Mars Pathfinder Mission Operations Concepts

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Abstract

The Mars Pathfinder Project plans a December 1996 launch of a single spacecraft. After jettisoning a cruise stage, an entry body containing a lander and microrover will directly enter the Mars atmosphere and parachute to a hard landing near the sub-solar latitude of 15 degrees North in July 1997. Primary surface operations last for 30 days.

Cost estimates for Pathfinder ground systems development and operations are not only lower in absolute dollars, but also are a lower percentage of total project costs than in past planetary missions. Operations teams will be smaller and fewer than typical flight projects.

Operations scenarios have been developed early in the project and are being used to guide operations implementation and flight system design. Recovery of key engineering data from entry, descent, and landing is a top mission priority. These data will be recorded for playback after landing. Real-time tracking of a modified carrier signal through this phase can provide important insight into the spacecraft performance during entry, descent, and landing in the event recorded data is never recovered.

Surface scenarios are dominated by microrover activity and lander imaging during 7 hours of the Mars day from 0700 to 1400 local solar time. Efficient uplink and downlink processes have been designed to command the lander and microrover each Mars day.

The work described in this paper was carried out by JPL, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Mission Overview

Mars Pathfinder will be launched on a Delta 7925 during a 30-day period beginning December 6, 1996. The flight system consists of a cruise stage and an entry stage (Fig. 1). The cruise stage is jettisoned just prior to entry into the atmosphere directly from the approach trajectory. Inside the entry body are the lander and parachute, retro-rocket, and air bag deceleration systems. The lander is a tetrahedron (Fig. 2), with a base plate and 3 petals covered with solar cells. A microrover rests on one petal. The mission uses a short Type I transfer trajectory and is targeted for a constant landing date on July 4, 1997 at 19.5° N, 32.8° W in the Ares/Tiu Valles outflow channel into Chryse Planitia. Primary surface operations, lasting 30 days, consist of rover technology experiments, and imaging, alpha-proton-X-ray spectrometry and meteorology science. A lower activity extended mission may last for up to a year.

Costs

As a Discovery mission, Mars Pathfinder costs are capped at $150M in FY92$ for development. This translates to $171M in real year dollars. In addition, the technology program contributes $25M for rover development and operations. The Mission Operations and Data Analysis budget from launch+30 days to End of Project is $14M. Tables 1-2 show cost data for the major systems and details of the Ground Data and Mission Operations System budgets. At a total of $10.9M and 6%, the ground system development budget is smaller in both absolute dollars and as a percentage of total project costs than previous missions.

