# UNMANNED SURFACE TRAVERSES OF MARS AND MOON: SCIENCE OBJECTIVES, PAYLOADS, OPERATIONS

By

Leonard D. Jaffe and Raoul Choate

June 8, 1973

Backup Document for AIAA Synoptic Scheduled
for Publication in the Journal of Spacecraft and Rockets
June 1974

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

(NASA-CR-136810) UNMANNED SURFACE TRAVERSES OF MARS AND MOON: SCIENCE OBJECTIVES, PAYLOADS, OPERATIONS (Jet Propulsion Lab.) 41 p HC $4.25 CSCL 03B

N74-17538

Unclas

G3/30 29653

## SYNOPTIC BACKUP DOCUMENT

This document is made publicly available through the NASA scientific and technical information system as a service to readers of the corresponding "Synoptic" which is scheduled for publication in the following (checked) technical journal of the American Institute of Aeronautics and Astronautics.

- [ ] AIAA Journal
- [ ] Journal of Aircraft
- [x] Journal of Spacecraft & Rockets, June 1974
- [ ] Journal of Hydronautics

A Synoptic is a brief journal article that presents the key results of an investigation in text, tabular, and graphical form. It is neither a long abstract nor a condensation of a full length paper, but is written by the authors with the specific purpose of presenting essential information in an easily assimilated manner. It is editorially and technically reviewed for publication just as is any manuscript submission. The author must, however, also submit a full backup paper to aid the editors and reviewers in their evaluation of the synoptic. The backup paper, which may be an original manuscript or a research report, is not required to conform to AIAA manuscript rules.

For the benefit of readers of the Synoptic who may wish to refer to this backup document, it is made available in this microfiche (or facsimile) form without editorial or makeup changes.

# UNMANNED SURFACE TRAVERSES OF MARS AND MOON: SCIENCE OBJECTIVES, PAYLOADS, OPERATIONS

Leonard D. Jaffe*

Jet Propulsion Laboratory, California

Institute of Technology, Pasadena 91344

and Raoul Choate†

TRW Systems Group, Redondo Beach, California 90278

(Formerly, Jet Propulsion Laboratory*)

## ABSTRACT

Science objectives and properties to be measured are outlined for long surface traverse missions on the surface of Mars and the moon, with remotely-controlled roving vehicles. A series of candidate rover/Science payloads is proposed for each planet, varying in weight, cost, purpose, and development needed. The smallest weighs 35 kg; the largest almost 300 kg (including instruments in three permanently emplaced science stations). A high degree of internal control will be needed on the Mars rover, including the ability to carry out complex science sequences. Decision-making by humans in the Mars mission includes supervisory control of rover operations and selection of features and samples of geological and biological interest. For the lunar mission, less control on the rover and more on earth is appropriate. Science portions of the

---

*Member, Technical Staff

†Engineering Geologist

rover mission profile are outlined, with timelines and mileage breakdowns. Operational problem areas for Mars include control, communications, data storage, night operations, and the mission operations system. For the moon, science data storage on the rover would be unnecessary and control much simpler.

## INTRODUCTION

This paper provides an initial evaluation of science aspects of a remotely-controlled roving vehicle for a long traverse mission across a planetary or lunar surface. Primary attention is given to a Mars mission, but a lunar mission is also considered. Previous studies of Mars and lunar roving vehicles have been recently reviewed (Ref. 1).

Lunokhods 1 and 2 are remotely-controlled lunar roving vehicles. These vehicles performed local exploration in the vicinity of their landing sites. Lunokhod 1 travelled a total of 10 km and Lunokhod 2 moved 37 km.

A Mars roving vehicle mission differs from a lunar mission in that the Mars mission would probably be concerned with biology and meteorology, as well as with the geology and geophysics to which a lunar mission would be addressed. In the harsh environment of Mars, life may exist only in limited areas where conditions are most favorable. Thus, whether or not earlier lander missions find evidence of life, an important reason for sending a rover to Mars may be to use its mobility to search systematically for places where life may exist.

Other important differences between Mars and lunar missions arise from the radio transmission times to earth: 2.5 sec round trip for the moon, 6 to 44 min for Mars. These lead to major contrasts in control of the vehicle, in timeline, and in mission operations.

A rover forms only one element of a desirable Mars traverse mission. Other elements of scientific importance should include:

(1) A Mars orbiter.

(2) A science package at the landing site.

(3) Science packages emplaced by the rover, away from the landing site.

(4) Possibly instruments for measurements during atmospheric entry and descent.

These elements appear less important for a lunar traverse mission. In this paper, items (2) and (3) are considered as "emplaced science packages" and discussed to some extent. The orbiter, a very important part of the Mars mission, and the entry payloads, are not discussed here (see Ref. 2).

The return to earth of samples gathered by the rover is considered here only for lunar missions, and that briefly; the topic deserves further attention. Also, only science concerned with Mars and the moon is considered, not the use of Mars and the moon as stations for other kinds of scientific measurement.

No mission constraints were imposed on this work, and no attempt is made here to define the minimum missions that would be worthwhile.

## SCIENCE OBJECTIVES AND MEASURABLES

Nine questions have been selected for which a remotely-controlled Mars roving vehicle, making a long traverse, could collect critical data (see Ref. 3). They are:

(1) What is the distribution of surface chemical and isotopic compositions?

(2) What is the internal structure, i.e., density, rigidity, and nature of the principal petrologic phases, as functions of depth and location?

(3) What is the present thermal regime of the interior and what were the past regimes, i.e., temperature as a function of depth?

(4) What is the nature of major geologic provinces and larger surface features, and what processes formed them?

(5) What were the dates of major geological events, e.g., differentiation events?

(6) What is the present atmospheric regime, what were the past regimes, and what are the causes of short- and long-term variations and changes occurring in the atmosphere?

(7) What are the present and what were the past environmental conditions that may have affected evolution and development of life, i.e., presence of protobiological materials, sources of nutrients, moisture, temperature, incident radiation, incubation and host materials, toxicity, etc.?

(8) Does life now exist or has it existed in the past?

(9) If life now exists or has existed, what is its form, type, complexity, extent, etc.?

For a lunar rover, questions 1 and 4 would be of primary interest, and some useful data might be obtained on questions 2, 3, and 5.

To answer the above questions, a number of quantities can be measured. Those considered critical to answering these questions, and also appropriate to a long-range Mars traverse mission (with emplaced science packages, in some cases) are listed in Table 1. For the moon, the meteorology and biology measurables would be omitted. Seismicity and body motions would probably also be omitted as adequately covered by existing fixed site lunar instruments, unless emplaced packages associated with a rover mission are needed to replace seismometers or laser reflectors that may no longer be functioning.

The appropriateness of the listed measurables to a rover mission must be qualified in terms of scale: large-scale geomorphic features, gravity field characteristics, etc., are more appropriately measured with an orbiter, small-scale with a rover. Temporal changes, such as meteorological, are most appropriately observed from a fixed site or with an emplaced package. The measurables are discussed in Refs. 2 & 4; associated science tasks, requirements, functions, and candidate instruments are reviewed in Refs. 2 & 5.

## SCIENCE PAYLOADS

No attempt is made in this report to pick a payload to meet prescribed weight, cost, or schedule constraints, since these have not yet been defined.

Rather, series of Science payloads have been selected that provide a spectrum of possibilities in weight, power, complexity, cost, development required, and scientific capability.

Mars Payloads. For Mars, four of the payloads (Payloads C to F) are "balanced" in that they provide measurements in all four of the scientific areas for which need was outlined in Table 1: geology and geochemistry, geophysics, meteorology and atmosphere, and biology. Of these balanced payloads, Payload C is the smallest and Payload F the largest in all the respects mentioned. Payloads A and B are specialized payloads in which all capability for measurements in one or more of the scientific areas is omitted to provide lower weight than is practical for a balanced payload.

Payload A is oriented toward the geological sciences and has no biological instrumentation. It includes a TV camera rather than the facsimile cameras planned for Viking '75. The TV camera provides greater resolution than the facsimile, adds considerably to the geological work that can be done, and also is needed for rover guidance. This camera and an X-ray diffractometer (added to the X-ray spectrometer in the Viking payload) will permit petrological work. A general purpose manipulator, in place of the Viking soil sampler, provides improved sampling and aids in petrographic and soil mechanics observation. A magnetometer and gravimeter are included for geophysical investigation; the Viking passive seismometer is omitted as less appropriate for a rover. The meteorological instruments are similar to Viking's. The weight of Payload A is estimated (Table 2) as 35 kg with a solid-state TV camera (option A1) or 42 kg with a vidicon camera (option A2); the solid state camera would require advanced development. These compare with a current estimated Viking '75 payload weight of 78 kg, including surface sampler and sample processors.

Payload B is most like the Viking '75 payload. On it, the X-ray and geophysical instruments of Payload A are replaced by molecular analysis and biological instruments generally similar to those originally planned for Viking. The payload weight is estimated as 38 kg with a solid-state TV camera (option B1) or 45 kg with a vidicon camera (option B2).

Payload C includes the instruments of both Payloads A and B. It has two TV cameras to provide stereoscopic viewing and added reliability. A soil-gas exchange chamber and upgraded instruments for molecular analysis and biology add capability in these areas.

