Rover Design for Edutainment-Based Lunar Mission

The Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

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Preface

The Lunar Rover Initiative (LRI) has been formed with the intention of placing a robotic vehicle on the Moon before the year 2000. The LRI was undertaken by the Planetary Robotics Program in the Robotics Institute, Carnegie Mellon University (CMU) in early 1993. In August 1993, the National Aeronautics and Space Administration (NASA) endorsed the LRI in a charter for commercial lunar ventures. In February 1994, the LRI and LunaCorp, of Arlington VA, announced a collaborative plan to perform a lunar traverse whose main purpose is to provide edutainment; a radical departure from the scientific emphasis of traditional space exploration.

A rational design study was completed in May 1994 as part of the course curriculum of the Robotics Institute Ph.D. program and yielded a list of key issues and primary risks. These risks were addressed over the Summer 1994 effort which led to a Configuration Review in October 1994. In the spring of 1995, solutions were identified which would enable uninterrupted operation during the lunar night. The rationalization of the configuration, along with more detailed design of the major subsystems, have been the focus during Summer 1995. This document has been produced for the September 1995 Preliminary Design Review of the LRI mission and rover design.

The purpose of this design document is to present a design which is believable from both commercial and technological perspectives. In addition to providing a snapshot of the design evolution, solutions for key issues are rationalized, potential components and vendors are given, and remaining risks are detailed. This version (1.0) of the document will be augmented in the future with appendices showing the techniques and results of performed analyses as well as describing alternative solutions to key issues. A second volume will be added by November 1995 which is a compendium of all previous analyses and design efforts.

The 1996 fiscal year sees a change in the focus of the LRI from design to development. The culmination of the next two years will be the completion of a lunar analog terrestrial traverse, whose purpose is the demonstration of lunar-relevant technologies required for the success of the space mission. After a year of software and component development, a prototype of the flight rover will be constructed for the traverse. The generation of the product and the teleoperation interface will also be evaluated.

This work is currently supported by Code X of NASA by the TeleRobotics Intercenter Working Group led by Dave Lavery, and is one of the projects being considered for participation in the NASA Robotics Engineering Consortium established in 1995 for the purpose of bringing NASA funded technology developments into industry use. In addition to LunaCorp, who is the primary commercial sponsor for the mission, International Space Enterprises (ISE) of San Diego CA and the Lavochkin Institute in Moscow, Russia are currently providing assistance in the design process. Individuals from numerous organizations have provided valuable input and technology into this initiative. These include Sandia Labs, Lawrence Livermore, NASA Lewis, NASA Goddard, NASA Ames, University of Maryland, McDonald Douglas, Martin Marietta, Boeing, Matra-Marconi, PVSI, and Dalsa.

At this time, the LRI has made no contractual agreements for creating rover components. The corporate names and products referenced in this document are included to demonstrate rationality of the technical solutions, not to claim that a particular vendor has agreed to develop or provide the component.

Additional project information is available via the world-wide web at: http://www.ri.cmu.edu/lri or phone (412)268-8098.

On the cover: Synthesized image showing a rover traversing the lunar terrain with Earthrise in the background. The rover shown is of a previous design stage which required actuation of the circular phased array and utilized a ring of cameras to acquire panoramic imagery. The image is taken from the LRI web page.

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Executive Summary

The Lunar Rover Initiative (LRI), undertaken by the Planetary Robotics Program at the Robotics Institute, Carnegie Mellon University, is chartered to place a robotic vehicle on the Moon before the year 2000. Endorsed by NASA as part of the Telerobotics Program in Code X, the LRI has chosen a commercial mission focused on providing entertainment and education, or “edutainment”, rather than the science agenda of traditional space exploration. The main product of the mission is high-quality, panoramic, color video returned to Earth and displayed in real-time, which is suitable for movies, television broadcasts, CD-ROMS, and photographic stills, and when combined with the rover motion history can be used to generate highly realistic telepresence experiences or inputs for geological analysis. The goal of the mission is to increase awareness about robotics and planetary exploration among mass audiences and to demonstrate financial success of commercial space missions.

The mission is accomplished through the use of two identical rovers which traverse 1000km while visiting historic sites on the Moon. High resolution, immersive, panoramic video is acquired through omnidirectional “pano-sphere” optics and compressed using wavelet algorithms. Telemetry and video are transmitted to Earth simultaneously by both rovers using right and left circular polarization from an X-band phased array antenna with 60 degree electronic beam-steering, and a low-gain omnidirectional antenna is used to receive command information. The rover is heated using plutonium heat sources and AMTEC (alkali metal) is used to convert the heat to electrical power. Custom designed multi-chip modules provide the computing power and are based around rad-hard R3000’s and single-chip multi-processor DSP’s (i.e. the TI MVP-C80). The rover is composed of aluminum ribs mounted on a honeycomb base-plate and wrapped in a fabric layer of kevlar and kapton sheeting (3 layer MLI). Terrainability is achieved using an explicitly steered six-wheeled distributed drive chassis with passive-linkage rocker-bogie suspension. Each rover is 2m x 2m x 1.2m, weighs 238kg, uses 540 Watts, and it costs 59.8 Million to develop and fabricate two rovers.

1.1 Mission Overview

The mission involves a 1000 km journey by a pair of semi-autonomous, teleoperated, unmanned lunar rovers over a two year period starting in the winter of 1998. The pair of robots will visit five historical sites during the traverse, starting at the first manned lunar landing site, Apollo 11. The trip then passes by the impact crater of Ranger 5 and the landing site of the unmanned Surveyor 8 probe and crosses the Mare Tranquilitatis (Sea of Tranquility). Climbing into the lunar highlands, the rovers will visit Apollo 17 (the last manned lunar landing site) and then quest for the landing site and grave of the Soviet Lunokhod 2 unmanned rover.

The two rovers operate primarily in a leap-frog scenario (one rover remaining stationary and observing the exploration of its partner and then reversing roles) with role transitions occurring the shorter of 250 meters or 30 minutes. The rovers operate continuously, even during the fourteen Earth-day lunar nighttime (seen as a new moon from Earth). The average speed of the rovers during the traverse will be 0.3 m/s, a slow hiking pace. While exploring, the rover is mostly teleoperated from earth (the round trip time-delay is about 5 seconds) by an amateur driver. During this time, the rover must safeguard itself from unforeseen events, human error, and deliberate operator mischief. Each rover is thermally regulated with self-power distribution, and is also responsible for managing the communication link integrity and imaging quality. The pair of rovers will reach the Moon via Proton launch vehicle and Phobos lander. During the voyage, the rovers are positioned on their back ends with the wheels attached to ramps. Upon landing, the ramps lower and the rovers drive off onto the lunar surface.