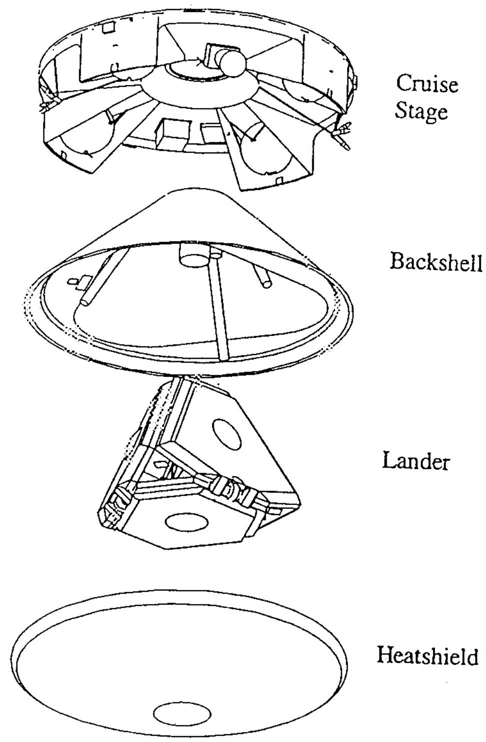

Fig 1. Flight System in Launch Configuration

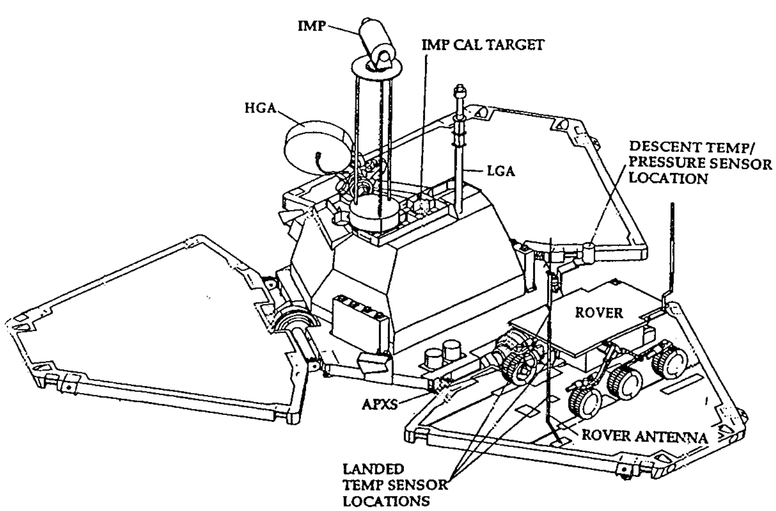

Figure 2. Lander in Deployed Configuration

Table 1. Major System Obligations, $M

FY	94	95	96	97	98	Total
Proj Mgt	2.5	2.0	1.5	0.4	0.0	6.4
MD&Ops	3.1	4.4	4.1	1.1	0.0	12.7
Flt Sys	37.7	41.1	15.2	3.5	0.0	97.5
Sci&Inst	6.1	4.7	2.7	0.8	0.0	14.3
Reserve & other	4.6	21.4	13.9	0.2	0.0	40.1
Dev Total	54.0	73.6	37.4	6.0	0.0	171.0
Rover	6.0	8.0	6.7	2.0	0.0	25.0
(total includes $2.3M in FY93)						
MO&DA				8.0	6.0	14.0

Table 2. Ground System Costs, $K

FY	94	95	96	97	98	Total
Mgt	170	199	209	70	0	648
Sys Engr	421	470	459	75	0	1425
Loan Pool	80	150	150	35	0	415
H/W	605	560	71	0	0	1236
S/W	541	845	566	0	0	1952
Ops Supt	43	178	189	78	0	488
Reserve	158	50	25	0	0	233
GDS Dev	2018	2452	1669	258	0	6397
Mgt	153	228				381
Reqt&Des	116	0				116
Exp Team	150	422				572
Eng Team	178	557				735
Test-Train			1524	875		2399
Reserves	56	105	155	0		316
MOS Dev	653	1312	1679	875		4519
GDS+MOS	2671	3764	3348	1133		10916
Mgt				1404	1072	2476
Exp Team				1995	2529	4524
Eng Team				2825	1225	4050
GDS Sup				860	503	1363
Reserve				916	671	1587
MO&DA				8000	6000	14000

Organization

The operations organization for Mars Pathfinder is smaller and has fewer teams than typical JPL flight projects. The organization, as illustrated in Fig. 3, consists of a Project Office, a Mission Director, and 5 operations teams: Experiment Team, Engineering Team, MOSO Support Team, GDS Maintenance, and DSN Operations Team. These teams report to the Mission Director, who in turn reports to the Project Manager, who heads the non-operations Project Office. The staffing numbers shown in Fig. 3 denote the maximum level planned for operations. This organization is in place in October 1995 at the beginning of ATLO (assembly, test, and launch operations).

The Experiment Team provides operations support for rover operation and science and technology experiments during surface operations phases. This team includes science investigators and rover technology experimenters when they are performing operations tasks.

The Engineering Team conducts mission planning, sequence generation, flight system performance analysis, navigation,and real-time flight control and commanding tasks that insure safe operations and achievement of mission objectives. This team also supports ATLO with planning and development of test sequences for test and training.

