands are reduced. An inverter is provided for changing a portion of the RTG DC power output to regulated square wave AC power for engineering and science. A standby inverter controlled by a failure detector sensing the main inverter voltage and frequency outputs is provided for redundancy. The remaining power from the RTG is available for mobility and communications.

Two 12 amp-hr nickel cadmium batteries are provided to supplement the RTGs during periods of mobility or locomotion when increased speeds are desired or increased slopes are encountered. The batteries are discharged in parallel through a regulator for operation at the maximum power point of the RTG. A standby regulator, controlled by a failure detector sensing the main regulator output voltage, is also provided for redundancy. A single battery may be adequate if compromises in other vehicle subsystems are made (e.g., mobility).

(c) Telecommunications

The telecommunications design associated with a Mars roving vehicle mission presents some particularly difficult design tradeoffs. For this concept, the number of tradeoffs was limited by considering only a direct link to earth. Use of a direct link primarily affects bit rate, antenna pointing accuracy, and communications visibility period. With limited power on board the vehicle, the direct link data rate is limited. Antenna pointing accuracies of ±21 mrad. must be achieved for reasonable data rates.

A diagram of the direct link telecommunications subsystem selected is shown in Figure 7. The flight telemetry subsystem provides data to the modulation/demodulation subsystem, which modulates the data onto a subcarrier. In the normal mode of operation, the subcarrier phase modulates the data onto an S-band or X-band RF carrier, which is amplified by a TWT, transmitted to earth through the high-gain antenna, and coherently received by the DSN stations. There is insufficient power to transmit telemetry data to earth through the low-gain antenna at 6 bits/sec (the DSN lower limit for coherent detection) and thus an M-ary Frequency Shift Keyed (MFSK) modulator is provided. For low-gain transmission, the data is MSFK modulated onto an S-band RF carrier at about 0.5 bits/sec and transmitted to earth through the low-gain antenna where the signal is incoherently received and detected. It is intended that the MSFK mode would be used only in the event of a failure of the pointing systems of the high-gain antenna.

For transmission of data to earth at the maximum data rate, the X-band carrier would be used. To obtain sufficient pointing accuracy of the high-gain antenna for X-band use, a monopulse antenna pointing system will be required. In any event, a gyro and sun sensor pointing system also would be used for backup with the S-band mode.

An S-band receiver is provided to receive commands from earth, and to provide the reference for a phase coherent down link S- or X-band signal when required. Ranging can be performed when required. The command waveform is sent from the receiver to the modulation/demodulation subsystem where the command subcarrier is removed and the data bits are detected. The detected data bits are then sent to the command decoder for further operation.

The baseline telecommunications subsystem consisting of a 20-W X-band TWT with monopulse tracking (backup S-band with gyro and sun-sensor antenna pointing) was not evaluated for its capability to provide for communication to earth during launch, cruise, entry or deployment phases of the mission. Also, it was not evaluated for providing a communication capability for a relay link to earth. Evaluation of these modes of operation must be considered before final selection of a telecommunications system for the Mars rover.

(d) Navigation

The basic requirements of the navigation subsystem are to direct the vehicle motion accurately and reliably over the planned mission traverse, which will be designed and over-laid on the best available photographic maps of the surface area of interest. General heading and location of the destination (major scientific sites) relative to the vehicle can be obtained from the planned traverse maps. Continuous vehicle position and heading information will be obtained and used in conjunction with the traverse map information (on earth) to provide the direction to the destination.

Accuracy requirements of the navigation subsystem are determined primarily from the exploration accuracy required by science. If regional accuracy is required, i.e., it is only necessary to reach an area or region of interest, then the accuracy requirements will be much less stringent than if it is required to reach a particular site within an area or region. It also will be desirable to accurately determine elevation changes which can be correlated with various scientific measurements to enhance their value.

The method used in navigating the vehicle must be capable of a certain degree of self-contained operation, relatively simple to mechanize and capable of meeting the accuracy requirements. The design must allow for operation under vehicle control for as many operations as possible in order to overcome the inefficiency of earth-based control through a communications link with a delay time on the order of minutes. The method selected to navigate the vehicle is a gyrocompass/odometer scheme, updated periodically by a surface landmark matching technique. This combination provides the accuracy, simplicity, and degree of self-contained operation required for a Mars roving vehicle. Other methods, such as total inertial or celestial navigation, have limitations (primarily in accuracy capability) which make them less attractive.

A performance analysis$^{(6)}$ comparing the gyrocompass/odometer subsystem with a total inertial subsystem has shown that the gyrocompass/odometer is superior. The primary reason is that the odometer serves as an external reference (as compared to a calculated reference), limiting errors in computed distance to a small percentage of total distance traveled. The frequency of updates also is reduced considerably as a result, providing a more time-efficient surface operation.

The gyrocompass performance is affected by gyro misalignment and drift, and platform tilt. External navigation updates are required to compensate the vehicle location error which accumulates with time. A diagram of the gyrocompass/odometer navigation subsystem is shown in Figure 8.