The major challenges of the mission are surviving the lunar environment for over two-years and 1000km, successfully navigating the unknown terrain between historic sites, maintaining continual high-bandwidth communication and generating an exciting and impressive product. The complete mission costs are estimated at $200 Million, with $60 M for rover development, $80 M for launch, $20 M for ground station (communication relays, control stations and operating costs), $10 M for marketing and coordination, $10 M for insurance and risk mitigation, and $20 M for contingency.

Following the September 1995 PDR, the terrestrial demonstration will occur in May 1997. Predicated on available commercial funding, the Critical Design Review would then be scheduled for July 1997. With approval at this time, component ordering begins, along with the construction of the engineering mock-up, software verification and subsystem integration, with a September 1998 deadline for accepted and tested components. After the final US system testing and preliminary acceptance, the rover is shipped to Russia in December 1998. The power system integration and final systems evaluation should be completed by February 1999 with acceptance testing completed in March 1999. After three months of lander integration, launch can occur in June 1999. This allows one month of slippage in the schedule to still be at Apollo 11 on its 30th anniversary.

The primary future work of the LRI is twofold: continue the design effort by identifying components and vendors, performing system reliability and finite-element analysis, and determining the required software algorithms; develop a lunar-relevant earth prototype which demonstrates the critical components and test it in a lunar-analog setting in Spring 1997.

1.2 Design Overview

The design of the rover is separated into eight subsystems. Locomotion contains the chassis, drive actuators, and wheels. Communication contains the on-board antenna, telemetry/encoding scheme, and ground station/satellite relay. Visualization contains the imaging system, processing software, and display techniques. Computing contains the electronics hardware, image compression scheme, and sensor processing. Power contains the radioactive heat source, thermo-electric converters, and power regulation/conversion. Thermal contains the radiators, heat pipes, and insulation. Structure contains the weight-bearing members, exterior framework panels, and interface and attachments to the lander. Safeguarding contains the on-board range and systems monitoring sensors. One rover requires 249 kg mass and 538 W power. This includes a 5% system and progressive component maturity margins (5% for known hardware to 30% for conceptual designs).

In order for the rover to accomplish its specified mission, it must perform certain tasks. These tasks define the responsibilities of the different subsystems. Table 1.1 lists the top level function of each subsystem, from which the subsystem functionality and requirements are drawn.

TABLE 1.1 *Subsystem Top-Level Functions*

Subsystem	Function
Locomotion	Generate Motion
Communication	Handle Encoding and Telemetry
	Perform Downlink/Uplink Communications
Visualization	Acquire and Process Video
	Process and Display Video
Computing	Sensor Fusion and Control
	Video Compression

TABLE 1.1 *Subsystem Top-Level Functions*

Subsystem	Function
Power	Generate Power
	Regulate and Distribute Power
Thermal	Supply and Reject Heat
Structure	Provide Environment Protection and Maintain Physical Integrity
	Provide Mechanical Interfaces
	Form Vehicle External Shape
Safeguarding and Sensors	Determine Vehicle State
	Determine Range Map about Vehicle

These functions are shown graphically in Figure 1.1. Also shown are the relevant internal and external interfaces. Mechanical interfaces are shown with solid lines, communication/data interfaces with dotted lines, and power interfaces with dashed lines. Functions taking place off-board the rover are shaded. The interface between the rover and the lander module is the only interface that will be broken during the mission, when the vehicle is deployed from the lander.