Support is provided by MOSO (Multimission Operations Systems Office) for data system operations, data administration, and image processing. In addition, MOSO maintains the baseline GDS capabilities at no cost to the Project.

The Project adaptations to the baseline GDS are maintained by Project GDS personnel.

The DSN (Deep Space Network) Operations Team provides the interface between the Project and the DSN for obtaining network coverage for commanding and telemetry receipt at no cost to the Project.

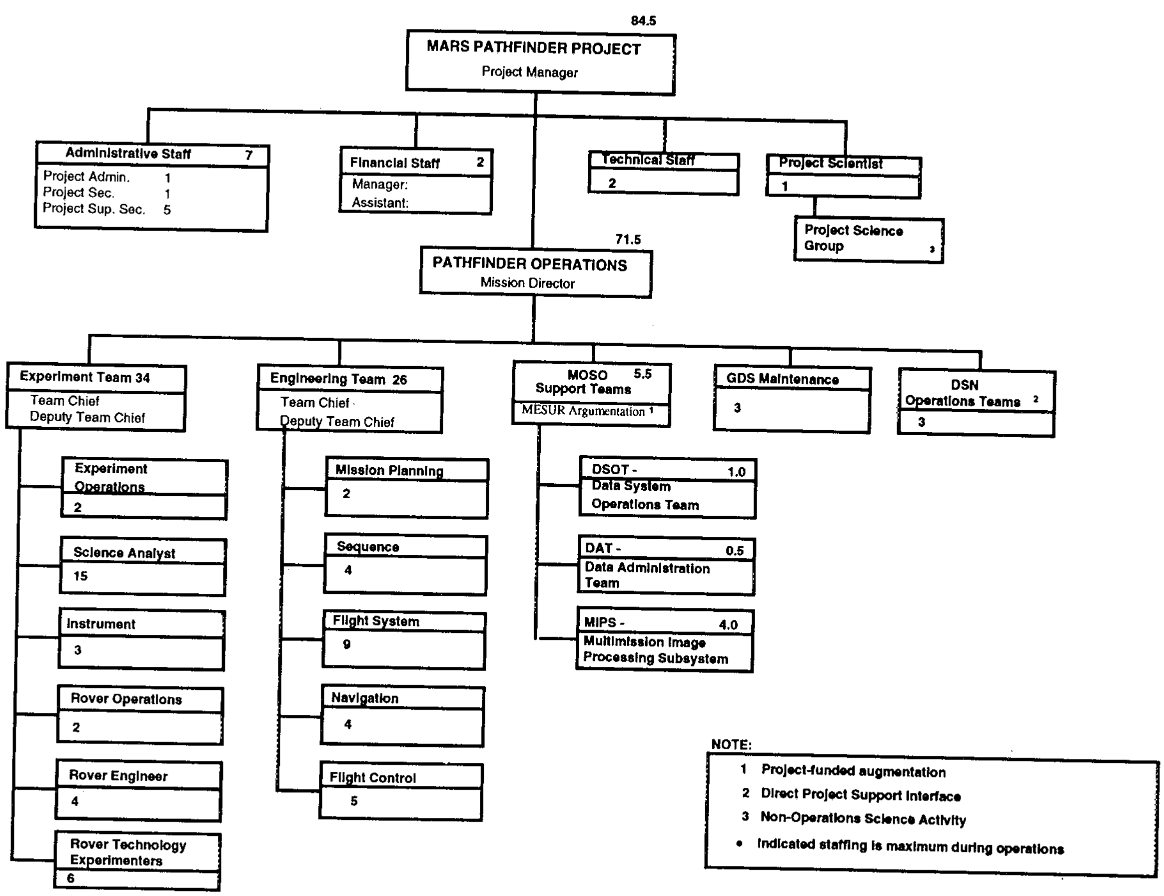

Figure 3. Mars Pathfinder Operations Organization

Enabling Characteristics

Low operations costs are enabled by system characteristics established from an end-to-end perspective and concurrent engineering of the flight and ground systems: **a. Acceptance of more risk as a Class C mission** enables the use of more autonomous capabilities onboard and thus enhances flight system operability. For ground operations, multiple levels are not needed for review and approval. **b. No cruise science and limited surface instruments. c. Large GDS inheritance** enables the project to build a GDS at minimum cost. **d. Better flight system operability.** The flight system is designed with emphasis on operability. Sample design decisions based on the operability view are: (1) A simple spin-stabilized flight system (2) Large flight computer margins - The provision of large computer resources (i.e. a 32-bit RISC processor with processing power up to 20 MIPS, sequence memory size at 4Mbytes, data storage capacity at 128Mbytes, and system backplane bandwidth $\geq$ 10Mbytes/s) negates the need for allocating the above resources during mission operations. (3) No external storage devices (such as a digital tape or solid state recorder) - only RAM and EEPROM are used for storing flight software and data - offering better flexibility and simplicity for uplink operations. (4) On-board sequence memory management simplifies the uplink process. (5) On-board autonomous capabilities - includes closed-loop monitoring and control of the thermal and power condition, lander high gain antenna Earth pointing, flight system mode control, a demand-driven rover-lander interface scheme, and autonomous rover traverses. (6) Asynchronous data-driven telemetry handling scheme which makes the telemetry data collection, data recording, data retrieval, and data downlink processes totally decoupled from each other. The MOS no longer has to design, test, and schedule the