Landmark navigation or "piloting"$^{(7, 8, 9)}$ is a relatively simple method requiring only a TV camera and terrain maps of the surface area of interest. Surface landmarks are observed in the TV field-of-view and correlated with landmarks on the terrain map. Bearings to the landmarks, relative to vehicle heading, are measured and lines-of-position determined. The intersection of at least two lines-of-position defines the vehicle's position and heading in map coordinates.

The accuracy of landmark navigation, relative to the map, is a function of landmark frequency, landmark distribution and the error in determining bearing. As the number of landmarks increases, the undertainty decreases. Uncertainty due to independent errors of feature location reduces with more measurements, but other errors such as map coordinate offsets are not reducible and, therefore, limit the accuracy.

The greatest disadvantage of this technique is that the navigation process must be performed on earth. TV pictures are transmitted to earth, landmarks identified, and vehicle position and heading computed. At Mars distance, this process consumes a significant amount of valuable mission time and does not appear practical as a single means of vehicle navigation. Because of the inherent accuracy and the expected photographic coverage of Mars from the Mariner 1971 and Viking missions, landmark navigation should be considered for updating the prime navigation subsystem.

(e) Obstacle Detection

The effectiveness of a Mars roving vehicle can, in part, be measured in terms of the vehicle's ability to detect and avoid all obstacles interfering with vehicle motion. Obstacles which can impede vehicle motion are expressed in terms of the mobility capability of the vehicle. Both short- and long-range obstacle detection (typically, 1 m and 30 m, respectively) techniques, using tactile and electro-optical sensors, will be required. The short-range sensors are used primarily to assure vehicle safety, whereas the long-range sensor(s) is (are) used for measuring the conditions at some distance from the vehicle for obstacle warning and path adjustment.

Obstacle avoidance strategies, which use data from the sensors, provide the necessary heading commands to the vehicle for negotiating the obstacles. These strategies not only influence vehicle safety, but they have a direct bearing on the traverse efficiency. The likelihood of the vehicle traveling the minimum distance to the destination is directly governed by early obstacle detection and avoidance maneuvers.

Functionally, the range obstacle detection subsystem must provide data that can be used to identify an obstacle in the path of the vehicle at a predetermined range. Once the obstacle has been identified, the vehicle computer determines the commands necessary to avoid the obstacle. The sector of coverage of the long-range system should include an azimuth angular range sufficiently wide to encompass likely vehicle paths. Resolution is determined by the physical characteristics of the obstacles.

A possible sensor configuration for obstacle detection is a laser whose beam is scanned back and forth through a range of azimuths on either side of the vehicle. By detecting the time of the return signals and correlating these returns with the beam scan position and vehicle attitude, the position and type of obstacle can be determined.

Figure 9 is a block diagram of such an obstacle detection subsystem. Here, the beam is shown being scanned through a ±0.35 rad. azimuth range in a 1-sec time interval. The return signal is detected by the receiver and sampled every 0.09 rad. of azimuth change. The range of detection is determined by receiver sensitivity and Mars surface reflectivity properties. The output of the sampling gate is conditioned and input to the threshold detection element, along with vehicle attitude. The threshold level is determined by the range to the intersection of the beam and the surface, assuming a flat surface and a level vehicle attitude. Threshold tolerance is a function of return signal strength, noise, and attitude determination accuracy.

(f) Antenna Pointing

High bit rate science data from the Mars roving vehicle requires that a high-gain antenna be pointed at the earth. Two antenna mounts can be considered for such an antenna: (1) an azimuth-elevation system in which north and local vertical are used as references and (2) a polar or hour-angle declination amount in which one axis is oriented parallel to the planet's spin axis. Because of its flexibility and simplicity during the earth tracking periods, the hour-angle declination mount is the selected baseline configuration.

The hour-angle declination mount, requiring two gyros and four gimbals, is more autonomous, more flexible, has better degraded mode capability, and requires minimum on-board computer requirements. The first gyro is used to sense north. The second gyro is used to erect the hour-angle axis parallel to the planet's spin axis. The sun is then acquired by a two-axis sun sensor which is biased to account for the sun-Mars-earth angle, pointing the antenna toward the earth.

The selected Antenna Pointing Subsystem (APS) is capable of tracking the earth within ±35 mrad. This corresponds to the -0.75 dB points of a 1.2 m-diameter parabolic antenna at S-band. Therefore, the S-band operations can be performed by the APS alone. For X-band, the required improvement in pointing accuracy can be achieved either by calibrating out the bias errors or by using a monopulse loop to track the uplink.

The APS will acquire the earth within about 15 to 20 min on the first day. Subsequent daily acquisitions will be shorter if the rover daily orientation changes are small. The APS will be capable of pointing the antenna at any part of the sky which is greater than 0.26 rad. above the local horizon.

