MARTIAN AND LUNAR SCIENCE WITH REMOTELY-CONTROLLED LONG-RANGE SURFACE VEHICLES[1]

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Summary Science objectives are outlined for long surface traverse missions on Mars and the moon, with remotely-controlled roving vehicles. Series of candidate rover science payloads are proposed, varying in purpose, development needed, cost, and weight (35 to almost 300 kg). 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. 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 discusses science aspects of a remotely-controlled roving vehicle for a long traverse mission across a planetary surface. Primary attention is given to a Mars mission, but a lunar mission is also considered. Lunokhods 1 and 2 are remotely-controlled lunar roving vehicles. However, they performed local exploration in the vicinity of their landing sites, rather than long traverses covering many areas (ref 1 and 2). Previous studies of Mars and lunar roving vehicles have been recently reviewed (ref 3).

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,

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whether or not earlier lander missions find evidence of life, an important reason for sending of 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 s 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.” The orbiter and entry payloads are not discussed here (see ref 4).

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

The overall goals of a long traverse mission on Mars are considered to be determination of: distribution of surface composition; internal structure and thermal regime of the planet; nature of the major surface features and of the processes that formed them; atmospheric regime; environmental conditions pertinent to the development of life; past or present existence of life; and, if life is found, the nature of that life. On the Moon, determination of surface composition and surface features would be of primary interest, with some attention to internal structure and thermal regime (ref 5).

Among the geological and geophysical properties to be directly measured or observed are: geomorphic features, rock units, structural elements an rock texture; mineralogic and elemental composition and volatiles; chemical, physical, optical, and mechanical properties of soils and rocks; magnetic field and gravity. On Mars, planetary rotation and seismicity are appropriate observables. Meteorological properties include atmospheric composition, pressure, temperature, wind, suspended solids, and sunlight at the surface. Biological characteristics at Mars include both organic matter and life. Preferably, the rover should also provide measurements and observations of isotopic composition, time of chemical differentiation, and fossils, but this may be beyond the state of the art.

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 ref 4 and 6; associated science tasks, requirements, functions, and candidate instruments in ref 4 and 7.

SCIENCE PAYLOADS

No attempt is made in this report to pick a science 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 in Table 1) are “balanced” in that they provide measurements in 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. The reasons for choosing these payloads and characteristics of the individual instruments are given in ref 4. The science payload weights range from 35 kg to almost 300 including instruments in emplaced science stations. The power estimates (Table 1) include diversity factors (ref 4); the average science 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 x 10^6 bits; a narrow-angle TV picture, 1 x 10^7 bits; a facsimile panorama, 3.9 x 10^7 bits. A TV data rate of 128 kb/s was assumed, based on a very preliminary look at the frame time required. The assumed transmission channel has a capacity of 32 kb/s of science imaging data (either 32 kb/s of raw data or 16 kb/s 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 x 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 2, 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), and 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 and 5) are considered more desirable than the specialized (1, 2, 4) but would be heavier and more costly. For each type, a small payload (S) and a large one (L) are given. Reasons for choosing these payloads are given in ref 7.

Instrument weights for the lunar science payloads range from 35 to 103 kg (Table 2) . Estimated average science payload power during science operations ranges from 38 to 95 W; 2 to 27 W are needed for analysis and sounding during vehicle motion. The transmission channel to earth is tentatively constrained to 0.5 Mb/s on the basis of limitations in digital ground data-handling equipment; a 2 Mb/s channel seems operationally desirable and could probably be provided without much difficulty. These rates would match the science (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 summarized here and discussed in more detail, for a Mars mission, in ref 8.

Mars. For Mars, a high degree of internal control should be possible on the rover. To the time for a signal to go between Mars and earth (6 to 44 min round trip) 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 9). 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 2.5 s; 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 2.5 s 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 perhaps 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 (see ref 4). 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 orber 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 lunar 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). 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. 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. 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. 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.

The mission traverse, science areas and sites, and a geophysical survey are sketched in ref 4, 8, 10.

Activities at a science site are illustrated by Table 4, part of the timeline for such a site. Assumptions made in deriving this timeline include

Vehicle speed:	0.25 km/h (along track)
Distance to earth:	2.2×10^8 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 Station 3 or 4, 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 11). 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 an 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.