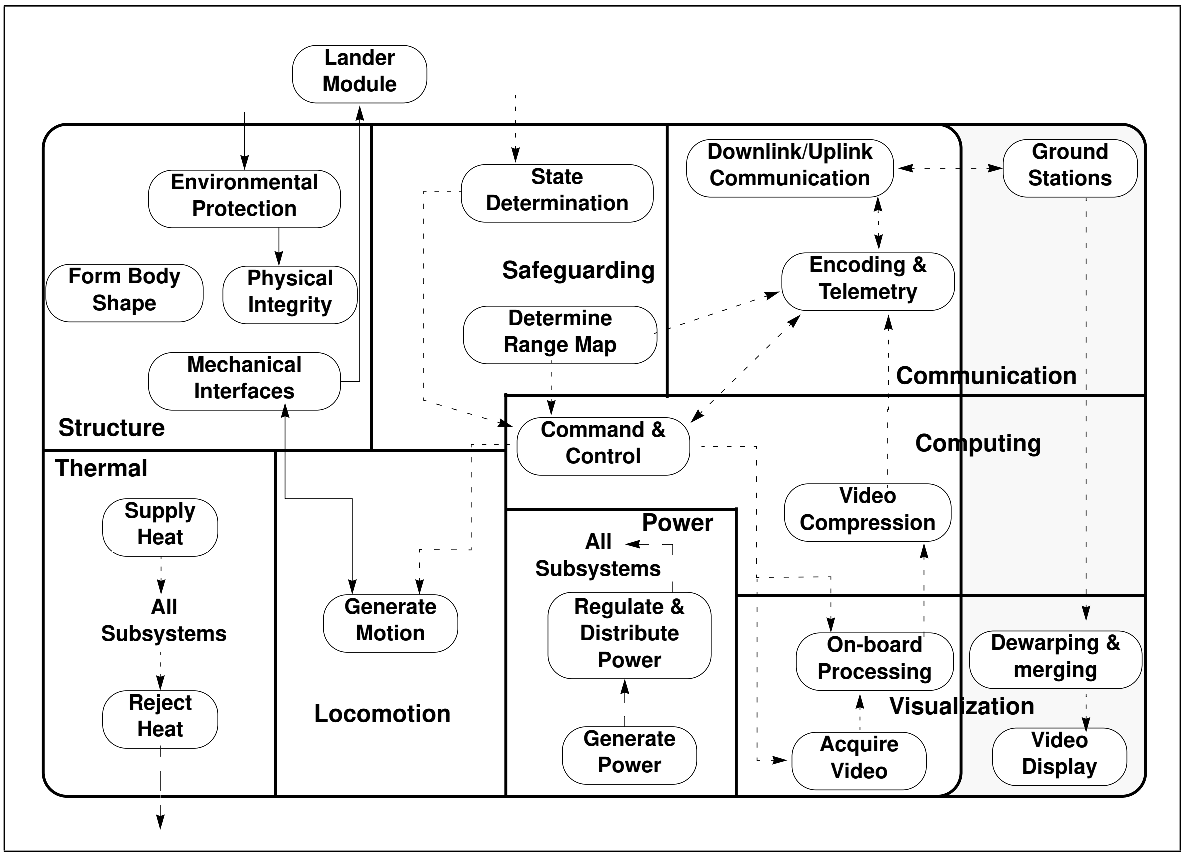

FIGURE 1.1 *System functional block diagram*

1.2.1 Locomotion

Six wheels, each independently driven, are suspended from the body using a passive linkage "rocker-bogie" chassis with the wheels equally spread along the side of the vehicle. The wheels (40 cm diameter, 30 cm width) have a mesh tread comprised of zinc coated steel wires, with 18 aluminum grousers attached for traction (2.5 cm high by 0.3 cm thick). The tread is attached to three perforated aluminum disks which are, in turn, attached to the wheel hub. The front and middle wheels on each side are connected via the short bogie (75 cm) which is attached to the rear wheel by the long bogie (115 cm). The rear wheels on both sides are connected via an averaging linkage. The bogie members are made of rectangular aluminum sections, again perforated to reduce weight. To prevent dust from being kicked onto the rover body by the wheels, the top sector of each wheel is covered by a fender. The six drive actuators contain redundant motors, a harmonic drive, brake, and Hall effect sensors for velocity feedback. Explicit steering on the corner wheels enhances the trafficability of the robot. The wheelbase of the vehicle is a 2.0 m x 2.0 m square. The locomotion system uses 58 W of power on average with a reserve storage of 320 J for peak needs, and the total mass of the actuators, wheels, and chassis are 54.2 kg.

1.2.2 Communication

Downlink communication from the rover to earth is achieved using a phased array antenna operating in X band, with a low-gain omnidirectional antenna for the uplink and as downlink backup. Applications have been filed for frequency licensing from bandwidth allocated for experimental space research. The 655 element antenna (0.55 m diameter) is capable of electronically steering the beam up to 60 degrees from the vertical. The steering vector is computed using a startracker and inertial measurements. The downlink transmission is modulated using Nyquist QPSK to band-limit the signal within the allocated frequency range. One rover utilizes right-hand circular polarization which the other uses left-hand to allow both rovers to communicate simultaneously while sharing the same frequency range. Error correction is accomplished via a rate 2/3 turbocode, and the anticipated bit-error-rate is 10^{-6}. Three ground stations with a 22m parabolic antenna are required around the world (US, Russia, Australia) to maintain continuous communication. The transmission is then relayed via satellite to the current control station location. In case of an uplink or downlink failure, that rover can relay its transmission through the other rover by using the inter-rover omnidirectional antennas (broadcasting in the VHF range). The communication system uses 102 W with a mass of 17.7 kg.

1.2.3 Visualization

Three redundant pairs of cameras are used to acquire panoramic imagery. The downward looking pair use 150 degree fish-eye optics on a 1000 x 1000 x 12bit color camera to capture a view of the wheels and their surroundings. Except when needed for maneuvering through difficult terrain, these images will be acquired once every body length (6 seconds on average). The other two pairs are located on the top of the rover at the front and back and are identical in format, with each camera acquiring a 2000 x 2000 x 12bit color image (equivalent of 12 video channels) at 10 frames per second. By using a "pano-sphere" optic (combination of birds-eye mirror and fish-eye optic) the acquired image contains both an overhead view (0 to 70 degrees from the vertical) and a 360 degree panorama (+25 to -60 degrees from the horizontal). All the optics are coated with thin-film diamond to resist scratching or pitting and covered with thin-film gold to allow grounding for dust removal. Merging the images of the front and back cameras (2000 x 1500 from each) provide an unobstructed panorama plus stereo to the right and left. As omnidirectional information is obtained in each frame, any number of viewers can be watching the imagery and choosing where to look. The high dynamic range of the cameras is suitable for the harsh lighting changes on the Moon, and on-board processing is be done to maintain a quality exposure and to compress the dynamic range to the traditional 8 bits/pixel. The cameras require 30 W with a mass of 12 kg.

1.2.4 Computing

The computing electronics are housed in a ruggedized 6 slot 3U-VME cage. Five slots are taken by boards centered around a custom multi-chip-module containing a rad hardened R3000 class processor, interfaces for three rad hardened single-chip multiprocessors with parallel DSP and RISC architecture (such as the TI MVP-C80), the I/O bus with connections for A/D, D/A &PIO, memory for capturing imagery and maintaining state data (2MB EEPROM, 24Mb VRAM, 16MB DRAM), a watchdog function, and connections for ethernet and the RF modem. One of these boards is primarily a backup and is not expected to be used. The extra slot contains a platform for electronics required to capture the raw safeguarding sensor information and send it to a serial output (RS422). The four R3000's perform housekeeping tasks (monitoring power, communication, thermal), actuator and camera control, telemetry/encoding, reading sensors, interpreting incoming commands, and scheduling processes. One of the DSP's is responsible for converting the safeguarding sensor data to range readings. Another handles sensor fusion from the IMU's, startracker, wheel encoders, range maps. Nine DSP's perform wavelet compression of two 2000 x 1500 images at 10 frames per second. The last DSP is left available for contingency, but may be used for image processing such as dynamic range reduction or automatic exposure correction. or compression. Each board requires 42 W, with a computing system total of 197.6 W and a mass of 12.3 kg.

1.2.5 Power

Fourteen Russian plutonium-based general purpose heat sources (GPHS) are linearly stacked and surrounded by 112 alkali metal thermal to electric converters (AMTEC) (8 per GPHS). The 3500 watts of thermal energy produced by the GPHS are converted at 15% efficiency to 525 Watts of electrical power at 24 VDC. The voltage is regulated using a 97% efficient space-qualified, switching, voltage regulator. 60 Watts are utilized for locomotion and the other 465 Watts are converted to 5V, 12V, 15V, etc. (with 85% efficiency) as needed by other components. Due to the inefficiencies in the power regulator and the DC/DC convertors, only 384W make it out to the components, but with a desired 5% system margin, only 364.8 Watts are truly available for components. Twenty 16J cappatteries are used to store energy for special case needs of the locomotion system. The mass of the subsystem is 69.9 kg, with 12 kg of that being used to mount the heavy Pu/AMTEC device.

1.2.6 Thermal

With the plutonium source generating power and heat, even during lunar night the major problem for the rover design is to disperse heat into the lunar environment. The rover is coated with a reflective white epoxy to reduce the heating effects of direct sunlight. Separate radiators are used to control the temperatures of the thermal source (two $0.35m^2$ black-plate panels on each side of the rover operating at 600K) and the electronics compartment (a $1.75m^2$ traditional space radiator on the top of the rover operating at 400K). The radiators are connected to the thermal enclosures via high-conductance heat pipes. The outlying electronics, such as cameras and the phased array, have heat pipe connections to the main electronics compartment, and are maintained at the same temperatures. To thermally control the electronics compartment and thermal source, they are wrapped with a sandwich of carbon aerogel insulation between sheets of 3 layer MLI (kapton sheets). Holes in the enclosures created by heat pipes, cabling, and rivets are sealed using epoxy. The heat pipes, radiators, and phased array are also thermally insulated with the same sandwiching technique. The mass is estimated at 40.6 kg, but the complete specifications of the components are not yet known.