Payload D adds to Payload C two facsimile cameras, mounted one above the other for vertical stereo. This provides improved geometrical and photometric accuracy and multispectral capability beyond that of the TV cameras, and avoids the need for mosaicking large numbers of pictures to get a panorama. A range finder, used also for navigation and guidance, aids in identifying and mapping surface features. A viewing stage, for low-magnification work, and a microscope improve the imaging of specimens. A sample buffer storage system holds samples awaiting analysis and frees the manipulator for other work. Payload D provides a passive seismometer in a permanently emplaced package that also includes a meteorological station, a magnetometer, and a dual-frequency radio transponder. These instruments, for which a fixed location is desirable, supplement the roving capability.

Payload E is a heavier payload that seems highly desirable scientifically. Compared to Payload D, it has an improved sampling and manipulation capability. Wet chemical analytical equipment adds greatly to the possibility of organic analysis; a balance and electromagnet are also added. For biology, there is a soil-gas probe. An active/passive seismometer and a seismic source improve the geophysics. Other additions include a soil mechanics instrument and an atmospheric dust detector. A heat flow/thermal conductivity probe is incorporated in the permanently emplaced package, and the rover carries a probe-driver with which to place both the heat flow and the soil-gas probes.

The large Payload F would be well worth carrying if the vehicle could do so. Beyond Payload E, it provides additional sampling and manipulation capability, including two manipulator arms. A high-powered optical microscope with biological auxiliaries, ion microprobe, scanning electron microscope/microprobe, polarimeter, and a variety of other equipment greatly increase the scope of the inorganic and organic analysis and the biology; the microprobes also increase the potential for remote age-dating. Three emplaceable science packages are provided to form a net. Because the three emplaced seismometers provide an adequate net for passive seismometry, the rover carries geophones for seismic sounding rather than another seismometer.

Characteristics of the individual instruments are given in Ref. 2. Instrument weights and payload power requirements are shown in Table 2. The payload weights range from 35 kg to almost 300, including instruments in emplaced science stations. The power requirements include diversity factors and are based on assumptions that certain high-power instruments will not be operated simultaneously (Ref. 2); the average payload power during science operations ranges from 36 to 139 W. Emplaced stations are to be left behind by the rover, and so must have their own power sources. Science power during vehicle motion is assumed limited to analytical equipment and the electromagnetic sounder, if one is carried; any camera or range-finder power needed during vehicle motion is assumed chargeable to guidance, since there is no science requirement for operation of these instruments during motion.

The payload data rate is fixed essentially by the cameras; other instruments add little. A wide-angle TV picture with the selected characteristics includes $6 \times 10^6$ bits; a narrow-angle TV picture, $1 \times 10^7$ bits; a facsimile panorama, $3.9 \times 10^7$ bits. A TV data rate of 128 kbits/sec was assumed, based on a very preliminary look at the frame time required. The assumed transmission channel has a capacity of 32 kbits/sec of science imaging data (either 32 kbits/sec of raw data or 16 kbits/sec of data compressed 2:1), and is continuously available except during rover motion. With these rates, a timeline was worked out (below) for activities at a science site. This includes 120 science pictures containing $1.1 \times 10^9$ bits, exclusive of TV needed for vehicle guidance at the site. The peak data storage involved in this sequence is 1.3 hr of science video transmission, or about $10^8$ bits precompressed 2:1.

Lunar Payloads

Lunar payloads, Table 3, were selected independently of the Mars payloads. Some of the differences between the two reflect only this independent choice, others reflect differences in mission constraints or objectives. For example, more cameras are proposed even for the smaller payloads; the wider communications bandwidth from the moon permits greater use of pictures. Seismometers are omitted on the assumption that the seismometers landed by Apollo are adequate.

Proposed are lunar payload types for 5 different missions:

Missions with no return of samples to earth--

1. Aimed primarily at geophysical studies.
2. Aimed primarily at geological and geochemical studies.
3. Balanced mission (geological/geochemical/geophysical).

Missions involving return of samples to earth--

4. Aimed primarily at geological and geochemical studies.

5. Balanced mission (geological/geochemical/geophysical).

The less specialized payload types (3 & 5) are considered more desirable than the specialized (1, 2, 4) but would be heavier and more costsly. For each type, a small payload (S) and a large one (L) are given.

The small geophysical payload, 1S, includes only terrain cameras, gravimeter, magnetometer, and electromagnetic sounder. The larger version, 1L, adds active seismic sounding and a remanent magnetism detector, plus two emplaceable science stations to make heat-flow measurements, which take a long time. It also provides some capability to acquire specimens and examine them optically, and a range finder.

Payload 2S, for geology and geochemistry without sample re[illegible] includes cameras, sample acquisition and processing equipment, a viewing stage and camera for petrography of rock specimens, and an X-ray spectrometer for elemental analysis. Payload 2S adds a range finder to improve and speed up terrain examination and analysis, a microscope for petrographic examination of soil and crushed rock, equipment to sample at greater depths, and instruments for improved analytical capability. This improved analytical capability is not needed on missions where samples are to be returned to earth for analysis (Payloads 4S and 4L), but provision must be made, instead, for storing these samples aboard the rover.

The balanced payloads (3S, 3L, 5S, 5L) combine most but not all of the instruments included in the two groups of specialized payloads.

Table 3 gives instrument weights for the lunar payloads; they range from 35 to 103 kg. Estimated average payload power during science operations ranges from 38 to 95 W; 2 to 27 W are needed for analysis and sounding during vehicle motion. (Power estimates were derived as in Ref. 2, but slightly updated). The transmission channel to earth is tentatively constrained to 0.5 Mbits/sec on the basis of limitations in digital ground data-handling equipment; a 2 Mbit/sec channel seems operationally desirable and could probably be provided without much difficulty. These rates would match the payload (camera) data rates, permitting transmission of science data in real time, without storage on the rover.

## FUNCTION ALLOCATION

Allocation of functions, between the rover and the ground operating complex of men and machines on earth, is key in the design of a roving vehicle mission. This problem is discussed, for a Mars mission, in a separate paper (Ref. 6). What follows is only a summary.

The science functions may be categorized as measurement of the properties of Mars or moon, handling material on Mars or moon, control of the status of each instrument, data reduction, data display and permanent recording, decision making as to what should be done and with what parameters, and scientific interpretation. Of these functions, measurement and handling must be done by the rover; display and recording, most data reduction, and scientific interpretation should be done on earth. More difficult is the allocation of instrument control and decision making.

### Mars

For Mars, a high degree of internal control should be possible on the rover. The round trip time for a signal to go between Mars and earth varies from 6 to 44 min. To this must be added the time for information critical to continued operation to enter the communications channel. In the science site operation discussed below, critical information is as much as $10^8$ bits, requiring 1 hr to enter the channel. A control mode in which all decisions are made on earth is therefore impractical. Sequences involving intermediate decisions would be executed so slowly that very little in the way of science would be returned from a mission of reasonable duration (Ref. 7). The rover should have sufficient internal control capability to carry out complex sequences involving imaging, manipulation, vehicle motion, chemical analysis, biological culturing, geophysical surveying, and meteorology. This capability should include using data obtained by the scientific measurements to change rover operating sequences and parameters. Decision making on earth, by humans, should include supervisory control of the rover and such major matters as changes in mission strategy and overall route. It should also, importantly, include decisions, on the basis of data transmitted by the rover, as to which Martian features found along the way should be investigated, which rocks or other Martian material should be chosen as samples, whether further testing of a sample is worthwhile, and which of the techniques available on the rover are most appropriate for the problems at hand.

Moon

Function allocation for the moon is simpler. The round trip signal transit time is only 2.3 sec; transmittal of $10^8$ bits at the rate mentioned will take only a few minutes. Making all science decisions on earth (by humans or machines) will not significantly delay the mission, and appears to be the most reliable and cost-effective approach. This is not to say that rover guidance will not require on-board decisions; as a minimum, the vehicle should be able to detect hazards and stop before it gets into trouble, without a delay of 2.3 sec or more.

# SCIENCE MISSION OPERATIONAL REQUIREMENTS

On the basis of the above discussions, the following operational requirements appear desirable from the science standpoint:

## Mars Rover

The rover should have an operating radius of at least 500 km (map distance); the corresponding track distance (length of path on the ground) is taken to be 1000 km. The rover should be capable of transmitting scientific data continuously to earth and receiving commands during science operation. While moving, the rover should be capable of analyzing on-board samples and of carrying out electromagnetic sounding (scientific imaging is not included). The rover should be capable of automatically carrying out motion and science operations, adjusting its operation on the basis of the data it obtains while so doing. All motion and science sequences, telemetry content and rover transmission sequences should be readily and quickly alterable by earth command. At night, the rover should be able to analyze on-board samples, transmit data from deployed instruments, and do a limited amount of sampling. The operating lifetime of the rover should be at least one Martian year; the operating lifetime of emplaced science packages should be at least two Martian years. It should be possible to land and operate the rover at latitudes up to 70° north and south.

## Mars Rover-Orbiter Relationships

A Mars orbiter should be in operating simultaneously with, and in support of the rover. The orbiter is discussed further in Ref. 2.