A block diagram of the APS is shown in Figure 10. The control loops for the azimuth and elevation drives are identical, utilizing gyros for position error sensors to drive the control axes. When the polar shaft is aligned parallel to the planet's spin axis, power is removed from these two loops. The stepper motors contain permanent magnet or mechanical detents which act as brakes when power is turned off. When the polar shaft erection mode is completed, the hour-angle and declination axes are enabled and the sun is acquired, using the sun sensors. A bias is mixed with the sun sensor output to point the antenna at the earth.

(g) Data Handling

A number of data handling design requirements have been established which will permit a more efficient utilization of the rover capabilities and will in effect progressively diminish the adverse effects of the long two-way transmission time associated with the mission. These requirements are:

(1) All primary control functions must be capable of being actuated by either ground commands or on-board commands.

(2) The degree to which ground commands and on-board commands are utilized in the execution of a given sequence must be variable.

(3) The sequence of issuance of on-board commands must be variable both via ground control and by automatic on-board state determination.

(4) An on-board logical element must be included which has access to appropriate rover sensor information and has the ability to control the sequence and time of the vehicle's actuators.

(5) The on-board logical element must be capable of performing fundamental arithmetic and Boolean operations.

(6) The data rate from rover instruments must be variable and capable of being controlled by a telemetry processing unit.

(7) The data from the rover instruments must be processed and stored for re-transmission to earth.

The functional block diagram of a data handling subsystem which meets the requirements stated above is shown in Figure 11.

MISSION OPERATIONS

The earth-based operations involved in the control of a Mars roving vehicle mission are quite extensive and complex(10). This study effort did not consider the mission operations area in sufficient depth to provide detail descriptions of the operational requirements. However, the operational aspects were given a general consideration and the results are described below.

A functional block diagram of the earth-based operations is shown in Figure 12. The mission operations system is seen to be comprised of the mission-dependent computing and processing, data printout and visual displays, mission control, science planning and evaluation and the vehicle command and control element. It should be noted that only those elements of the total mission operations system directly involved in the vehicle operations are considered. The various DSN stations, coverage, etc., are not considered.

Data received from the vehicle are conditioned and formatted for driving visual displays, magnetic tape recorders, and line printers. Mission control, whose function is to provide overall direction of all mission operations, establishes the vehicle objectives based upon recommendations of the science planning and evaluation team and the command and control operations team. Science planning and evaluation is concerned with maximizing the mission payoff and, thus, selects the potential sites to be surveyed and explored. The command and control element includes the "standby" human operator and the command and control console. The operator must know or have access to all internal and external vehicle status information, and must be prepared to execute emergency control measures.

The earth-based computer system, not unlike the vehicle system, is extensive and complex. These characteristics, however, can be accommodated more easily because they are not subject to the physical constraints imposed by spacecraft payload limitations. In a normal operation mode, the earth-based computer system will receive and process a data "dump" over the high-gain communications system following the completion of a programmed science investigation sequence, and receive and process a limited amount of data over the omnicommunications system during motion toward the destination. The system will be required to route the various portions of the processed data to the command and control operations team, the science planning and evaluation team, and mission control. Each group will analyze certain portions of the data and, under the direction of mission control, determine the next destination and/or the necessity to alter the operational mode.

At all times, the earth-based system must be in a position to take control of the vehicle. The computer software system must have capabilities identical to the vehicle-based software system qualities and, in addition, the capability to handle contingencies which the on-board system cannot handle alone. An earth-based "learning" process must be continuously operative in the command and control operations team to achieve the desired "near-optimal" control process. Earth-based data analysis software will be required for evaluation and improvement of the current vehicle-based model to support the learning process.

Command generation is another major requirement on the earth-based system. The command generation software must be sufficiently flexible and efficient to provide minimum-time command capability under a diverse range of circumstances. For example, the sequence of individual vehicle commands necessary to perform a particular operation must be assembled, verified, and transmitted to the uplink rapidly. Software flexibility also must be provided to allow for direct access discrete control of on-board sensors or actuators.

Transmitted data will be used to drive the ground display system for the three groups mentioned above. The mission control display will relate the overall mission status. Science operations will have software for filtering and enhancing television pictures and for processing (calibration and filtering) other data from the science instrument complement. The command and control team will be concerned with vehicle motion and, thus, the ground display will provide the vehicle operator with all vehicle status information.

Several relatively detailed studies have been performed on the subject of mission operations for a lunar roving vehicle. One is given in Reference 11. The referenced study, plus the cursory look at mission operations presented here, should provide considerable background for the design of a mission operations system for a Mars roving vehicle.

CONCLUSIONS

The successful development of a surface roving vehicle for a 1979 Mars mission hinges on many factors. The vehicle design must have the capability to operate for extended periods of time, relatively independent of the earth, to withstand the harshness of the Martian environment, and to travel hundreds of kilometers, independent of the surface delivery spacecraft. These capabilities imply, respectively, system techniques which focus on autonomy and reliability, environmental sensing and control, and a safe and effective motion control.