1.2.7 Structure

The base plate of the vehicle is a plate of aluminum honeycomb with five vertical 1/32" aluminum rib plates creating the structural skeleton. To provide further stability, aluminum gussets are used to brace the ribs. The outer framework of the rover which creates the body shape is composed of 3 kapton sheets covered in kevlar. Curving the surface, along with attachment to the structure, is done through the use of epoxy. The rib structures are perforated to reduce weight without degrading strength characteristics. The total mass of the structure is 27 kg.

1.2.8 Safeguarding

To gather range information, micropulse radar is used. 10 Spot sensors cover the bottom of the rover as well as the sides to detect when collisions are imminent. Two arrays of 30 sensors are positioned on the front of the rover. Readings at 40 Hz are integrated over time and coupled with the vehicle motion to generate a local hazard map from 0.1m to 3m. To determine vehicle position with respect to the low-resolution global lunar map, a stellar compass is used. These readings are fused with data from two inertial measurement units (IMU's) and wheel encoders to generate accurate terrain maps and maintain precise dead-reckoning. Further sensors such as thermometers, ammeters, etc. are utilized to monitor the status of the rover itself. Combined, all the sensors require 33 W and are 15 kg.

1.3 Power, Mass, Costing Budgets

The mass constraint for the mission is 600 kg. 50 kg are kept for contingency and 50 kg are reserved for integrating the rovers to the lander, leaving 250 kg for each rover. With 5% of this reserved for system margin, the target weight for each rover is 237.5 kg. With component margins, current mass estimates are: communication 17.7 kg, computing 12.3 kg, visualization/safeguarding 27.0 kg, power 59.3 kg, thermal 40.6 kg, locomotion 54.2 kg, and structure 27.1 kg, for a total of: 238.2 kg.

The generated power is 484 W including 5% system margin and 97% voltage regulator inefficiencies. The locomotion system requires 63 W, which is 70W after 90% amplifier inefficiency, leaving 414 W. Reduced by the 85% DC/DC converter inefficiencies, this leaves 352 W available for components. Communication uses 101.9 W, computing uses 197.6 W, visualization/safeguarding uses 63.6 W for a total of 363.1W. The mass and power budgets broken down by subsystem and components are given in Table 1.2.

The budgeted cost for the rover development is $60M. Current estimates for development and fabrication of 2 flight rovers are: communication $8.4M, computing $2.7M, visualization/safeguarding $7.6M, power $13.1M, thermal $8.0M, locomotion $3.7M, structure $1.3M for a total of $44.8M. With the addition of a 15% management margin and an overhead of 15% for contingency, the total development costs are $59.25M. This number does not include software development, and the thermal/locomotion/structure numbers are quite rough at this time. Cost and potential vendor information is shown in Table 1.3.

TABLE 1.2 *Rover mass and power budget.*

Component (#)		Component Mass (kg)	Support Mass (kg)	Power (W)	Margin Used
GOALS		**250 kg**		**525 W**	
Target including system margin and efficiency losses		**237.5 (250 x .95)**		**70 + 352 (525 x .95 x .97 - 70 loc - .85 x 352 rest)**	**5% system**
TOTAL FOR ONE ROVER		**238.2** **216.3 + 21.9**		**70 loco + 363 other**	
Locomotion		**54.2**		**70W avg**	
Driving Actuators	(6)	18.5	-	variable	13%
Steering Actuators	(4)	9.5	-	variable	13%
Wheels	(6)	11.8	-	-	13%
Chassis and Fenders	(1)	14.4	-	-	13%
Communication		**15.9**	**1.8**	**101.9**	
Phased Array	(1)	12.6	12%	94.5	5%
Transponder	(1)	1.0	12%	5.3	5%
Inter-rover Link	(1)	1.0	12%	1.0	5%
Backup omni Link	(1)	1.1	12%	backup	5%
Multiplexer	(1)	0.1	-	1.0	5%
RF Switching	(3)	0.1	-	0.1	5%
Visualization/Safeguarding		**24.1**	**2.9**	**63.6**	
Pano-sphere Cameras	(4)	7.3	15%	24.0	5%
Under-body Cameras	(2)	3.2	10%	5.4	5%
Stellar Compass	(1)	1.0	10%	0.1	5%
IMU's	(2)	1.1	-	16.8	5%
Impulse Radar	(150)	10.4	12%	11.7	30%
State sensors	(??)	1.1	10%	5.6	13%
Computing		**11.3**	**1.0**	**197.6**	
VME Cage	(1)	3.5	10%	16.2	8%
MCM's	(5)	7.3	10%	181.4	8%
Cabling to Power	(??)	0.5	-	-	8%

TABLE 1.2 *Rover mass and power budget.*

Component (#)		Component Mass (kg)	Support Mass (kg)	Power (W)	Margin Used
Power		**49.2**	**10.1**		
Plutonium GPHS	(14)	21.3	30%		5%
AMTEC	(112)	14.7	20%	15% effic	5%
Power Regulation	(1)	4.3	11%	97% eff	8%
DC/DC Conversion	(10)	1.1	10%	87% eff	8%
Cappatteries	(20)	2.3	10%		13%
Intersubsystem Cabling	(59m)	5.5	-		13%
Thermal		**34.5**	**6.1**		
Radiator	(3)	5.4	20%		8%
Heat Pipe	(??)	14.7	20%		13%
MLI	($100m^2$)	3.4	20%		13%
Carbon Aerogel	(??)	4.2	10%		5%
Joints	(??)	6.8	10%		13%
Structure		**27.1**			
Base	(1)	7.9			13%
Ribs	(5)	10.4			13%
Gussets	(??)	3.2			13%
External Covering	($50m^2$)	5.6			13%