The orbiter should provide imaging coverage of areas to be traversed by the rover, as far in advance as possible, at as high a resolution as possible (preferably 2-m line resolution or better). The orbiter should measure magnetic field fluctuations simultaneously with the corresponding measurements by the rover and its emplaced packages. The orbiter should monitor planet-wide and regional changes in the atmosphere and on the surface; it should be used to provide weather predictions for the rover through observations of atmospheric patterns. On a lower priority basis, the orbiter should provide detailed orbital examination of selected scientific areas. The operating lifetime of the orbiter should be at least one Martian year. The orbiter should be able to support the rover at latitudes up to 70° north and south.

Lunar Rover and Orbiter

The rover should have an operating radius of at least 1000 km (map distance); the corresponding track distance (length of path on the ground) is taken to be 2000 km. The rover should be capable of transmitting scientific data continuously to earth and receiving commands during science operation. While moving, the rover should be capable of analyzing on-board samples and of carrying out electromagnetic sounding (scientific imaging is not included). At night, the rover should be able to analyze on-board samples, transmit data from deployed instruments, and do a limited amount of sampling. The operating lifetime of the rover should be at least one year. Imaging coverage of areas to be traversed by the rover should be provided from orbit, as far in advance as possible, with a line resolution of 2 m.

# SCIENCE PROFILE

## Mars Profile

The science profile assumed as a basis for mission design may be summarized as follows (Payload D is assumed here):

(1) The rover will investigate the landing area and ten other science areas within 500 km of the landing (mission traverse, Fig. 1). Science areas will ordinarily be chosen prior to the mission.

(2) Within each science area, approximately 4 km in radius, measurements will, on the average, be made at six science sites and one geophysical survey (Fig. 2). Science sites will ordinarily be selected on the basis of high-resolution imaging and other data obtained by Mars orbiters. Geophysical surveys will be selected on the basis of data obtained by Mars orbiters and by the rover.

(3) At each science site, the rover will stop at three or four science stations, on the average, within a 50-m radius, to take pictures, deploy instruments, and collect samples (Fig. 3). The rover may move a few meters at each station. Science stations will generally be selected on the basis of rover observations at the site.

(4) A geophysical survey will average about 1 km long and will consist of 8 to 15 geophysical stations (Fig. 4). Geophysical stations will be selected on the basis of rover and orbiter observations. In many cases they may be spaced at fixed intervals along the survey line.

Activities at a science site are illustrated by Fig. 5, part of the timeline for such a site. Assumptions made in deriving this timeline include:

| | |
|---|---|
| Vehicle speed: | 0.25 km/hr (along track) |
| Distance to earth: | $2.2 \times 10^8$ km |

On arriving at the science site, the rover stops (Station 1) and takes a panoramic picture of the general scene and some views, in arbitrary directions, of the surface nearest to itself. When these pictures reach earth, humans examine them and select the more interesting portions for additional pictures at higher resolution. The rover takes them and sends them back. The cycle is repeated, providing pictures of the most interesting features at highest resolution. The rover takes weather readings while it waits for human inputs.

When they examine the pictures, the humans note and select stations where samples should be taken, stations where geophysical instruments should be deployed, and, if warranted, stations for examination of objects at closer range.

At Station 2, the rover deploys the magnetometer, then moves off so its magnetic field will not disturb the instrument. It remains connected to the magnetometer by cable.

At a station where sampling is to be done, the rover takes a picture for location and selection of individual samples. Humans, when they have this picture, choose prospective samples and send back commands. The rover takes pictures at higher resolution to confirm the sample selection and the position of the sample, and pictures to document the sample and the surrounding surface. The rover waits for the confirmation pictures to get to earth and for confirmation to return. (Pictures purely for documentation do not involve similar operational waits; they are stored at Mars and transmitted when the communications channel becomes available.) While the rover waits for sample confirmation, it carries out operations in place: meteorology, continued magnetic readings, deploying instruments that do not require motion of the vehicle.

When the rover receives a go-ahead to pick up a sample, it does so under on-board control (see Ref. 8). It takes more pictures (stereo pairs) to document the sample (in the manipulator hand) or the hole left in the ground. If the sample is a rock, the rover, with its manipulator, places the rock on its viewing stage. The rover rotates the stage and takes pictures of the rock in several orientations and at several magnifications.

After the humans have received and examined the pictures of the rock on the stage, they decide which areas of the rock should be examined at higher resolution, with polarized light, etc., and send the appropriate commands. The rover completes the on-stage imaging, then crushes the rock, places some of the fragments under a microscope, and transmits micrographs. It transfers other portions of the crushed rock to analytical instruments, and starts their work. After humans have examined the first micrographs, they decide on additional ones and send commands for them. These pictures can be taken as analysis proceeds. For a soil sample, the procedure is generally similar.

When the rover completes manipulation and picture-taking with one sample it goes on to the next, at the same station or the next one. On-board analysis of the first sample may continue. When the scientific work at the site is done, the rover retrieves any deployed instruments and is ready to go to the next site. It may wait for on O.K. from earth to confirm that all data look good and nothing need be repeated. Biological culturing, which takes 10 days or more for each sample, will continue as the rover goes to and works at subsequent sites. Some other on-board analysis may also continue after the rover leaves the site. If the rover at any point runs into difficulties which it cannot handle alone, it will request help from earth, or humans may intervene on their own initiative. Control of the rover at the science site alternates between an automated mode with human monitoring, and a remote-control mode in which the rover waits for commands from earth.

Figure 5 shows the first 8.4 hr of a timeline totaling 14.4 hr at the science site. This timeline, however, does not consider engineering operations which will have to be interspersed with science. It does not allow any start-up time associated with initiating vehicle motion or resuming full science operations after motion. The timeline in Fig. 5 does not consider sunlight or time of day, but assumes continuous operation. Clearly, sunlight and time of day will be important in the operations. Weather on Mars may also have an influence. Success the first time for almost all operations, including those that involve interaction with the Martian surface, was also assumed. For all these reasons, the total time of 14.4 hr for a science site is certainly overambitious and unrealistically short; Fig. 5 and its continuation serve only as starting points for design of the operations.

Figure 6 gives a timeline for the geophysical survey of Fig. 4. Activities at the individual stations include deploying magnetometer and gravimeter, moving away from the magnetometer, taking pictures to check deployment, taking magnetometer and gravimeter readings, and retrieving the instruments, as well as taking pictures to check the suitability of the stations ahead.

Control of the rover in the geophysical survey example is highly automated, after an initial check of the route with a picture by humans. The local control loop on Mars will take care of all subsequent operations in the full survey of 15 stations, if no difficulties arise. Humans monitor robot operation continuously and can intervene on their own initiative whenever they wish. The profile is set up to provide opportunity for intervention, if necessary, with as little delay to operations on Mars as possible. The survey is shown as taking 13 hr, but the qualifications mentioned for the science site time apply here also.

Turning from these elements of the mission to the entire mission traverse, Table 4 gives a mission timeline based on nominal area and site locations and the unit times mentioned. The corresponding mission time breakdown is Table 5. For simplicity, both the communications transit time and the communications channel capacity were assumed constant throughout the mission (at 12 min one-way time and 32 kbits/sec of uncompressed video); in practice they would vary with the earth-Mars distance. The rover mileage for the mission is also given in Table 5.

## Mars - Operational Problems

Control. The alternation between local on-Mars control and remote control is characteristic of the science operations as a whole. Measures to reduce the delay in the remote loop and the number of times this loop is used are, accordingly, important in increasing the scientific return per day of operation. Man-machine relations in the control of science operations are discussed in Ref. 6, motion control in Ref. 9.

Communications. The science site operations are highly sensitive to communications channel capacity and delay. If the time to transmit a given quantity of data, or the time the data spend en route, is increased over the values assumed, the time required for site operations generally will increase to the same extent.

The profile for operations at a science site calls for eleven waits, in series, for decisions on earth. With a communications system that involved communications only once a day, operations at the site would take eleven days, as compared to the 14 hr called for by Fig. 5 and its continuation. This seems quite intolerable; continuous communications are required during operation. Two or three ground stations will be needed for communication.

Data Storage. The order in which the pictures are transmitted is considerably different from that in which they are taken (Fig. 5); pictures needed for immediate operational decisions have a higher transmission priority than pictures which are taken for scientific analysis only. As a result, the system must be capable of storing many pictures at Mars and of transmitting them in any order as governed by immediate operational needs.

Night Operations. The 8 hr of operation per day, indicated in Tables 4 & 5, arises not from operational convenience on the ground, but from the assumed need for sunlight, at suitable angles, to provide lighting for imaging during science operations and for vehicle guidance. This means that the rover spends two-thirds of its operational life waiting for the sun. Clearly, there is much incentive to develop techniques, using artificial lighting or other approaches, that would permit more active operation at night and during low sun. Some limited night science operation is contemplated in any case, but is not included in the profiles above. The problem of interruptions by dust storms or other Martian weather is not considered in this paper, nor that of interruptions by weather on earth (if a wavelength shorter than the current S-band is used to increase the communications bandwidth).

Mission Operations System. The profiles given allow some time for human decisions, but to stay within the times allocated will require efficient humans, competent in geology and biology and well-trained in mission operations. Fast ground communications and, especially, very rapid setting up, checking, and transmitting of command sequences also will be needed. Past experience in lunar and planetary operations indicates that achieving this performance will require a major effort.