telemetry modes as in other planetary missions. (7) Priority downlink of telemetry data so that high priority operations data can be downlinked ahead of lower priority data. **e. No complex navigation data types** -only Doppler and ranging data are used for orbit determination. Thus not only the process of flight path estimation but other activities, such as sequence development, are greatly simplified.

Cruise Scenario

The cruise mission phase begins at separation of the flight system from the launch vehicle upper stage and ends with the turn to entry attitude at Mars arrival -1 day. The initial cruise sequence continues from the launch load, and includes spin down, attitude stabilization, telemetry acquisition and the first of two complete flight system health and status checks (Fig. 4). For launch on the opening day of the 30-day launch period, 8 cruise sequence loads are planned with the first 7 about 4 weeks and the 8th about 1 week in duration. The 8th load contains the second and last health and status check. No other experiment activity is planned for cruise.

Four trajectory correction maneuvers (TCMs) are scheduled. Navigation is based on two-way Doppler and range data. TCM-1 removes launch injection errors and most of the aiming point bias necessary for Planetary Protection. TCM-2 corrects execution errors of TCM-1. The 3rd TCM targets the flight system for Mars atmospheric entry and TCM-4 corrects execution errors of TCM-3. Delivery accuracy on the surface is about 200 km downtrack and 100 km crosstrack (3 sigma).

The sequence load strategy for launch delays is to maintain the first three cruise sequences as designed with TCM-1 at L+30 and TCM-2 at L+60 near the beginning of loads C0002 and C0003. Cruise load C0004 will be shortened with each launch delay and will be deleted if the delay approaches 4 weeks.

The uplink process allocates three weeks for cruise sequences (4 working days for planning, 8 days for generation, 1 day for final updates, and 1 day for commanding). The allocation of three weeks to generate a four week sequence provides the margin to enable the mission operations teams to perform the following additional tasks while minimizing the requirement for extended work hours: (1) characterize and respond to flight system anomalies, (2) participate in test and training exercises and certification of team members for surface operations, and (3) design, generate and update entry, descent and landing, and nominal surface operation sequences.