TABLE 1.3 *Rover cost budget and vendor information*

Component (#)		Develop Cost ($M)	Unit Cost of 1 rover ($M)	Total Cost D+2*UC ($M)	Model / Vendor
TARGET COST: ($60M adjusted with 15% management and 15% contingency)				**45.4**	
TOTALS		**13.4**	**15.8**	**45.0**	
Locomotion		**0.8**	**1.45**	**3.7**	
Driving Actuators	(6)	0.2	0.5	1.2	Inland RBE-01512, HD Systems CSF-2A-GR
Steering Actuators	(4)	0.2	0.4	1.0	
Wheels	(6)	0.2	0.3	0.8	CMU fabrication
Chassis	(1)	0.2	0.25	0.7	CMU fabrication
Communication		**3.3**	**2.7**	**8.7**	
Phased Array	(1)	3.2	1.6	6.4	Ball Aerospace
Transponder	(1)	0.1	0.45	1.0	Motorola
Inter-rover Link	(1)	-	0.25	0.5	E-systems
Backup Omni Link	(1)	-	0.25	0.5	E-systems
Multiplexer	(1)	-	0.05	0.1	Loral
RF Switching	(3)	-	0.1	0.2	Loral
Visualization/Safeguarding		**3.95**	**1.825**	**7.6**	
Pano-sphere Cameras	(4)	1.5	0.5	2.5	DALSA, CA-D9
Under-body Cameras	(2)	1.0	0.25	1.5	DALSA, CA-D9
Startracker	(1)	-	0.15	0.3	Lawrence Livermore, STSC
IMU's	(2)	0.1	0.75	1.6	Litton, Honeywell
Impulse Radar	(150)	1.3	0.1	1.5	Lawrence Livermore, MIR
State Sensors	(??)	0.05	0.075	0.2	-
Computing		**1.55**	**0.575**	**2.7**	
VME Cage	(1)	0.1	0.2	0.5	-
MCM's/Rad hardened C80	(5)	1.4	0.3	2.0	TI, MVP-C80; Harris, RH3000
Cabling to Power	(??)	0.05	0.075	0.2	-

TABLE 1.3 *Rover cost budget and vendor information*

Component (#)		Develop Cost ($M)	Unit Cost of 1 rover ($M)	Total Cost D+2*UC ($M)	Model / Vendor
Power		**2.6**	**5.2**	**13.0**	
Plutonium GPHS	(14)	1.0	2.0	5.0	Lavochkin Institute
Thermo-Electric Conv	(112)	1.0	2.0	5.0	AMPS,
Power Regulator	(1)	0.4	0.4	1.2	Matra Marconi, INMARSAT
DC/DC Conversion	(10)	0.1	0.35	0.8	Interpoint, MHP270
Cappatteries	(20)	0.1	0.2	0.5	Evans, Cappatery
Intersubsystem Cabling	(59m)	-	0.25	0.5	-
Thermal		**0.8**	**3.6**	**8.0**	
Radiator	(3)	0.2	0.9	2.0	????
Heat Pipe	(??)	0.2	0.8	1.8	Noren Products
MLI	($100m^2$)	0.1	0.3	0.7	Thermo Electron Technologys Corp
Carbon Aerogel	(??)	0.1	1.45	3.0	BMDO/JPL
Joints	(??)	0.2	0.15	0.5	-
Structure		**0.4**	**0.45**	**1.3**	
Base	(1)	0.1	0.15	0.4	Hexcel
Ribs	(5)	0.06	0.05	0.16	CMU Fabrication
Gussets	(??)	0.04	0.03	0.1	CMU Fabrication
External Covering	($50m^2$)	0.1	0.12	0.34	DuPont, Thermo Electron Tech. Corp
Pyrotechnic Disconnects	(6)	0.1	0.1	0.3	

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Mission Description

The LRI proposes a two year, 1000km traverse of robotic vehicles to visit historic sites on the Moon, while returning a rich, panoramic video stream in real time, for the purposes of entertainment and education. The Moon is a suitable target for current mobile robotics technology due to its environment and relationship to Earth. The traverse starts near the Apollo 11 landing site of Tranquility Base, proceeds by the impact crater of Ranger 5 and landing spot of Surveyor 8, ascends into the lunar highlands by the Apollo 17 site and ends with a quest for the gravesite of the Soviet Lunokhod 2 rover. Both rovers are in continual communication with earth, and alternate between the roles of explorer and observer. The rovers are delivered to the Moon via a Proton launch vehicle and Phobos lander. The $200 Million mission is planned for launch around June 1999, depending upon the timing of commercial funding influx.

2.1 Motivation and Purpose

Nearly a quarter century has elapsed since the last lunar landing, and the Moon remains an exotic world. Aspirations to retrace the footsteps of the Apollo missions and its astronauts have yet to succeed. The LRI proposes a robotic lunar mission to give the experience of exploring the Moon to millions of interested people through live tele-experience. With enormous launch costs and restrictive launch vehicles the primary barriers to viable space enterprise, it will be years before sustained human presence in space becomes commercially viable. Meanwhile, space activity can be expanded through robotic devices which generate commercial enthusiasm by performing novel or cost saving tasks like satellite repair or planetary exploration. Future generations of robotic devices can lay the groundwork and construct habitations for human presence.

Traversing the Moon is within reach of current mobile robot technology. The surface is stable and barren, which suits current perception and navigation systems. A direct line of sight between the lunar near-side and the Earth is always available for maintaining communication. Without a filtering atmosphere or clients, sunlight is a rich and guaranteed power source. Low radiation levels make usage of state-of-the-art computing and electronics possible. The low time delay between Earth and the Moon makes real-time human interaction and remote operations possible.

Unlike traditional space exploration missions, which have been concerned primarily with science, the LRI mission focuses on edutainment. With the transmission of live panoramic video, participants will be provided the opportunity for interactively exploring the Moon. Participants include visitors to theme parks or science centers, TV viewers, school kids, and internet surfers. These visitors will be immersed in a live lunar telepresence previously had only by heroes of the Apollo program who set foot on the Moon. Customers of the mission include theme parks, marketing firms, TV networks and scientists. Together with state-of-the-art robotics technology, these customers will bring lunar exploration, experience and science to the masses.

success criteria and mission objectives

The mission will be considered a success if the following four criteria are met:

1. Both rovers are on the lunar surface and operational on December 31, 1999.
2. Imagery of both Apollo landing sites are returned which enable these sites to be reconstructed in 3D.
3. One rover reaches the Lunokhod 2 vehicle and returns imagery of the find.
4. One rover is fully operational on its second anniversary of landing on the Moon.

The mission objectives are to: return imagery of the moon and the rover state date, capture views of the rover crossing the lunar landscape, allow teleoperation from earth by amateurs, and to support educational exploration. The imagery and state data must be sufficient to enable "tele-experience" rides at a theme park. The views of the rover crossing the lunar landscape could be captured from above, otherwise an off-board camera must be available. Amateur use of the rover implies random theme park customers as well as the educational and scientific community who are not familiar with robotic vehicles. A portion of the rover time will be set aside to pursue educational and scientific opportunities. While no specific science payload is carried, significant exploration can be achieved through the imagery itself.

2.2 Route Specification and Operating Scenario

The traversal route is designed to visit five historic sites over a two year period. In addition, interesting geological features are visited along the way to increase the overall quality of the product and value of the mission for education and science. Performing the traverse are two identical rovers which operate continuously. Although both rovers can be teleoperated simultaneously, the primary mode of operation is to have one rover observing while its partner explores.