The 1979 opportunity is both favorable and unfavorable in terms of implications on the mission design. The foremost implications are that 1979 requires a low launch energy (C_3 from 9-15 km^2/sec^2) and, because the earth and Mars are at extreme distances, the round trip light time delay is quite large. During the anticipated 1-yr mission, the time delay reaches 41 min, round trip. This has serious implications on the ability of the vehicle to travel large distances over the surface. It requires some degree of onboard control in order to limit the inefficiency associated with strictly earth-based control. During the early phases of the mission, the dependence on earth-based control will be higher. As mission confidence increases, more reliance will be placed on the on-board control system. Consequently, the vehicle traverse capability will be low initially and increase appreciably as the mission lifetime increases.

The nature of the roving vehicle system requires a complex interconnection of many vehicle-based and earth-based elements, linked by the telecommunications capabilities of the Deep Space Network and the communications system of the vehicle. Each element must possess the qualities of functional performance and reliability dictated by the mission requirements, and each must be capable of functioning in the total, integrated system environment.

To develop the capability to perform a Mars rover mission, a strong research and advanced development program is needed several years prior to a technology cut-off. (For a 1979 rover, the cut-off may be as early as 1975 or 1976). The program should be structured to give high priority to obstacle detection and avoidance, on-board control philosophy, computer capabilities, and mobility. Efforts in these areas will contribute needed technology for developing a vehicle with a range of hundreds of kilometers and capable of surviving 1 yr on the Martian surface. In each of the areas, system reliability must be a dominant factor in the development process.

ACKNOWLEDGEMENT

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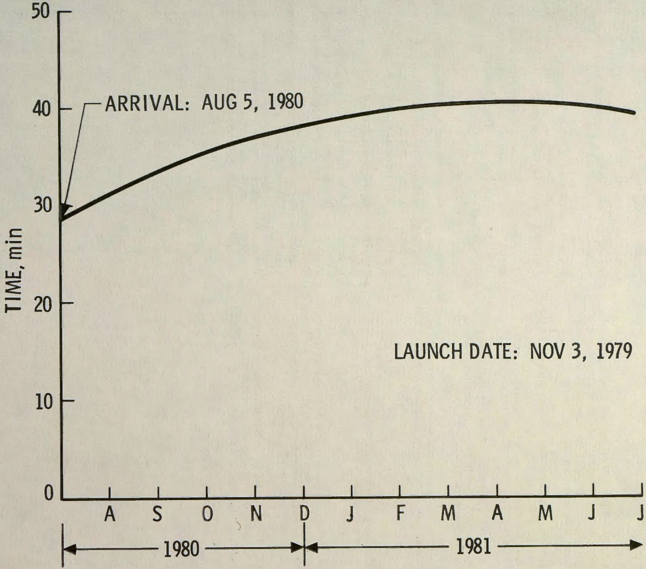
(12) Moore, J. W., et al, "An Exploratory Investigation of a 1979 Mars Roving Vehicle Mission," JPL Document 760-58, December 1, 1970. (JPL Internal)

ILLUSTRATIONS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40
30
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TIME, min
ARRIVAL: AUG 5, 1980
LAUNCH DATE: NOV 3, 1979
A
S
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M
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1980
1981

Figure 1

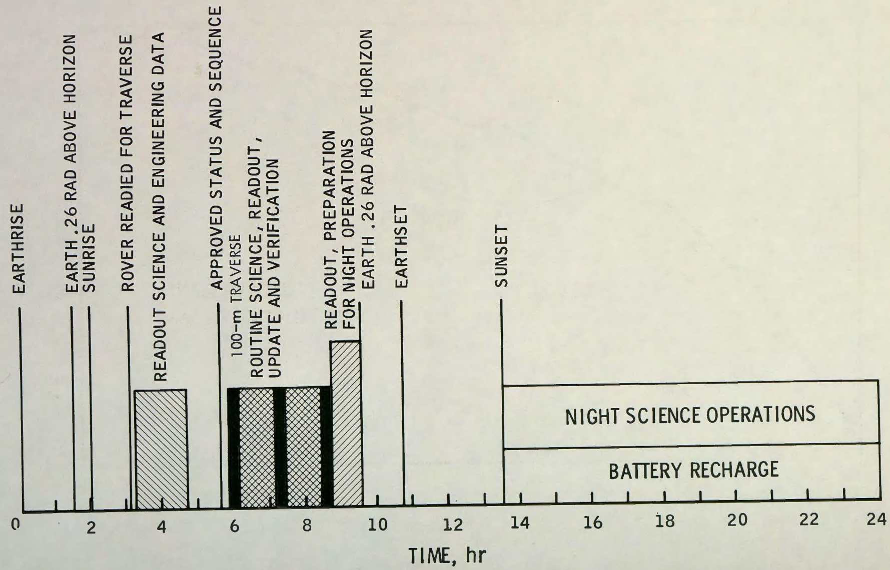
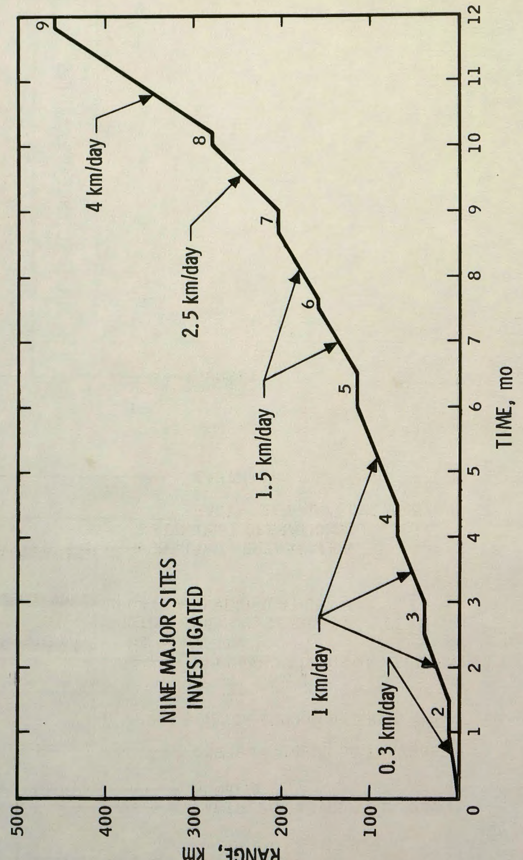