## Lunar Profile and Operational Problems

The science elements of a lunar rover mission traverse are the same as those outlined above for Mars, and sketched in Fig. 1-4. Operation at science sites and on geophysical surveys will differ from the corresponding Mars operations in two major respects:

(1) The intervals of waiting for decisions on earth are greatly reduced, because of the short signal transit time and greater communications channel capacity. The time for the science site operations given in Fig. 5 and its continuation would accordingly be less than 4 hr instead of 14.4 hr, and for a geophysical survey (Fig. 6) to less than 10 hr, instead of 13.3 hr.

(2) The number of pictures taken can be considerably increased, because of the greater channel capacity and quicker decisions on what to take.

Mission time and mileage breakdowns are included in Table 5. Because of the longer overall track length (2000 km), the greater vehicle speed (1.5 km/hr assumed, along track), and much less time spent waiting for communications, the number and size of science areas can be increased; Table 5 assumes 16 science areas averaging 6 km radius. Even with a shorter mission traverse time (365 days instead of 687), the number of science sites and geophysical surveys can also be increased, investigation at the sites can be more detailed, and time will be available for more targets of opportunity (such as the "special sites" shown in Fig. 1).

Of the operational problems discussed for Mars, control of science operations will be considerably simpler. Almost all science control can be from earth, as for Surveyor and Lunokhod. (This is not necessarily true for motion control.) To permit such control, continuous communication with earth will again be needed for science operations. Science data storage will not be required: the communications channel of 0.5 - 2 Mbits/sec should permit science data to be transmitted as quickly as it is acquired. Night operations may be somewhat less important, since time will be less critical, but may still be worthwhile.

## CONCLUSIONS

A long-range remotely-controlled surface roving vehicle could collect critical data on a number of scientific questions concerning both Mars and the moon. Series of appropriate Science ~~payloads~~ are suggested in this paper; they range in weight from 35 to almost 300 kg and in average payload power from 36 to about 140 W. Examination of science function allocation and some possible profiles, for missions extending across 500-2000 km of planetary surface, suggests that control, of the payload and vehicle, and communications are likely to be key problem areas for Mars. On-board data storage will be necessary for Mars but not for the moon. Only a small fraction of the mission time is likely to be available for science activities; much will be spent in moving between science areas and sites and in waiting for the sun to reach a satisfactory angle for illumination.

## ACKNOWLEDGEMENTS

G. Hobby, R. Phillips, F. Fanale, E. Haines, and A. Metzger offered helpful suggestions on Mars science. R. B. Coryell, A. Eisenman, G. K. Hornbrook, C. McCormick, and R. A. Strelitz took part in the lunar studies, as did R. Sullivan of IITRI. This work was carried out at Jet Propulsion Laboratory under NASA Contract NAS 7-100.

## REFERENCES

1. Moore, J. W., "Lunar and Planetary Rover Concepts," in Remotely Manned Systems -- Exploration and Operation in Space, ed. E. Heer, California Institute of Technology, Pasadena, 1973, pp. 149-158.
2. Choate, R. and Jaffe, L. D., "Science Aspects of a Remotely Controlled Mars Surface Roving Vehicle," Internal Doc. 760-76, July 1972, Jet Propulsion Laboratory, Pasadena, Calif.
3. Nash, D. B., Conel, J. E., and Fanale, F. P., "Utility of Unmanned Lunar Roving Vehicles," The Moon, Vol. 3, 1971, pp. 221-230.
4. Jaffe, L. D., Choate, R., and Coryell, R. B., "Spacecraft Techniques for Lunar Research," The Moon, Vol. 5, 1972, pp. 348-367.

5. Jaffe, L. D., Choate, R., Coryell, R. B., Eisenman, A., Hornbrook, G. K., and Strelitz, R. A., "Payload Requirements for Remotely Controlled Long-Range Lunar Traverse Vehicles," Internal Doc. 760-62, Jan. 1971, Jet Propulsion Laboratory, Pasadena, Calif.

6. Choate, R., and Jaffe, L. D., "Science Aspects of a Remotely Controlled Mars Surface Roving Vehicle," in Remotely Manned [illegible]ems -- Exploration and Operation in Space, ed. E. Heer, California I[illegible]ute of Technology, Pasadena, 1973, pp 133-147.

7. Moore, J. W., Hornbrook, G. K., McDonald, W. S., Gilder, J. R., Dorroh, W. E., Swerdling, M., Bank, H., Imus, R. E., Gottlieb, T., Lim, L. Y., Kurtz, D. W., and Roberts, P. H., "An Exploratory Investigation of a 1979 Mars Roving Vehicle Mission," Internal Doc. 760-58, Dec. 1970, Jet Propulsion Laboratory, Pasadena, Calif.

8. Bejczy, A. K., "Remote Manipulator Systems, Technology Review and Planetary Operation Requirements," Internal Doc. 760-77, July 1972, Jet Propulsion Laboratory, Pasadena, Calif.

9. Anthony, V. F., "Motion Control Requirements for Planetary Surface Roving Vehicles," Internal Doc. 760-78, July 1972, Jet Propulsion Laboratory, Pasadena, Calif.

TABLE 1. SELECTED MEASURABLES FOR MARS MISSION

| | PRIMARY | SUPPORTING |
|---|---|---|
| Geology and Geochemistry | Geomorphic features<br>Rock units<br>Structural elements<br>Elemental composition<br>Mineralogic composition<br>Rock texture<br>Volatiles<br>Isotopic composition<br>Time of chemical differentiation<br>Physical and chemical properties of rocks and soils | Optical properties<br>a) Color<br>b) Optical polarization<br>c) Index of refraction |
| Geophysics | Seismicity<br>Magnetic field<br>Remanent magnetism<br>Heat flow<br>Body motions | Seismic wave propagation<br>Gravity field<br>Magnetic field anomalies<br>Electrical properties |
| Meteorology and Atmosphere | Barometric pressure<br>Temperature, atmospheric<br>Wind<br>Atmospheric composition<br>Clouds<br>Suspended solids in the atmosphere; erosional transport, realtime | Sunlight at the surface |
| Biology | Organic matter<br>Fossil matter<br>Life | Life characteristics<br>a) Carbon assimilation<br>b) Gas release<br>c) Growth and multiplication<br>d) Shape and form |

FOLDOUT FRAME

Table 2. Mars Rover Pa[illegible]ds & Instru

(Values not otherwise speci[illegible] are weight

| Payload Type | Geological | | Biological | | Balanced | | | |
|---|---|---|---|---|---|---|---|---|
| Payload Identification | A1 | A2 | B1 | B2 | C | D | E | F |
| TV[a]: 1 camera | 8[b] | 15[c] | 8[b] | 15[c] | -- | -- | -- | -- |
| TV[a]: 2 cameras[c] | -- | -- | -- | -- | 30 | 30 | 30 | 30 |
| Facsimile[a]: 2 cameras | -- | -- | -- | -- | -- | 6 | 6 | 6 |
| Laser range finder[a] | -- | -- | -- | -- | -- | 8 | 8 | 8 |
| Microscope and slide preparer | -- | -- | -- | -- | -- | 3 | 3 | 4 |
| TV camera for microscope | -- | -- | -- | -- | -- | -- | -- | 3 |
| General purpose manipulator(s), with tools | 6 | 6 | 6 | 6 | 6 | 6 | 12 | 24 |
| Soil probe/tube driver | -- | -- | -- | -- | -- | -- | 3 | 5 |
| Soil core tubes | -- | -- | -- | -- | -- | -- | -- | 2 |
| Soil auger | -- | -- | -- | -- | -- | -- | -- | 4 |
| Soil casing tubes | -- | -- | -- | -- | -- | -- | -- | 0.2 |
| Soil-gas probe | -- | -- | -- | -- | -- | -- | 2 | 2 |
| Crusher | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Siever and screens | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Viewing stage, with illuminating mirror | -- | -- | -- | -- | -- | 3 | 3 | 3 |
| Sample buffer storage system | -- | -- | -- | -- | -- | 3 | 5 | 10 |
| X-ray diffractometer/ spectrometer | 7 | 7 | -- | -- | 7 | 7 | 7 | 7 |
| Pulsed neutron/gamma spectrometer | -- | -- | -- | - | -- | -- | -- | 6 |
| Alpha/proton spectrometer | -- | -- | -- | -- | -- | -- | -- | 3 |
| Electromagnet | -- | -- | -- | -- | -- | 0.2 | 0.2 | 0.2 |
| Ion microprobe | -- | -- | -- | -- | -- | -- | -- | 15 |

Payl
Paylo
Grav
Magn
Seisr
Geop
Thur
Expl sour
Elec soun
Rem dete
Soil inst
Bar
Ane win indi
Atm sen
Hy
Atr nep
Ult
Ra
En St
Sa
M

...ads & Instrument Weights

...d are weights in kilograms)