2.2.1 Traversal Route and Timeline

The mission route is designed to visit historic sites which are remembered and cherished by adults world-wide. Both manned and unmanned landing sites and both U.S. and Soviet sites are included in the tour. The route also should instill excitement and suspense, especially regarding the uncertainty of when a site will be first visited, and if the rovers will survive to discover the Soviet Lunokhod 2 vehicle. Visiting pre-Apollo sites allow for explanation and education regarding the early years of the lunar exploration program. The coordinates of the historic sites are shown in Table 2.1 and the traversal route is shown in Figure 2.1.

TABLE 2.1 *Lunar coordinates of historic sites on the traversal route*

Historic Site	Longitude	Latitude
Apollo 11	24.0° East	0.8° North
Surveyor 5	22.1° East	1.5° North
Ranger 8	24.9° East	3.4° North
Apollo 17	30.2° East	19.6° North
Lunokhod 2	30.4° East	27.0° North

The rovers will land during the lunar morning in the Sea of Tranquility within 20 km to 30 km of Tranquility Base, the Apollo 11 site. Following an initial check-out period of several Earth days, the rovers will leave their landing site, and venture toward the Apollo 11 site. Arrival will occur during the afternoon on the same lunar day in which the rovers landed. This ensures that a usable product is acquired (imagery and terrain maps of the Apollo 11 site) even in the event of catastrophic failures during the rover's first lunar night. This historic landing spot of the Eagle is remembered as a fulfillment of the spirit of exploration, and is considered to be one of the greatest achievements of the American space program.

Leaving Apollo 11 after about a month of exploring and mapping, the route will offer two segments, each less than 100 km, to the Ranger 8 and Surveyor 5 sites; two important missions which enabled successful manned Apollo landings. Each segment will take about three Earth weeks of travel and three weeks of exploring around the site gathering imagery from many different angles. These visits will allow successive media events to which will increase the public interest in the mission as the rovers begin the long traverse north.

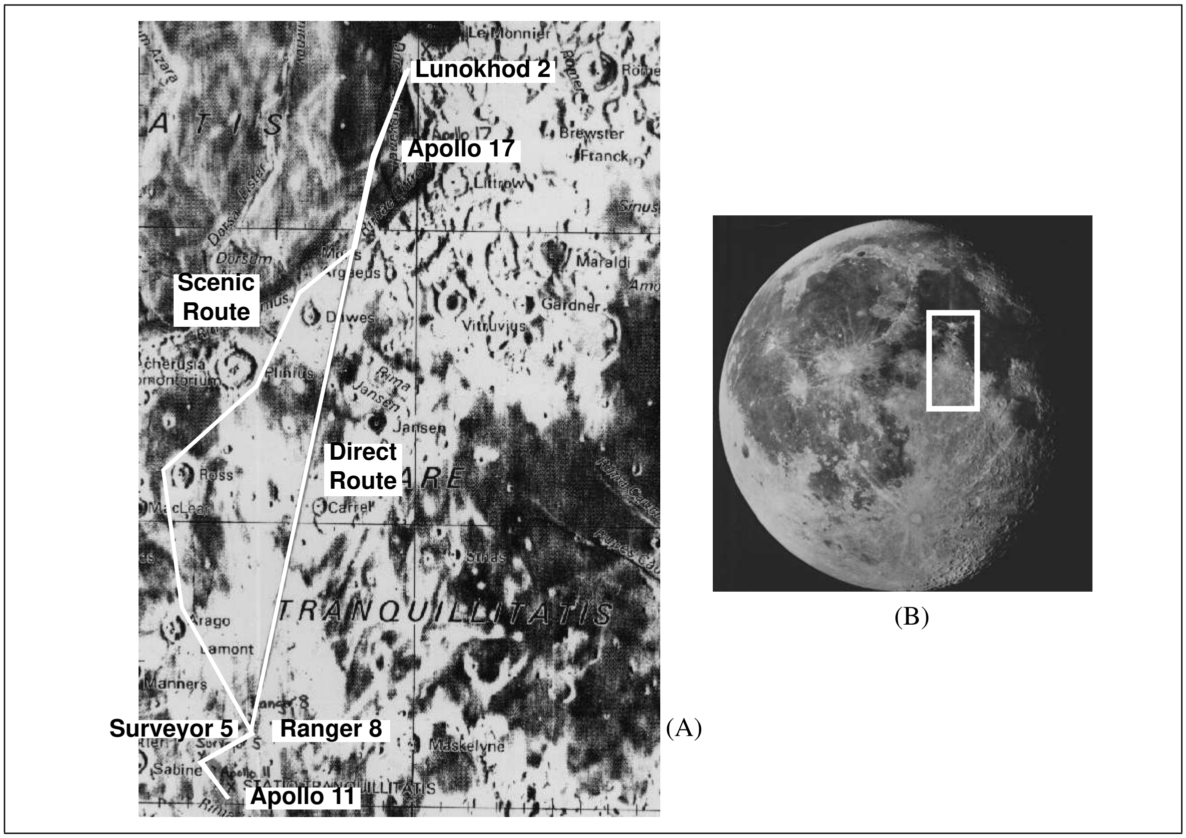

FIGURE 2.1 *(A) Traversal route and historic sites (B) Location of route on Lunar near side.*

As the terrain in the Sea of Tranquility is fairly devoid of features, and might not be interesting enough to maintain the public interest, the rovers will take a scenic route north which passes near to the large craters of Arago, Ross, Plinius, and Dawes while skirting the border between the Seas of Tranquility and Serenity. The trek to each crater is roughly 150 km and will take two months. Additional time (about three months total) will be spent along the way to examine the ejecta and other interesting geological features. Although the treks to the craters will be exciting, arrival is not anticipated to generate an extreme media event.

After leaving Dawes, the rovers move into the lunar highlands and pass Vitruvius crater on their way toward Littrow crater and the site of Apollo 17, America's final manned lunar mission. This trek of nearly 150 km will take considerably longer (about three months) with one month spent exploring features in the highlands. At Apollo 17, about one and a half months will be spent exploring and gathering imagery since the astronauts could venture further with their Lunar Roving Vehicle (LRV) than their walking Apollo 11 predecessors. The return to Apollo 17 is again expected to capture mass attention and interest.

Finally, the mission will offer a quest to discover the landing site and trail of the Soviet Lunokhod 2 unmanned vehicle, by again heading northward for about 200 km. This trip is again over rough terrain, and will last nearly four months. Once the landing site or the tracks are intersected, the rovers will follow them to find the Lunokhod vehicle (about a half month since the Lunokhod only traveled 50 km). The predecessors of this rover, as they are the only telerobotic vehicles to have operated on the Moon. Because the exact location where Lunokhod became mired in a crater and failed is unknown, the possibility that Lunokhod's trail will end just over the next horizon will likely maintain a high interest and media attention. Furthermore, the arrival at Lunokhod 2 will occur nearly 24 months after landing, and means the complete success of the mission.