EARTHRISE
EARTH .26 RAD ABOVE HORIZON
SUNRISE
ROVER READIED FOR TRAVERSE
READOUT SCIENCE AND ENGINEERING DATA
APPROVED STATUS AND SEQUENCE
100-m TRAVERSE
ROUTINE SCIENCE, READOUT, UPDATE AND VERIFICATION
READOUT, PREPARATION FOR NIGHT OPERATIONS
EARTH .26 RAD ABOVE HORIZON
EARTHSET
SUNSET
NIGHT SCIENCE OPERATIONS
BATTERY RECHARGE
0
2
4
6
8
10
12
14
16
18
20
22
24
TIME, hr

Figure 2

NINE MAJOR SITES INVESTIGATED
RANGE, km
0
100
200
300
400
500
TIME, mo
0
1
2
3
4
5
6
7
8
9
10
11
12
0.3 km/day
1 km/day
1.5 km/day
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4 km/day
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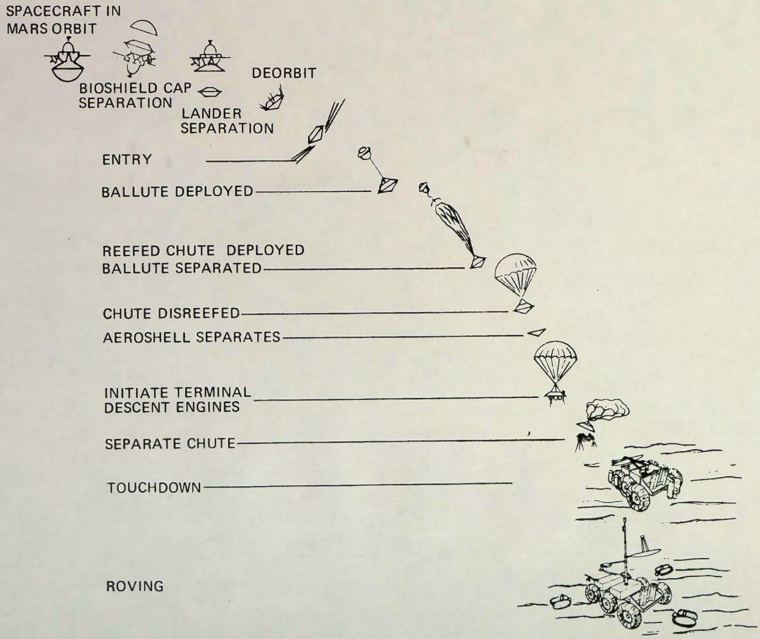
3
4
5
6
7
8
9

Figure 3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BIOSHIELD CAP SEPARATION
DEORBIT
LANDER SEPARATION
ENTRY
BALLUTE DEPLOYED
REEFED CHUTE DEPLOYED
BALLUTE SEPARATED
CHUTE DISREEFED
AEROSHELL SEPARATES
INITIATE TERMINAL DESCENT ENGINES
SEPARATE CHUTE
TOUCHDOWN
ROVING