FOLDOUT FRAME 2

| Payload Type | Geological | | Biological | | Balanced | | | |
|---|---|---|---|---|---|---|---|---|
| Payload Identification | A1 | A2 | B1 | B2 | C | D | E | F |
| Gravimeter | 7 | 7 | -- | -- | 7 | 7 | 7 | 7 |
| Magnetometer | 3 | 3 | -- | -- | 3 | 3 | 3 | 3 |
| Seismometer | -- | -- | -- | -- | -- | -- | 4 | -- |
| Geophones | -- | -- | -- | -- | -- | -- | -- | 2 |
| Thumper | -- | -- | -- | -- | -- | -- | 4 | 4 |
| Explosive seismic sources | -- | -- | -- | -- | -- | -- | -- | 4 |
| Electromagnetic sounder | -- | -- | -- | -- | -- | -- | -- | 7 |
| Remanent magnetism detector | -- | -- | -- | -- | -- | -- | -- | 2 |
| Soil mechanics instrument | -- | -- | -- | -- | -- | -- | 2 | 2 |
| Barometer | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Anemometer(s) and wind direction indicator(s) | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.8 |
| Atmosphere thermal sensor(s) | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.6 |
| Hygrometer | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Atmosphere nephelometer | -- | -- | -- | -- | -- | -- | 2 | 2 |
| Ultraviolet photometer | -- | -- | -- | -- | 0.2 | 0.2 | 0.2 | 0.2 |
| Radio transponder [d] | X | X | X | X | X | X | X | X |
| SUBTOTAL WEIGHT, excluding emplaceable stations | 35 | 42 | 38 | 45 | 93 | 116 | 157 | 235 |
| Emplaceable Science Stations Quantity: | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 |
| Seismometer | -- | -- | -- | -- | -- | 11 | 11 | 11 |
| Magnetometer | -- | -- | -- | -- | -- | 3 | 3 | 3 |

FOLDOUT FRAME 3

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pulsed neutron/gamma spectrometer | -- | -- | -- | -- | -- | -- | -- | 6 |
| Alpha/proton spectrometer | -- | -- | -- | -- | -- | -- | -- | 3 |
| Electromagnet | -- | -- | -- | -- | -- | 0.2 | 0.2 | 0.2 |
| Ion microprobe | -- | -- | -- | -- | -- | -- | -- | 15 |
| Scanning electron microscope/microprobe | -- | -- | -- | -- | -- | -- | -- | 15 |
| Gas chromatograph/ mass spectrometer/ differential thermal analyzer | -- | -- | 10 | 10 | 20 | 20 | 20 | 20 |
| Water detector | -- | -- | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Pyrolysis/gas reaction chamber | -- | -- | -- | -- | 1 | 1 | 1 | 1 |
| Furnace for fusing samples | -- | -- | -- | -- | -- | -- | -- | 1 |
| Gas handling equipment | -- | -- | 1 | 1 | 3 | 3 | 3 | 3 |
| Deployed soil-gas exchange chamber | -- | -- | -- | -- | 2 | 2 | 2 | 2 |
| Wet chemical analytical equipment | -- | -- | -- | -- | -- | -- | 5 | 5 |
| Balance(s) | -- | -- | -- | -- | -- | -- | 2 | 2 |
| Column chromatograph | -- | -- | -- | -- | -- | -- | 1 | 1 |
| Labelled-compound radiation detector | -- | -- | 2 | 2 | 2 | 2 | 2 | 2 |
| Optical rotation/ polarimeter | -- | -- | -- | -- | -- | -- | -- | 3 |
| Soil temperature/pH probe | -- | -- | -- | -- | -- | -- | 2 | 2 |
| Culture chambers | -- | -- | 2 | 2 | 2 | 2 | 2 | 5 |
| Culture-medium dispenser | -- | -- | 2 | 2 | 3 | 3 | 3 | 3 |
| Liquid suspension nephelometer | -- | -- | 2 | 2 | 2 | 2 | 2 | 2 |

(continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| SUBTOTAL WEIGHT, excluding emplaceable stations | 35 | 42 | 38 | 45 | 93 | 116 | 157 | 235 |
| Emplaceable Science Stations Quantity: | 0 | 0 | 0 | 0 | 0 | 1 | 1 | [illegible] |
| Seismometer | -- | -- | -- | -- | -- | 11 | 11 | 11 |
| Magnetometer | -- | -- | -- | -- | -- | 3 | 3 | 3 |
| Heat flow/thermal conductivity probe | -- | -- | -- | -- | -- | -- | 3 | 3 |
| Barometer | -- | -- | -- | -- | -- | 0.4 | 0.4 | 0.4 |
| Anemometer(s) and wind direction indicator(s) | -- | -- | -- | -- | -- | 0.4 | 0.4 | 0.8 |
| Atmospheric thermal sensor(s) | -- | -- | -- | -- | -- | 0.3 | 0.3 | 0.6 |
| Hygrometer | -- | -- | -- | -- | -- | 0.8 | 0.3 | 0.3 |
| Atmospheric nephelometer | -- | -- | -- | -- | -- | 2 | 2 | 2 |
| Ultraviolet photometer | -- | -- | -- | -- | -- | 0.2 | 0.2 | 0.2 |
| Radio transponder | -- | -- | -- | -- | -- | X | X | X |
| SUBTOTAL, WEIGHT of science instruments per emplaceable station | -- | -- | -- | -- | -- | 18 | 21 | 21 |
| TOTAL PAYLOAD WEIGHT, including instruments in emplaceable stations | 35 | 42 | 38 | 45 | 93 | 134 | 178 | 298 |
| Average payload power, watts, during science operations, excluding emplaceable stations | 36 | 46 | 46 | 56 | 92 | 118 | 132 | 139 |
| Average payload power, watts, during vehicle motion | 8 | 8 | 26 | 26 | 37 | 40 | 50 | 61 |

a. Cameras and range finder shared with guidance and navigation
b. Solid state camera
c. Vidicon camera
d. Transponder weight charged to communications and navigation

FOLDOUT FRAME

Table 3.

Lunar Rover Payloads and Instrument Weights

(Values not otherwise specified are weights in kilograms)

| Payload Type | No Sample Return | | | | | | Sample Return | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Geophysical | | Geological/ Geochemical | | Balanced | | Geological/ Geochemical | | Balanced | |
| Payload Identification | 1S | 1L | 2S | 2L | 3S | 3L | 4S | 4L | 5S | 5L |
| TV for terrain examination | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| Mirror, for stereoscopic viewing | - | - | - | 2 | - | 2 | - | 2 | - | 2 |
| Facsimile camera | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Laser range finder | - | 8 | - | 8 | - | 8 | - | 8 | - | 8 |
| TV camera for rock specimen examination | - | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Microscope and slide preparer | - | - | - | 3 | - | 3 | - | 3 | - | 3 |
| General purpose manipulator, with tools | - | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 12 |
| Soil tube driver | - | - | - | 3 | - | - | - | 3 | - | 3 |
| Soil core tubes | - | - | - | 1 | - | - | - | 3 | - | 3 |
| Soil auger | - | 4 | - | 4 | - | 4 | - | 4 | - | - |
| Crusher | - | - | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Siever and screens | - | - | - | 1 | - | 1 | - | - | - | - |
| Viewing stage, with illuminating mirror | - | - | 3 | 3 | - | 3 | 3 | 3 | - | 3 |
| Sample buffer storage system | - | - | 3 | 5 | 3 | 5 | 3 | 5 | 3 | 5 |
| Returnable "permanent" sample storage | - | - | - | - | - | - | 1 | 2 | 1 | 2 |
| X-ray diffractometer | - | - | - | } 7 | - | } 7 | - | - | - | - |
| X-ray emission spectrometer | - | - | 3 | } | 3 | } | 3 | 3 | 3 | 3 |
| Pulsed neutron/gamma spectrometer | - | - | - | 6 | - | 6 | - | - | - | - |

FOLDOUT FRAME

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| system | | | - | - | - | - | - | - | - | - |
| Returnable "permanent" sample storage | - | - | - | - | - | - | 1 | 2 | 1 | 2 |
| X-ray diffractometer | - | - | - | 7 | - | 7 | - | - | - | - |
| X-ray emission spectrometer | - | - | 3 | | 3 | | 3 | 3 | 3 | 3 |
| Pulsed neutron/gamma spectrometer | - | - | - | 6 | - | 6 | - | - | - | - |
| Mass spectrometer | - | - | - | 7 | - | 7 | - | - | - | 4 |
| Gravimeter | 7 | 7 | - | - | 7 | 7 | - | - | 7 | 7 |
| Magnetometer | 3 | 3 | - | - | 3 | 3 | - | - | 3 | 3 |
| Geophones | - | 2 | - | - | - | 2 | - | - | - | 2 |
| Thumper | - | 4 | - | - | - | 4 | - | - | - | 4 |
| Electromagnetic sounder | 7 | 7 | - | - | - | 7 | - | - | - | 7 |
| Remanent magnetism detector | - | 2 | - | - | - | 2 | - | - | - | - |
| SUBTOTAL WEIGHT, excluding emplaceable stations | 35 | 64 | 38 | 79 | 45 | 100 | 39 | 65 | 46 | 94 |
| Emplaceable Science Stations Quantity: | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Heat flow/thermal conductivity probe | - | 3 | - | - | - | 3 | - | - | - | - |
| TOTAL PAYLOAD WEIGHT, including instruments in emplaceable stations | 35 | 70 | 38 | 79 | 45 | 103 | 39 | 65 | 46 | 94 |
| Average payload power, watts, during science operations, excluding emplaceable stations | 38 | 95 | 48 | 95 | 52 | 95 | 48 | 95 | 52 | 76 |
| Average payload power, watts, during vehicle motion | 2 | 5 | 8 | 25 | 8 | 27 | 8 | 8 | 8 | 17 |