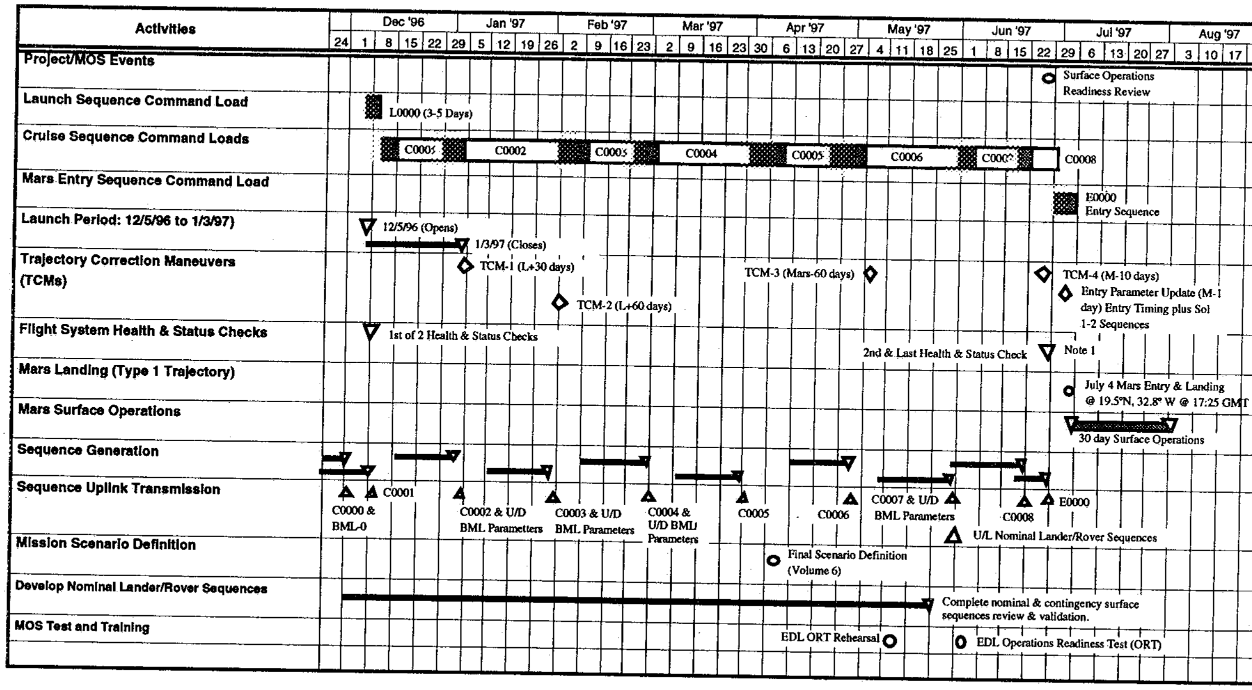

Figure 4. Mars Pathfinder Cruise Timeline

EDL Scenario

The entry, descent, and landing (EDL) phase of the Pathfinder mission begins one day prior to Mars arrival and ends with the touchdown of the lander on the Mars surface. An EDL sequence, a sol 1 and sol 2 sequence, and a contingency sequence (covering the entire surface operations phase in the event landing damage prevents normal operations) are uplinked prior to jettison of the cruise stage. The EDL operational scenario is characterized by the following:

a. Continuous DSN coverage is provided through a 70-M DSN station.

b. Continuous real-time engineering telemetry monitoring of the flight system state up to parachute deploy.

c. Continuous carrier tracking to obtain flight system state information concerning key EDL events. Real-time tracking and recording of carrier signals are performed at the DSN station. Real-time display of frequency spectrum through a Spectrum Signal Indicator (SSI) gives some visibility into EDL status. Telemetry acquisition will not be possible after parachute deploy due to large varying angles between the flight system low gain antenna boresight and Earth. MOS will obtain knowledge of critical events using the following two mechanisms: (1) Determine the deviation from the nominal entry profile by measuring the line-of-sight velocity using a recovered Doppler frequency profile. (2) Analyze the transition of amplitude modulated carrier signals to determine the modulation index changes. These changes are commanded by the flight system to obtain a carrier suppression of 0 or 6 dB (and perhaps other levels) upon the occurrence of key events in the EDL sequence. They provide critical state information to the MOS. Figure 5 depicts a potential strategy for obtaining telemetry and EDL state information.

d. Autonomous execution of on-board EDL activities by the flight system. These autonomous actions, e.g. cruise stage separation, chute deploy, heatshield release, lander release, RAD firing, are controlled by the flight software based on pyro event timing parameters in the EDL sequence. This means that no real-time ground control of the flight system is possible after cruise stage separation.