After completing the planned traverse, the rovers will continue to explore interesting sites until catastrophic failure occurs. With the mission successfully completed, slightly higher risks can be taken, resulting in traversals of more extreme terrain and more impressive video return. Possible continuation targets are the Taurus Mountains and the huge crater of Posidonius 500 km to the north or the Haemus Mountains and the Apennines about a 1000 km to the west.

2.2.2 Operating Scenario

The operating scenario of the mission is comprised of three major decisions: number of rovers, times of operation, and qualification of the driver. With the large mass which can be delivered to the lunar surface by the Proton Rocket (600kg) it is possible to send one, two, or three rovers. The use of a radioactive heat/energy source and orthogonal polarization of the communication downlink allows both rovers to operate continuously during both lunar night and day. The safeguarding required to enable operation of the rover while experiencing a five second time delay makes safe operation of the rover possible by an amateur driver.

Further rationale for two rovers is increased reliability. Two rovers increase the reliability of the overall system in many ways. In the case of a catastrophic failure caused by terrain or micrometeorite damage, two rovers doubles the reliability. Two rovers also increase the reliability in the case of a randomly malfunctioning part. As long as the malfunction isn't caused by environmental effects or faulty design, two rovers again mean increased reliability. Lastly, having two rovers on the moon allows cooperation between the rovers. If a rover gets stuck in soft soil or becomes high-centered, the second rover can attempt to free the first rover from its problem.

Two rovers have significant advantage over one rover in completing the mission requirements, and three rovers actually make the design process more difficult. Capturing video of the rover crossing the lunar landscape is trivial from a stationary second rover as compared to a deployable camera platform which must be continually placed and retrieved to gather off-board footage. To cross the lunar terrain, a minimum locomotion capability is needed, and with three rovers, the reduction in mass would have to come from the vehicle payload, resulting in reduced product.

Since the rovers are not dependent upon solar energy for power, night operations is feasible. The excess heat generated by the radioactive thermal source makes surviving the cold of lunar night a straightforward task. Also, with constant power generation, there are no batteries to recharge and each rover can operate 100% of the time rather than being forced to a 50% charge/explore duty cycle. Since right and left circular polarization can be utilized on the downlink transmission, it is possible for both rovers to simultaneously use the allocated bandwidth. This allows double the video product to be returned as compared to splitting the bandwidth between the two rovers, and allows each rover to utilize a 100% duty cycle rather than being forced to wait for each other in if the bandwidth is time-shared. Although both rovers can be teleoperated simultaneously, the primary mode of operation is to have one rover observe while its partner explores.

To complete the mission, a simple and robust interface is required to prevent a fatigue induced accidental human error from damaging the rover. With such an interface in place, it is possible to allow anyone to operate the vehicle regardless of their prior experience with robotic teleoperation. With an amateur operator at the helm, both the rover safeguarding and a trained driver will provide assistance and feedback. During critical maneuvers the vehicle will be controlled by the trained driver using lower-level motor commands. In the case of an extreme situation, the rover safeguarding can be overridden by the trained driver.

2.3 Launch and Landing

The rovers will be delivered to the Moon through the use of a Proton launch vehicle and compatible Phobos lander. While alternative launch and landing possibilities exist, none have the believability and payload/cost ratio of the Proton/Phobos combination. The launch will occur from Russia during the late spring/early summer of 1999. Integration to the lander will be done in Russia, and the rovers will be deployed by anchoring the rovers vertically during flight, and then lowering the anchor platforms (i.e. ramps) for the rovers to drive away.

launch and landing specifications

The decision to use the Russian Proton C Launch Vehicle was based on the cost and its large payload capacity as well as the availability of a lunar lander design. In addition to size constraints that are dictated solely by the payload volume available above the lander, the loads felt by the rover in the launch vehicle will exceed any loads applied to the rover while operating on the moon. These loads are detailed in Table 2.2. The launch vehicle is shown in Figure 3.1. The Proton has a 0.8777 reliability over its 187 mission career, and it has gone 31 launches since the last failure. The fairing envelop is 3.3 m in diameter with a length of 4.2 to 7.5 m.

TABLE 2.2 *Launch Vehicle Characteristics-Proton C*

Property	Value
Mass to LEO, 51.6° inclination	20,000 kg
Max. Axial Acceleration	+6 gravities
Max. Lateral Acceleration	+/- 3 g
Fundamental Frequency	30Hz axial, 15Hz lateral
Vibration Spectrum	0.05 g^2/Hz max: 20 -> 2000 Hz
Frequency Spectrum	135 dB max: 20 -> 2000 Hz
Shock from explosive nut separation system	2500 g @ 1700 Hz 6000 g @ 5500 Hz
Shock from payload separation	4000 g max @ 2000 -> 6000 Hz
Cleanliness	Class 100,000

The Russian Phobos lander was chosen for similar reasons as the Proton Launch Vehicle. The design is baselined for the joint NASA/Russian Mars 96 mission, and should not be difficult to adapt for a lunar mission. The lander can deliver a total payload, including adaptor, of 600kg to the moon. The lander loads are lower than the launch loads, and are not design drivers. The lander can deliver the payload to within approximately 4.3 km of the designated landing location with a standard circular error probability (CEP). The lander characteristics are detailed in Table 2.3. The lander is shown from a side-view along with the Proton fairing in Figure 3.1, and from a top-view in Figure 3.2.

TABLE 2.3 *Lander Characteristics-Phobos Lander*

Property	Value
Mass to Lunar Surface	600 kg
Max. Landing Position Error	4.3 km
Max. Landing Velocity	2 m/s vertical 1.2 m/s horizontal
Payload Center of Gravity Height	< 1 m
Deployment Ramp Angle	30°