Table 4. Mars Mission Time-line

Rover operating 8 hr/day

1 Mars year = 687 earth days = 669 Mars days

| Mars Days | Activity |
|---|---|
| 1-15 | Checkout rover; emplace science package |
| 16-17 | Area 1, site 1 |
| 18 | Area 1, site 1; go to area 1, site 2 |
| 19 | Moving to area 1, site 2 |
| 20 | Go to and at area 1, site 2 |
| 21-22 | Area 1, site 2 |
| 23-24 | Go to area 1, site 3 |
| 25-26 | Area 1, site 3 |
| 27 | Area 1, site 3; to to area 1, site 4 |
| 28 | Moving to area 1, site 4 |
| 29 | Go to and at area 1, site 4 |
| 30-31 | Area 1, site 4 |
| 32-33 | Go to area 1, site 5 |
| 34-35 | Area 1, site 5 |
| 36 | Area 1, site 5; go to area 1, site 6 |
| 37 | Moving to area 1, site 6 |
| 38 | Go to and at area 1, site 6 |
| 39-40 | Area 1, site 6 |
| 41-42 | Go to area 1 survey location |
| 43 | Area 1 geophysical survey |
| 44 | Area 1 geophysical survey; go to area 2 |
| 45-60 | Moving to area 2 |
| 61 | Special science site |
| 62-77 | Moving to area 2 |
| 78 | Moving to area 2; at area 2, site 1 |
| 79-80 | Area 2, site 1 |
| 81 | Go to area 2, site 2 |
| . | . |
| . | . |
| . | . |
| 668 | Area 11 geophysical survey |
| 669 | Area 11 geophysical survey |

FOLDOUT FRAME

/

Table 5. Mission Time and Mileage Br

| | Mars Mission | | | |
|---|---|---|---|---|
| Activity | Quantity | Percent of mission time[a] | Map distance km | Track distance km[b] |
| Science sites | 76 @ 19 hr & 0.25 km | 9 | 19 | 29 |
| Geophysical surveys | 11 @ 12 hr & 1 km | 1 | 11 | 16 |
| Within science area, moving between sites | 11 @ 108 hr & 18 km | 7 | 200 | 300 |
| Moves between science areas | 10 @ 264 hr & 44 km | 16 | 440 | 655 |
| Postlanding checkout | 1 @ 200 hr | 1 | - | - |
| Waiting; night and sun too low[c] | 668 @ 14 hr | 56 | - | - |
| Waiting; sun too high[c] | 669 @ 2.5 hr | 10 | - | - |
| TOTAL (scalar) | | 100 | (670)[d] | 1000 |
| TOTAL (vector) | | | 500 | |

a. Total mission time: Mars, 687 earth days (1 Mars year); moon, 365 days.
b. Track distance for individual items taken as 1.5 x map distance. Track speed: Ma
c. Assumes sun must be at least 10° above horizon for active operation, and not with
13 lunar days/year.
d. The total map distance is the vector sum of the individual map distances and is t

FOLDOUT FRAME 2

ion Time and Mileage Breakdown

| | | Lunar Mission | | | |
| --- | --- | --- | --- | --- | --- |
| Map distance km | Track distance km[b] | ~~Quality~~ Quantity | Percent of mission time[a] | Map distance km | Track distance km[b] |
| 19 | 29 | 240 @ 6 hr & 0.25 km | 16 | 60 | 90 |
| 11 | 16 | 30 @ 9 hr & 1 km | 3 | 30 | 45 |
| 200 | 300 | 16 @ 26 hr & 26 km | 5 | 415 | 625 |
| 440 | 655 | 15 @ 55 hr & 55 km | 9 | 825 | 1240 |
| - | - | 1 @ 50 hr | 1 | - | - |
| - | - | 12 @ 390 hr | 54 | - | - |
| - | - | 13 @ 80 hr | 12 | - | - |
| (670)[d] | 1000 | | 100 | (1330)[d] | 2000 |
| 500 | | | | 1000 | |

n, 365 days.
nce. Track speed: Mars, 0.25 km/hr, moon 1.5 km/hr.
eration, and not within 20° of local noon. 669 Mars days/Mars year;

ap distances and is taken as 0.75 of the scalar sum.

# Figure Captions

1. Schematic of mission traverse
2. Schematic of science area
3. Schematic of science site
4. Schematic of geophysical survey

5. Portion of time-line for science site (Fig. 3)

   Abbreviations: Fax = facsimile (picture )