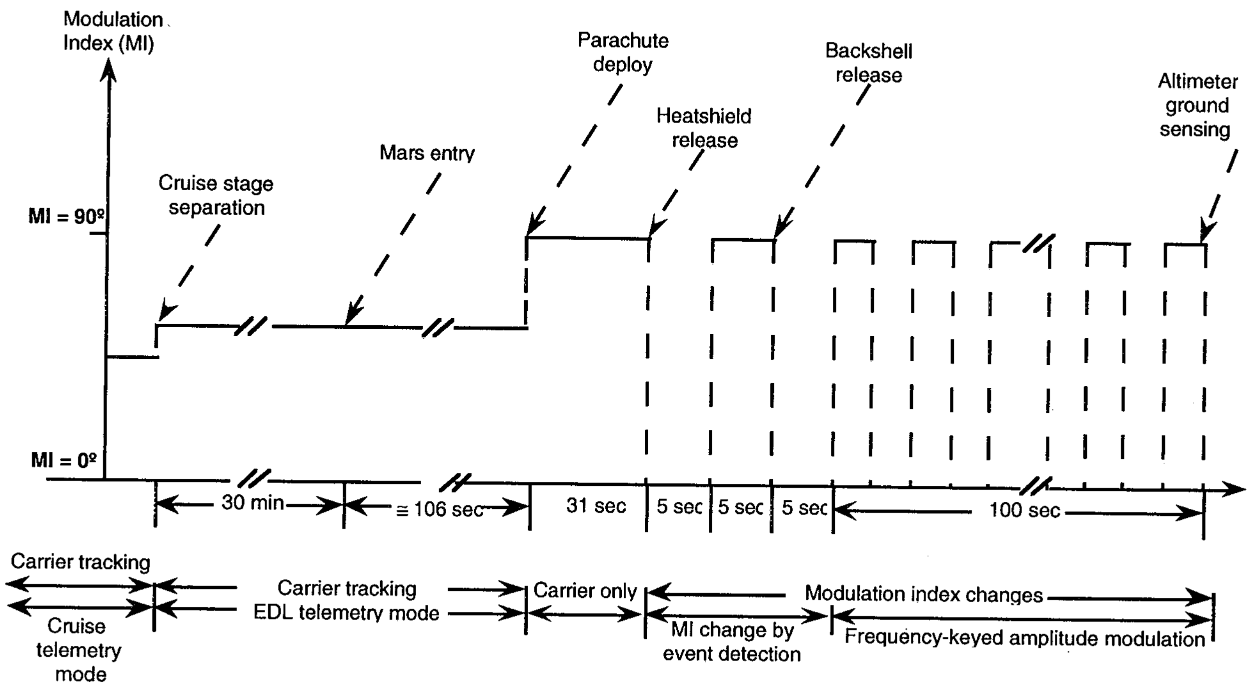

Figure 5. EDL Telemetry and State Information Acquisition Strategy

Surface Scenario

Most JPL spacecraft operate in the relatively well-understood environment of deep space. Pathfinder, however, must land and operate on a largely unknown planetary surface. The tilt of the lander with respect to the Sun, Earth and local horizontal all affect battery charging, communications and rover maneuvering operations. The amount of atmospheric dust affects solar panel response and amount of battery heating required. Nearby rocks or features might block the Sun or rover exit paths. Lander orientation in azimuth with respect to the Sun changes the time of day when various amounts of power states are reached and when pictures can be taken. These are all factors which can be statistically surmised but not known in advance. They make prediction of activity sequences and mission data return time tables more problematic than for most other types of missions -- even if the lander were to work perfectly.