Figure 4

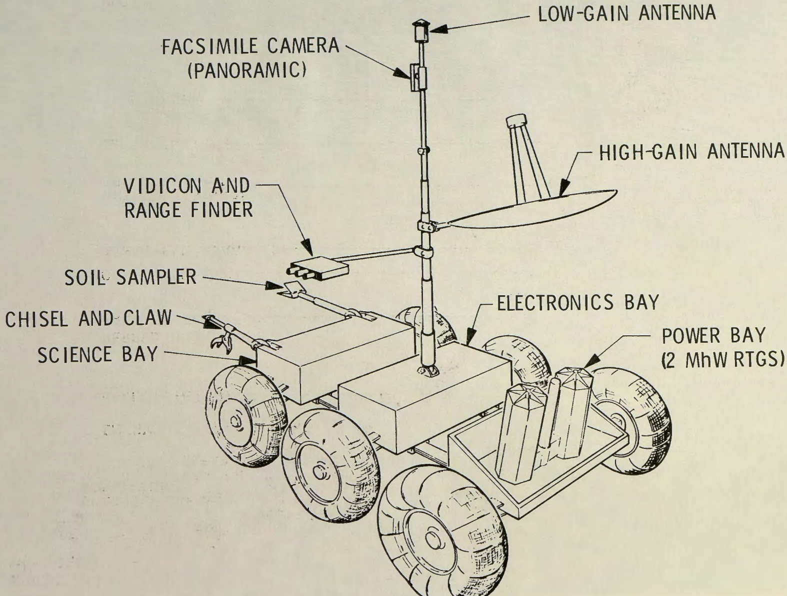

LOW-GAIN ANTENNA
FACSIMILE CAMERA (PANORAMIC)
HIGH-GAIN ANTENNA
VIDICON AND RANGE FINDER
SOIL SAMPLER
ELECTRONICS BAY
CHISEL AND CLAW
POWER BAY (2 MhW RTGS)
SCIENCE BAY

Figure 5

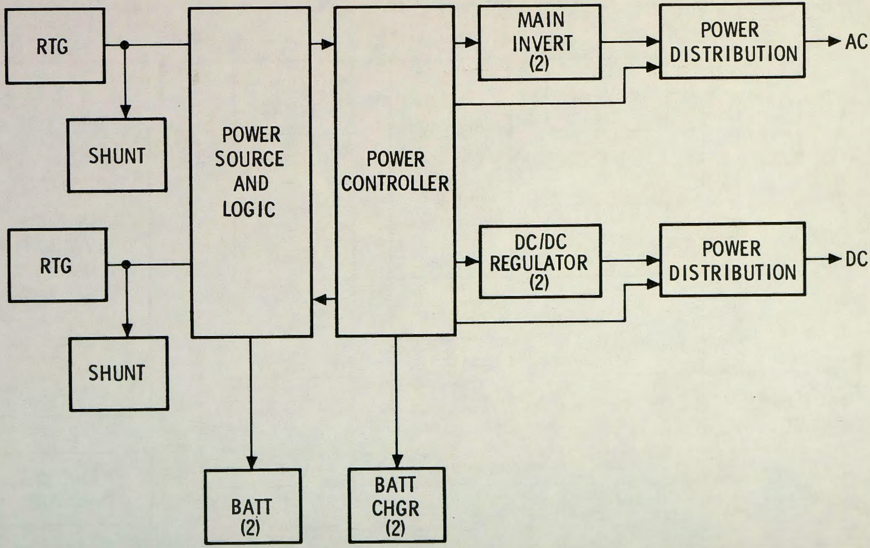

RTG
SHUNT
RTG
SHUNT
POWER SOURCE AND LOGIC
POWER CONTROLLER
MAIN INVERT (2)
DC/DC REGULATOR (2)
POWER DISTRIBUTION
AC
POWER DISTRIBUTION
DC
BATT (2)
BATT CHGR (2)

Figure 6

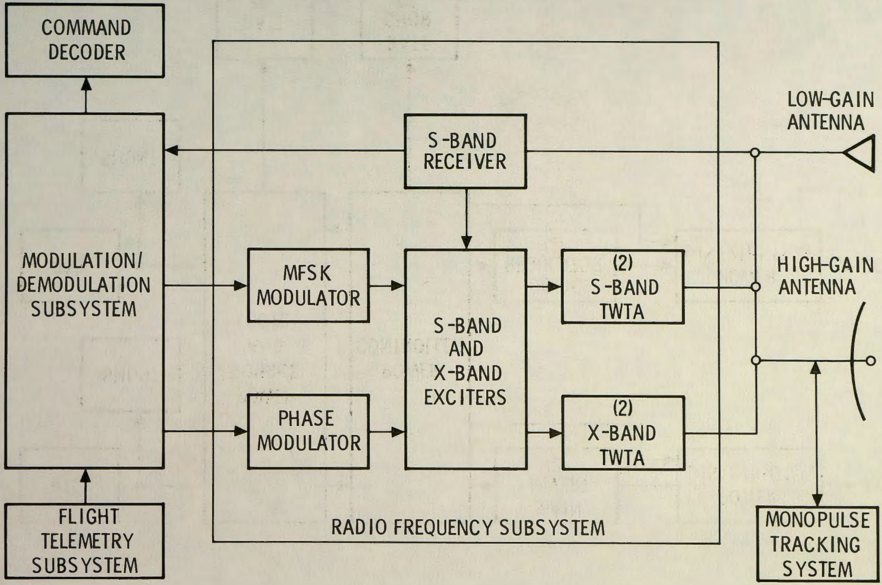

COMMAND DECODER
MODULATION/ DEMODULATION SUBSYSTEM
FLIGHT TELEMETRY SUBSYSTEM
S-BAND RECEIVER
MFSK MODULATOR
PHASE MODULATOR
S-BAND AND X-BAND EXCITERS
(2) S-BAND TWTA
(2) X-BAND TWTA
RADIO FREQUENCY SUBSYSTEM
LOW-GAIN ANTENNA
HIGH-GAIN ANTENNA
MONOPULSE TRACKING SYSTEM