   Pan = panorama

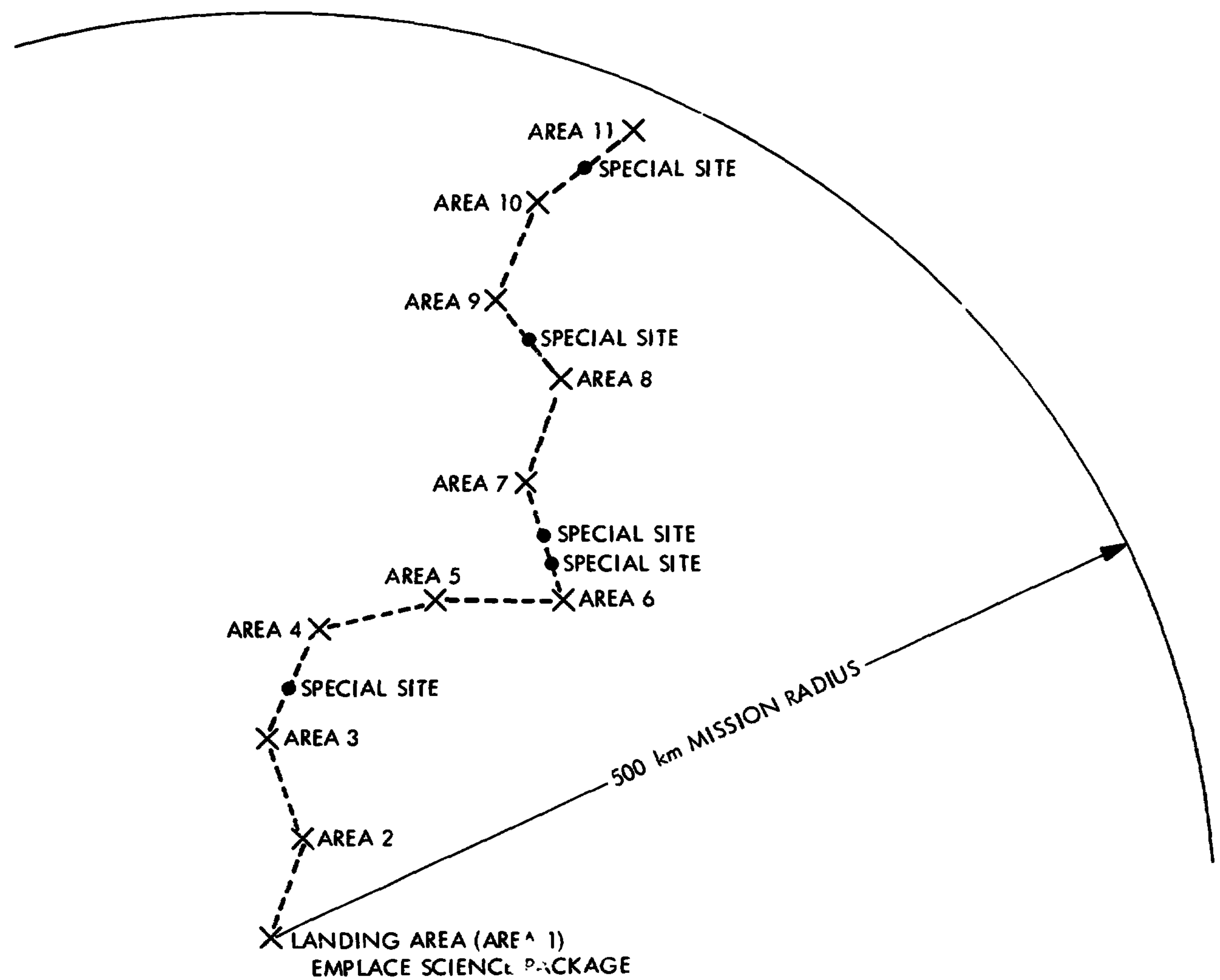
   WA = wide angle TV picture

   NA = narrow angle TV picture

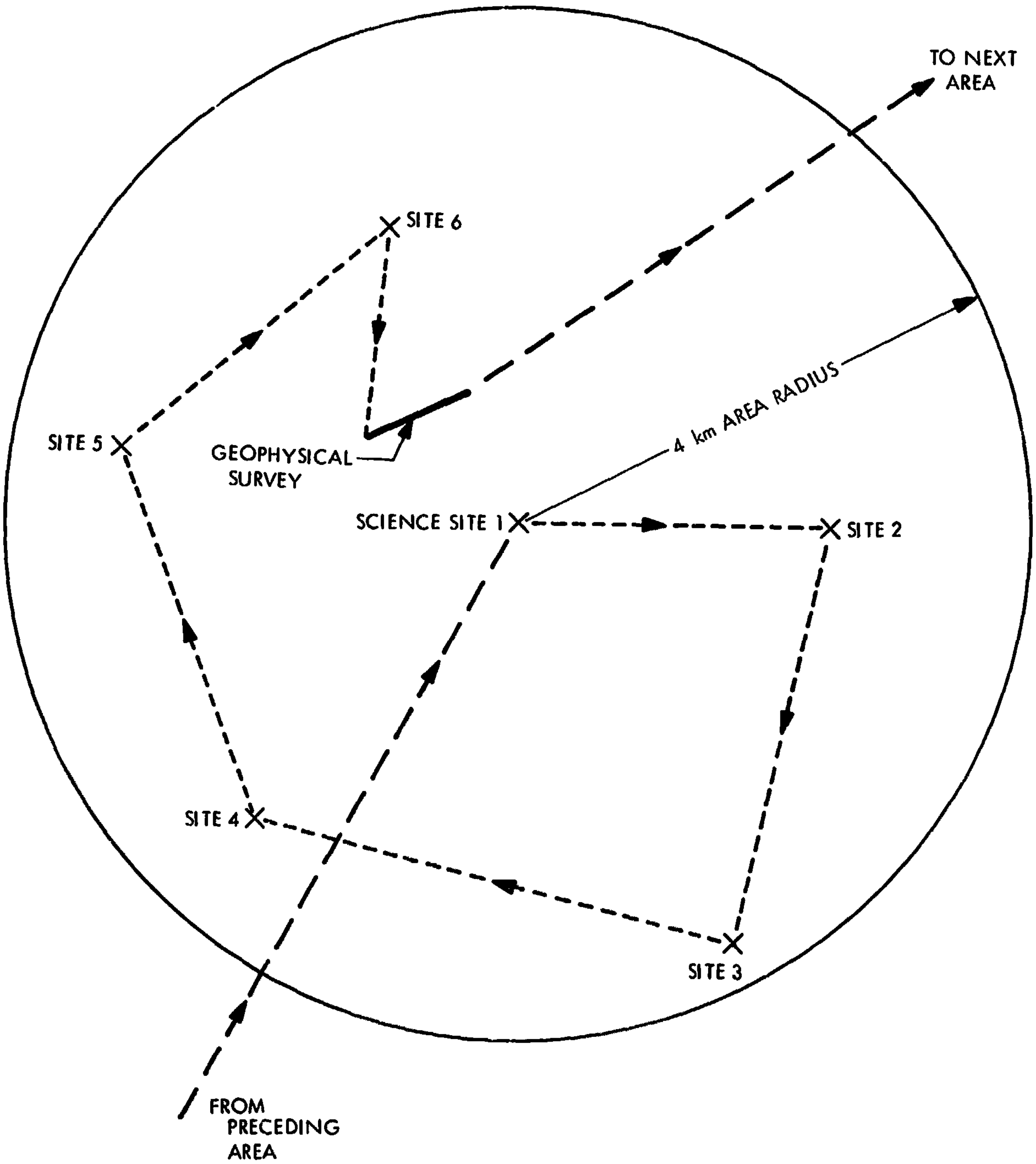
6. Time-line for a geophysical survey (Fig. 4)

   Abbreviations: WA = wide angle TV picture

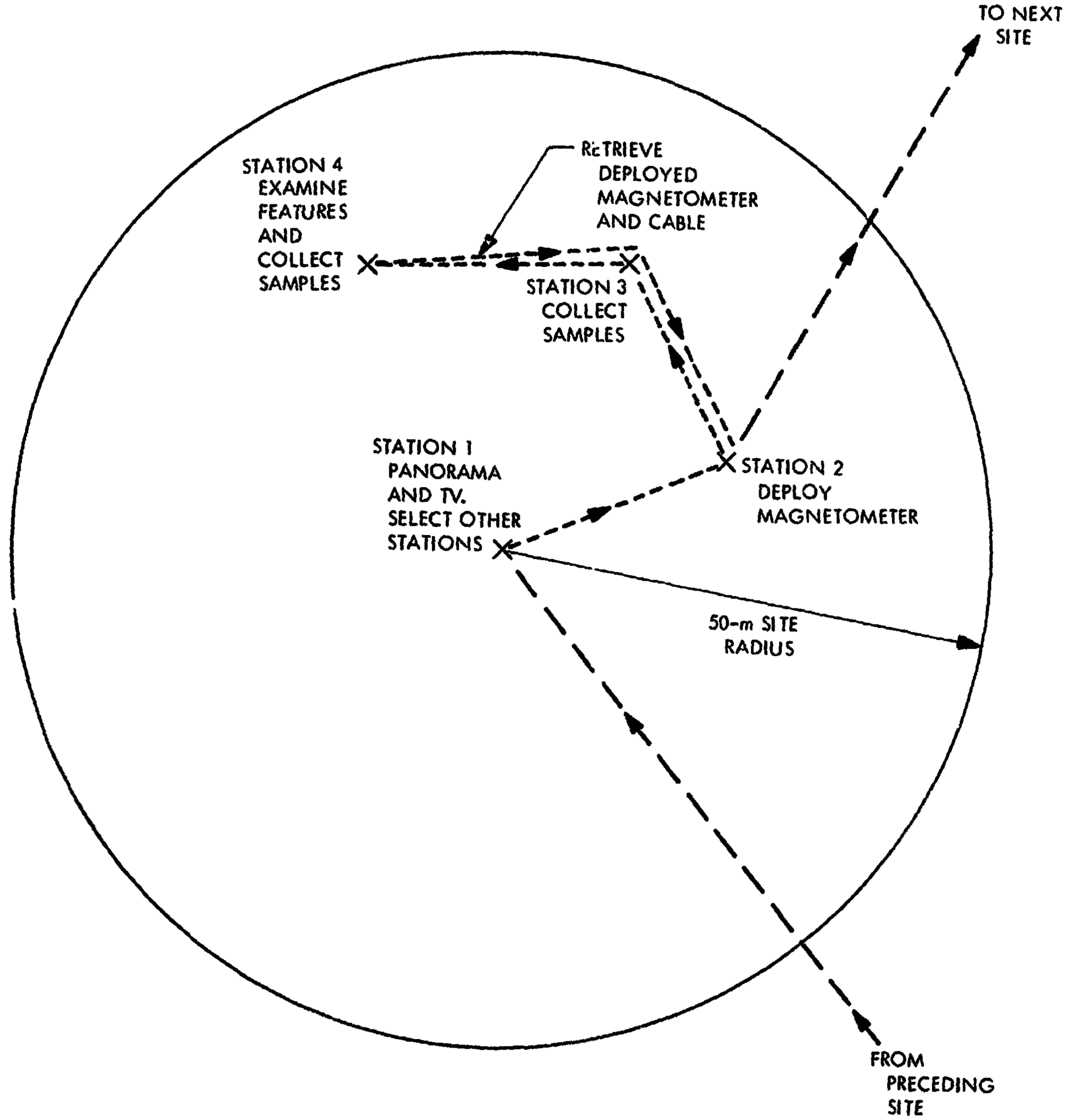
   Culturing = biological culturing of samples previously acquired


AREA 11
SPECIAL SITE
AREA 10
AREA 9
SPECIAL SITE
AREA 8
AREA 7
SPECIAL SITE
SPECIAL SITE
AREA 5
AREA 6
AREA 4
SPECIAL SITE
AREA 3
500 km MISSION RADIUS
AREA 2
LANDING AREA (AREA 1)
EMPLACE SCIENCE PACKAGE

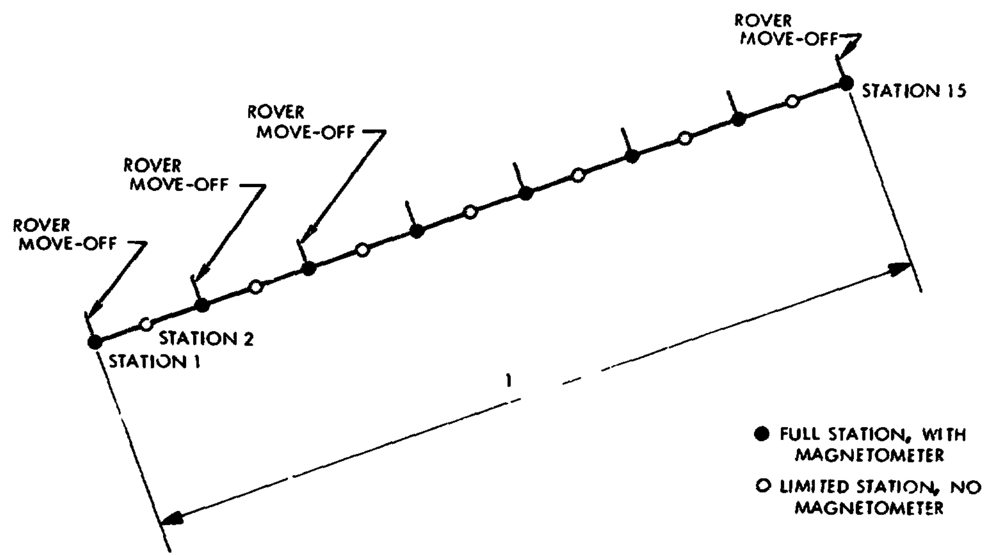
JAFFE
Fig 1


TO NEXT AREA
SITE 6
SITE 5
GEOPHYSICAL SURVEY
4 km AREA RADIUS
SCIENCE SITE 1
SITE 2
SITE 4
SITE 3
FROM PRECEDING AREA

Jaffe
Fig 2


TO NEXT SITE
RETRIEVE DEPLOYED MAGNETOMETER AND CABLE
STATION 4 EXAMINE FEATURES AND COLLECT SAMPLES
STATION 3 COLLECT SAMPLES
STATION 1 PANORAMA AND TV. SELECT OTHER STATIONS
STATION 2 DEPLOY MAGNETOMETER
50-m SITE RADIUS
FROM PRECEDING SITE