Nominal lander performance and surface scenarios are based on an optical depth, tau, of 1.0 and an adverse lander tilt of 15°. Rough estimates indicate a probability of about 82% that these values will not be exceeded. They are bad enough to significantly limit activity schedules. Contingency scenarios will be ready if conditions are better or worse.

We hope to accomplish the basic mission quickly, since thermal cycling could end the mission early. As shown in Table 5, much of the imaging is done on sol 1 and stored. This is because the data acquisition scheme includes imaging as much as possible early and storing the compressed data in memory, in case anything goes wrong with the camera later. The plan is to complete the basic rover mission in a week.

To account for a range of environments, as well as for possible hardware problems, the project has adopted a policy of maintaining some number of both "nominal" and "contingency" scenarios. These scenarios are to be negotiated before landing to reduce decision times.

Table 3 shows a range of activity schedules and milestones for three different example conditions: optimistic, reduced, and loss of High Gain Antenna (HGA). These scenarios are generated in a system of spreadsheets which include formulas for battery charging and discharging, data compression, and engineering data acquisition, and tables for DSN coverage, solar array input, activity schedules, rover and lander power modes, and data rates. As shown, each scenario can be reported against a schedule for achievement of formal mission success milestones.

Data acquisition and data return projections for an "optimistic" nominal mission are shown in Tables 4 and 5. Among the optimistic assumptions is the amount that can be achieved on sol 1, as shown in Table 3.

The EDL and sol 1 sequences (as loaded before entry) run until telemetry can be received and the lander can be commanded from Earth, at which point sol 1 activity can be modified if necessary. Rover deployment is enabled from the ground based on downlinked images. The operations plan for each sol thereafter is to command the lander and rover in the Mars morning just after receipt of important overnight telemetry to confirm acceptable status. Depending on the amount of solar power available and lander energy balance, up to 5 hours of additional telemetry is obtained during the rest of the sol for rover and lander status and science data. The nominal communications period is from 0700 to 1400 LST. During the other 17 hours each sol, 5 hours are allocated for telemetry analysis, and 15 hours for replanning and a highly automated generation of the sequence for the next sol, leaving a 2 hour margin. This process repeats each sol for the rest of the 30 sol prime mission.

Operations after the 30 sol prime mission continue similarly, except that the data rates will go down by 75% when the project switches to 34-meter DSN stations. The data rate continues to drop to a low of 150 bits/s in June 1998, as the Earth-Mars distance increases.