Figure 7

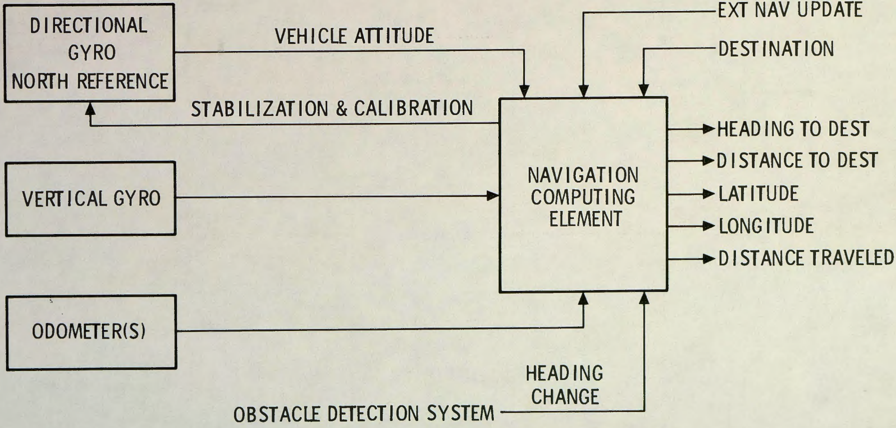
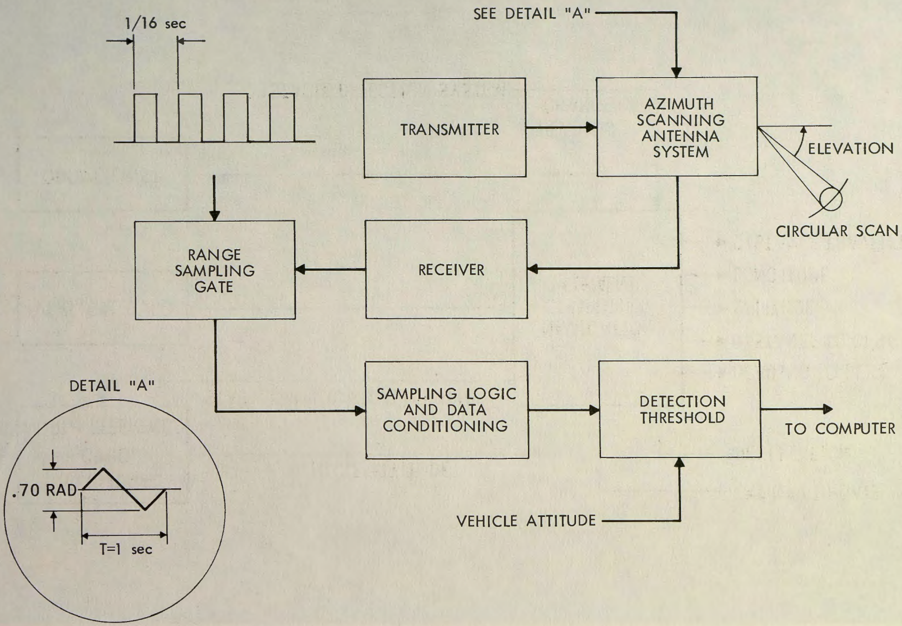

DIRECTIONAL GYRO NORTH REFERENCE
VEHICLE ATTITUDE
STABILIZATION & CALIBRATION
EXT NAV UPDATE
DESTINATION
VERTICAL GYRO
NAVIGATION COMPUTING ELEMENT
HEADING TO DEST
DISTANCE TO DEST
LATITUDE
LONGITUDE
DISTANCE TRAVELED
ODOMETER(S)
HEADING CHANGE
OBSTACLE DETECTION SYSTEM