JAFFE
Fig 3



ROVER MOVE-OFF
ROVER MOVE-OFF
ROVER MOVE-OFF
ROVER MOVE-OFF
STATION 1
STATION 2
STATION 15
l
● FULL STATION, WITH MAGNETOMETER
O LIMITED STATION, NO MAGNETOMETER


Jaffe Fig 4

| Station | Time Hours | Rover TV, Control, and Manipulators | Other Mars Activity | On-board Science Data Store in Hours: Data Put In | On-board Science Data Store in Hours: Balance in Store | Facing Transmission or Earth Activity: Sending | Down Delay | Earth Activity | Up Delay |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | Fax pan of terrain | | .4 | .5 | | | | |
| | .2 | [illegible] sectors | | .2 | .4 | | | | |
| | | | Meteorology | | .3 | | | | |
| | .4 | | | | .2 | | | | |
| | .5 | | | | .1 | | | | |
| | .6 | | | | | | | | |
| | .7 | | | | | | | Choose initial WA and fax of features | |
| | .8 | | | | | | | | |
| | .9 | | | | | | | | |
| | 1.0 | | | | | | | | |
| | 1.1 | | | | | | | | |
| | 1.2 | | | | | | | Choose more WA of features | |
| | 1.3 | | | | | | | | |
| | 1.4 | 6 WA of features | | .3 | .2 | | | | |
| | 1.5 | 4 fax sectors | | .2 | .3 | | | | |
| | 1.6 | | | | .2 | | | | |
| | 1.7 | | | | .1 | | | | |
| | 1.8 | | | | | | | | |
| | 1.9 | 6 WA of features | | .3 | .2 | | | Choose initial NA of features | |
| | 2.0 | | | | .1 | | | | |
| | 2.1 | | | | | | | | |
| | 2.2 | | | | | | | | |
| | 2.3 | | | | | | | | |
| | 2.4 | | | | | | | Choose stations and more NA of features | |
| | 2.5 | | | | | | | | |
| | 2.6 | 6 NA of features | | .6 | .5 | | | | |
| | 2.7 | | | | .4 | | | | |
| | 2.8 | | | | .3 | | | | |
| | 2.9 | | | | .2 | | | | |
| | 3.0 | | | | .1 | | | | |
| | 3.1 | 12 NA of features | | 1.2 | 1.2 | | | | |
| — | 3.2 | Go to station 2 (move 50 m) | | | 1.2 | | | | |
| | 3.3 | ↓ | | | 1.2 | | | | |
| 2 | 3.4 | Deploy magnetometer | | | 1.1 | | | | |
| | 3.5 | WA to check deploy | | .1 | 1.1 | | | | |
| — | 3.6 | Go to station 3 (move [illegible] m) | | | [illegible] | | | | |
| | .7 | ↓ | | | 1.1 | | | | |
| 3 | 3.8 | Fax sector to observe samples | Magnetometry and Meteorology | .1 | 1.1 | | | | |
| | 3.9 | | | | 1.0 | | | | |
| | 4.0 | | | | .9 | | | | |
| | 4.1 | | | | .8 | | | Choose samples | |
| | 4.2 | | | | .7 | | | | |
| | 4.3 | | | | .6 | | | | |
| | 4.4 | | | | .5 | | | | |
| | 4.5 | | | | .4 | | | | |

(Continued)

Jaffe
Fig 5 (a)

| At Station | Time Hours | Rover TV Motion and Manoeuvre | Other Mars Activity | On-board Science Data Store in Hours: Data Put in | On-board Science Data Store in Hours: Balance in Store | Pacing Transmission or Earth Activity: Sending | Pacing Transmission or Earth Activity: Down Delay | Pacing Transmission or Earth Activity: Earth Activity | Pacing Transmission or Earth Activity: Up Delay |
|---|---|---|---|---|---|---|---|---|---|
| [illegible] | 4.6 | Local move (2 m) | | | .4 | | | | |
| | 4.7 | WA to confirm sample choice | Magnetometry and Meteorology | .1 | .4 | | | | |
| | 4.8 | NA to confirm sample choice | | .1 | .4 | | | | |
| | 4.9 | Deploy soil gas exchange chamber | | | .5 | | | | |
| | 5.0 | Deploy gravimeter | | | .2 | | | | |
| | 5.1 | WA to check deploy of chamber | Gravimetry | .1 | .2 | | | Confirm sample | |
| | 5.2 | NA to document sample | | .1 | .2 | | | | |
| | 5.3 | Pick up gravimeter | | | .1 | | | | |
| | 5.4 | Pick up rock sample | | | | | | | |
| | 5.5 | 2 NA of sample in manipulator | | .2 | .1 | | | | |
| | 5.6 | 8 NA of rock on stage | | .8 | .8 | | | | |
| | 5.7 | Deploy x-ray spectroscope | | | .7 | | | | |
| | 5.8 | | X-ray spectroscopy | | .6 | | | | |
| | 5.9 | | | | .5 | | | | |
| | 6.0 | | | | .4 | | | | |
| | 6.1 | | | | .3 | | | | |
| | 6.2 | Pick up x-ray spectroscope | | | .2 | | | | |
| | 6.3 | NA to confirm soil sample | | .1 | .2 | | | | |
| | 6.4 | NA to document soil sample | | .1 | .2 | | | | |
| | 6.5 | | | | .1 | | | | |
| | 6.6 | | | | | | | | |
| | 6.7 | 2 NA of electromagnet | | .2 | .1 | | | Choose more stage pictures | |
| | 6.8 | | | | | | | | |
| | 6.9 | | | | | | | | |
| | 7.0 | | | | | | | Confirm soil sample | |
| | 7.1 | | | | | | | | |
| | 7.2 | 4 NA of rock on stage | | .4 | .3 | | | | |
| | 7.3 | Crush and sieve | | | .2 | | | | |
| | 7.4 | 4 NA of crushed rock through microscope | | .4 | .5 | | | | |
| | 7.5 | | Analysis of rock | | .4 | | | | |
| | 7.6 | | | | .3 | | | | |
| | 7.7 | Pick up soil sample | | | .2 | | | | |
| | 7.8 | 2 NA of hole left in ground | | .2 | .3 | | | | |
| | 7.9 | 3 NA of soil on stage | | .3 | .5 | | | | |
| | 8.0 | | Culturing of soil sample | | .4 | | | Choose more micro pictures | |
| | 8.1 | | | | .3 | | | | |
| | 8.2 | | | | .2 | | | | |
| | 8.3 | Take gas from soil gas chamber | | | .1 | | | | |
| | 8.4 | Pick up soil gas chamber | | | | | | | |

(Continued)

Jaffe
Fig 5(a)

| At Station | Time, hours | Mars TV, Motion, and Manipulation | Other Mars Activities | On-Board Science Data Store in Hours: Data Put in | On-Board Science Data Store in Hours: Balance in Store | Pacing Transmission or Earth Activity: Sending | Pacing Transmission or Earth Activity: Down Delay | Pacing Transmission or Earth Activity: Earth Activity | Pacing Transmission or Earth Activity: Up Delay |
|---|---|---|---|---|---|---|---|---|---|
| 1 | .1 | WA of stations 1 and 2 | Culturing | .1 | | | | | |
| | .2 | | | | | | | | |
| | .3 | | | | | | | | |
| | .4 | | | | | | | OK stations | |
| | .5 | | | | | | | | |
| | .6 | | | | | | | | |
| | .7 | Deploy magnetometer | | | | | | | |
| | .8 | Move away | | | | | | | |
| | .9 | WA of magnetometer | Magnetometry | .1 | | | | | |
| | 1.0 | Go back to magnetometer | | | | | | | |
| | 1.1 | Pick up magnetometer | | | | | | | |
| | 1.2 | Deploy gravimeter | | | | | | | |
| | 1.3 | | Gravimetry | | | | | | |
| | 1.4 | Pick up gravimeter | | | | | | | |
| | 1.5 | Go to station 2 | | | | | | | |
| | 1.6 | | | | | | | | |
| 2 | 1.7 | WA of station 3 | | .1 | | | | | |
| | 1.8 | Deploy gravimeter | | | | | | | |
| | 1.9 | | Gravimetry | | | | | | |
| | 2.0 | Pick up gravimeter | | | | | | | |
| | 2.1 | Go to station 3 | | | | | | | |
| | 2.2 | | | | | | | | |
| 3 | 2.3 | WA of station 4 | | .1 | | | | | |
| | 2.4 | Deploy magnetometer | | | | | | | |
| | 2.5 | Move away | | | | | | | |
| | 2.6 | WA of magnetometer | Magnetometry | .1 | | | | | |
| | 2.7 | Go back to magnetometer | | | | | | | |
| | 2.8 | Pick up magnetometer | | | | | | | |
| | 2.9 | Deploy gravimeter | | | | | | | |
| | 3.0 | | Gravimetry | | | | | | |
| | 3.1 | Pick up gravimeter | | | | | | | |
| 4-15 | 3.2-13.3 | Repeat items at hours 1.5-3.1, 6 times, at successive stations | | | | | | | |

Jaffe
Fig 6