Table 3. Mission Activity Milestones for Optimistic, Reduced, and LGA Missions

	"OPTIMISTIC" NOMINAL MISSION				"SLOWED DOWN" NOMINAL MISSION				MISSION ON LOW GAIN ANTENNA			
		Numbers Achieved				Numbers Achieved				Numbers Achieved		
	Sol when First Achieved	on Sol 1	in Week 1	First Month	Sol when First Achieved	on Sol 1	in Week 1	First Month	Sol when First Achieved	on Sol 1	in Week 1	First Month
Mission Success Level	-	70%	90%	100%	-	50%	70%	100%	-	50%	70%	100%
Spacecraft Deployments												
Partially Deployed	1	-	-	-	1	-	-	-	1	-	-	-
Fully Deployed	1	-	-	-	1	-	-	-	2	-	-	-
Rover Ramp Deploy	1	-	-	-	2	-	-	-	2	-	-	-
Downlink												
EDL	1	-	-	-	1	-	-	-	1	-	-	-
Health	1	-	-	-	1	-	-	-	1	-	-	-
Imaging for Planning	2	-	2	2	3	-	1	2	6	-	1	2
Science	1	-	-	-	1	-	-	-	6	-	-	-
Rover Activities												
Deployment	1	-	-	-	2	-	-	-	3	-	-	-
Traversing	1	2 M	15M	150M	2	-	10M	75M	3	-	10M	20M
Image Lander (incl close-ups)	1	1	3	>20	2	-	2	3	1	-	1	1
Image Landing Path	18	-	-	10	18	-	-	5	-	-	-	-
Image Terrain	1	1	3	>20	2	-	3	10	3	-	1	3
Soil Mechanics	2	-	4	8	4	-	2	4	7	-	1	2
Soil APXS	1	1	1	3	2	-	1	2	7	-	1	1
Rock APXS	3	-	2	6	5	-	1	3	9	-	-	1
Stereo Pans	9	-	-	3	15	-	-	1	-	-	-	-
Materials Tests	1	1	7	30	1	1	7	30	3	-	3	10
High Gain Antenna												
Deployment	1	-	-	-	2	-	-	-	-	-	-	-
Point ±4.7º (1200 bps)	1	-	-	-	2	-	-	-	-	-	-	-
Point ±3.5º (2200 bps)	8	-	-	-	10	-	-	-	-	-	-	-
Lander Camera												
Deploy Imager Mast	1	-	-	-	2	-	-	-	3	-	-	-
Mission Success Pan	1	1	1	1	1	1	1	1	3	-	1	1
Mid-Res Science Pans *	1	1	2	2	2	-	2	2	-	-	-	1
Color Science Pans *	1	1	2	2	3	-	1	2	4	-	-	1
High-Res Science Pan *	2	-	4	6	6	-	1	3	-	-	-	-

* Sol numbers indicated are for data acquisition.
Downlink of much of the panorama data occurs on later sols.

Table 4. Optimistic Surface Mission Data Acquisition Timetable (Mbits)

DATA CATEGORY	LANDED MISSION WEEK				Data
	1	2	3	4	Totals
APXS Data					
Rock	0.2	0.1	0.1	0.1	0.6
Soil	0.1	0.1		0.0	0.2
Lander Imager Data					
Monochrome Science Pans	169.9		74.2		244.2
Eight-Color Pans	166.4				166.4
Mission Support Pans	26.2				26.2
Other Science Imaging	3.3	3.3	3.3	3.3	13.1
Rover Support Imaging	9.4	3.7	10.7	2.4	26.2
Rover Activities					
Mission Support Imaging	3.6	8.6	17.7	9.8	39.7
Science Imaging	1.4	1.4	0.7	1.4	4.8
Technology Imaging	6.9	2.8	0.4	1.2	11.4
Technology Experiments	3.6	1.8	0.9	1.0	7.4
Rover Engineering	0.9	2.0	1.6	1.2	5.7
Meteorology	0.7	0.7	0.7	0.7	2.8
Weekly Data Acquisition Totals	392.6	24.5	110.3	21.1	**548.5**

Table 5. Optimistic Mission Data Return Timetable (Mbits)

	Experiment Data				Engi- neering
Time Frame	Raw	Com- pressed	Downlink	Storage	Downlink
Sol 1	998.5	58.7	13.1	45.7	0.2
Sol 2	937.3	242.9	9.8	278.8	0.3
Sol 3	188.3	75.8	10.4	344.2	0.3
Sol 4	13.6	4.5	5.5	343.2	0.3
Sol 5	12.5	4.4	6.6	340.9	0.3
Sol 6	2.4	1.5	12.7	329.7	0.3
Sol 7	12.8	4.2	14.1	319.8	0.3
Week 1	2165.4	387.8	72.2	319.8	1.9
Week 2	126.8	39.5	116.1	243.2	2.0
Week 3	380.8	115.7	136.2	222.7	2.0
Week 4	94.1	31.1	127.6	126.1	2.0
Weeks 1-4	2767.2	574.1	452.1	126.1	7.9
Daily Average	98.8	20.5	16.1	32.6	0.3

Mission Management

* *Presented in Poster Session*