Figure 8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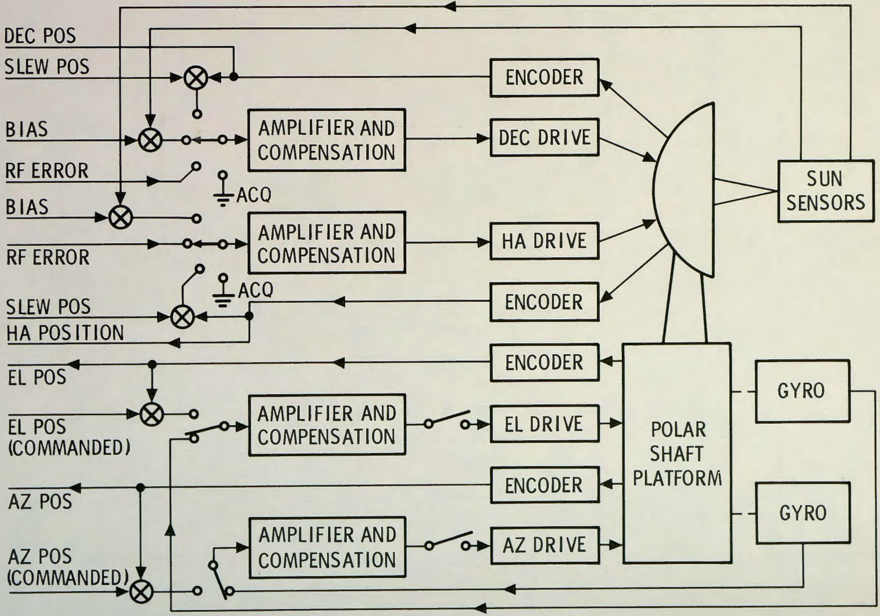
TRANSMITTER
AZIMUTH SCANNING ANTENNA SYSTEM
ELEVATION
CIRCULAR SCAN
RANGE SAMPLING GATE
RECEIVER
DETAIL "A"
.70 RAD
T=1 sec
SAMPLING LOGIC AND DATA CONDITIONING
DETECTION THRESHOLD
TO COMPUTER
VEHICLE ATTITUDE

Figure 9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SLEW POS
BIAS
RF ERROR
ACQ
BIAS
RF ERROR
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EL POS
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AZ POS
AZ POS (COMMANDED)
AMPLIFIER AND COMPENSATION
AMPLIFIER AND COMPENSATION
AMPLIFIER AND COMPENSATION
AMPLIFIER AND COMPENSATION
ENCODER
DEC DRIVE
HA DRIVE
ENCODER
ENCODER
EL DRIVE
ENCODER
AZ DRIVE
SUN SENSORS
POLAR SHAFT PLATFORM
GYRO
GYRO

Figure 10

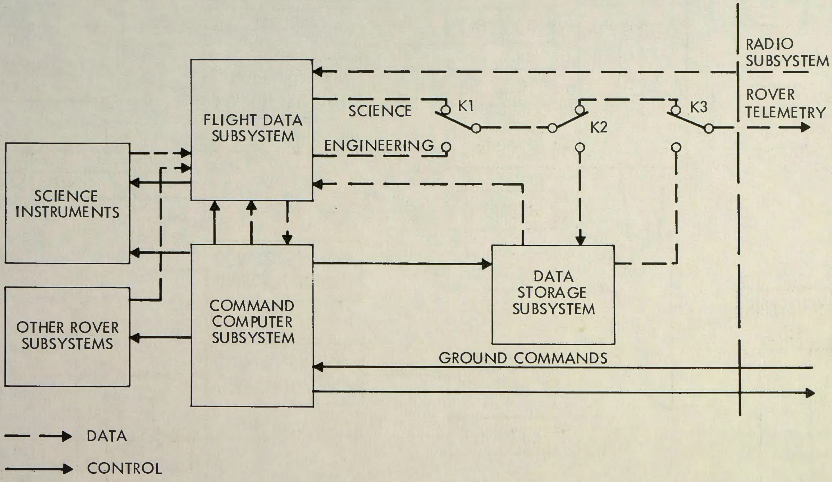
RADIO SUBSYSTEM
FLIGHT DATA SUBSYSTEM
SCIENCE
K1
K2
K3
ROVER TELEMETRY
ENGINEERING
SCIENCE INSTRUMENTS
DATA STORAGE SUBSYSTEM
COMMAND COMPUTER SUBSYSTEM
OTHER ROVER SUBSYSTEMS
GROUND COMMANDS
DATA
CONTROL

Figure 11

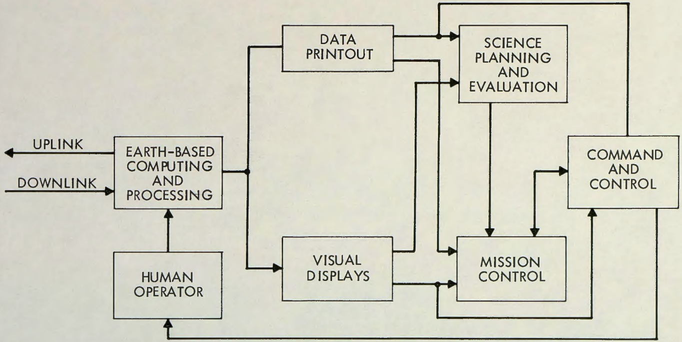
UPLINK
DOWNLINK
EARTH-BASED COMPUTING AND PROCESSING
HUMAN OPERATOR
DATA PRINTOUT
VISUAL DISPLAYS
SCIENCE PLANNING AND EVALUATION
MISSION CONTROL
COMMAND AND CONTROL

Figure 12