Table 4 shows the first few hr of a timeline totaling 14 hr at the science site. This timeline, however, does not consider engineering operations which will have to be interspersed with science, start-up time, weather on Mars, sunlight or time of day, but only effective science operating time. Success the first time for almost all operations was also assumed. The nominal time of 14 hr for a science site is therefore unrealistically short; Table 4 and its continuation serve merely as starting points for design of the operations.

Ref 4 gives a timeline for the geophysical survey. 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 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.

A timeline for the entire mission traverse has been sketched (ref 4). Table 4 shows the corresponding mission time breakdown and rover mileage. 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/s of uncompressed video); in practice they would vary with the earth-Mars distance.

Lunar Profile. The science elements of a lunar rover mission traverse are the same as those outlined above for Mars. 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 would accordingly be less than 4 hr instead of 14 hr, and for a geophysical survey to less than 10 hr, instead of 13 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 3. Because of the longer overall track length (2000 km), the greater vehicle speed (1.5 km/h assumed, along track), and much less time spent waiting for communications, the number and size of science areas can be increased; Table 3 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.

OPERATIONAL PROBLEMS

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 8, motion control in ref 12.

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 Table 4 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 (Table 4); 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 Table 3, arises not from oFe-rational 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.

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 Operational Problems. For the lunar vehicle, almost all science control can be from earth, as tor Surveyor and Lunokhod. (This is not necessarily true for motion control.) To permit this control, continuous communication with earth will be needed for science operations. Science data storage will not be required; the communications channel of 0.5 - 2 Mb/s 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 scientific questions concerning both Mars and the moon. Series of science payloads are suggested; they range in weight from 35 to almost 300 kg and in average 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.

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Table 1. Mars Rover Payloads & Instrument Weights

(Values not otherwise specified are weights in kilograms)

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]	--	--	--	--
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
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
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
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[d]	--	--	--	--	--	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

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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

Table 2. Lunar Rover Science Payloads and Instrument Weights

(Values not otherwise specified are weights in kilograms)

	No Sample Return						Sample Return			
Payload Type:	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	–	–	–	–
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, W, during science operations, excluding emplaceable stations	38	95	48	95	52	95	48	95	52	76
Average payload power, W, during vehicle motion	2	5	8	25	8	27	8	8	8	17

Table 3. Mission Time and Mileage Breakdown

	Mars Mission				Lunar Mission			
Activity	Quantity	Percent of mission time[a]	Map distance km	Track distance km[b]	Quantity	Percent of mission time[a]	Map distance km	Track distance km[b]
Science sites	76 @ 19 hr & 0.25 km	9	19	29	240 @ 6 hr & 0.25 km	16	60	90
Geophysical surveys	11 @ 12 hr & 1 km	1	11	16	30 @ 9 hr & 1 km	3	30	45
Within science area, moving between sites	11 @ 108 hr & 18 km	7	200	300	16 @ 26 hr & 26 km	5	415	625
Moves between science areas	10 @ 264 hr & 44 km	16	440	655	15 @ 55 hr & 55 km	9	825	1240
Postlanding checkout	1 @ 200 hr	1	-	-	1 @ 50 hr	1	-	-
Waiting; night and sun too low[c]	668 @ 14 hr	56	-	-	12 @ 390 hr	54	-	-
Waiting; sun too high[c]	669 @ 2.5 hr	10	-	-	13 @ 80 hr	12	-	-
TOTAL (scalar)		100	(670)[d]	1000		100	(1330)[d]	2000
TOTAL (vector)			500				1000	

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: Mars, 0.25 km/hr, moon 1.5 km/hr.

c. Assumes sun must be at least 10° above horizon for active operation, and not within 20° of local noon. 669 Mars days/Mars year; 13 lunar days/year.

d. The total map distance is the vector sum of the individual map distances and is taken as 0.75 of the scalar sum.

TABLE 4
Portion of Time-Line for Science Site

(Abbreviations: Fax = facsimile (picture), Pan = panorama,
WA = wide angle TV picture, NA = narrow angle TV picture.)

At Station	Time. Hours	Rover TV, Motion, and Manipulation	Other Mars Activity	On-Board Science Data Store in Hours		Pacing Transmission or Earth Activity			
				Data Put in	Balance in Store	Sending	Down Delay	Earth Activity	Up Delay
	.1	Fax pan of terrain		.4	.3				
	.2	4 fax sectors		.2	.4				
	.3		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 50 m)			1.1				
	3.7	↓			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)