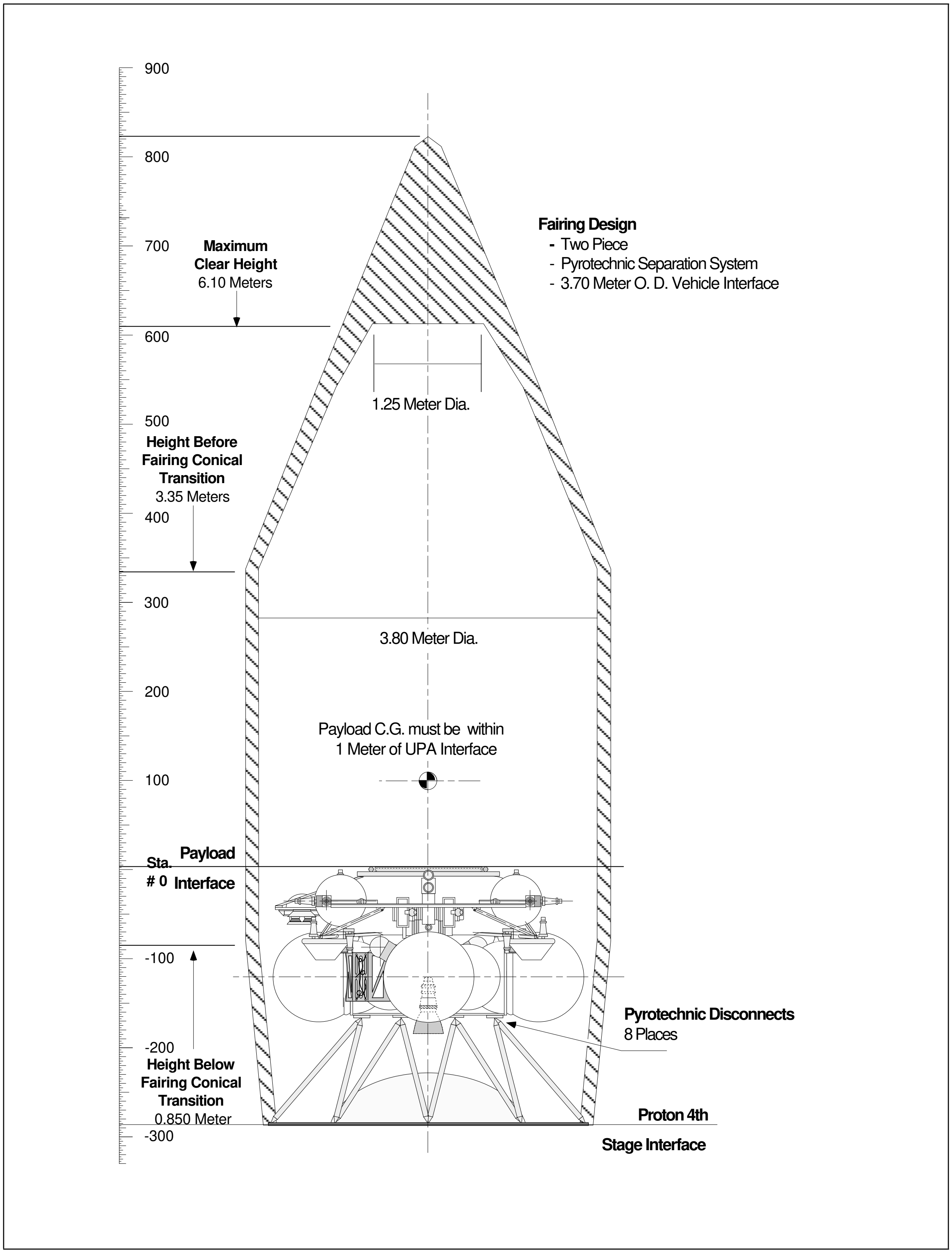

FIGURE 3.1 *Proton Launch Vehicle With Phobos Lander-Cross Section*

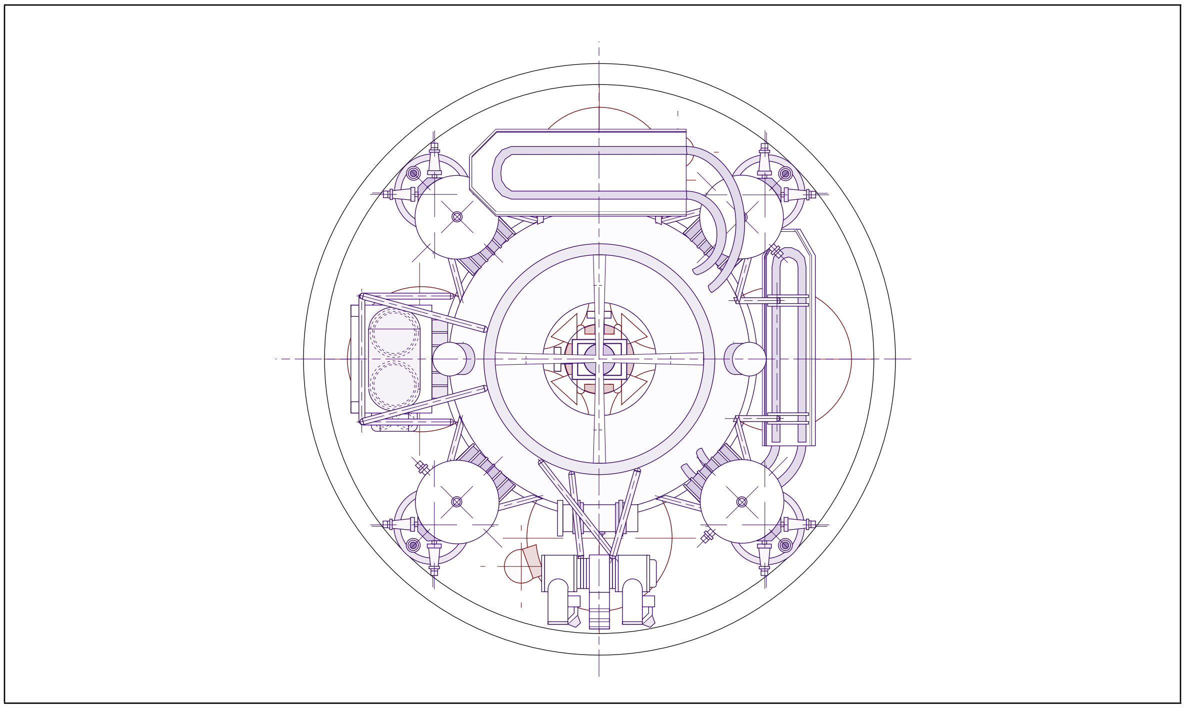

FIGURE 3.2 *Proton Launch Vehicle With Phobos Lander-Top View*

rover/lander integration

The current design of integration and deployment consists of placing the two rovers vertically with their tops facing each other and their fronts pointing up. The rovers are supported by pyrotechnic bolts which hold the pivots where the rocker bogie is connected to the body. The back end of the rover is supported by a pedestal at the point where the averaging linkage connects to the body. An insulation wall will be erected between the two rovers to prevent the radiators on the tops of the rovers from seeing each other. A large flexible collar will be gathered around the rovers while the fairing is in place, and serve to prevent dust from being kicked up onto the rovers by the landing. The wheels of each rover are attached to ramps which are held together in the vertical position by pyrotechnic bolts. Once the lander has reached the surface, this bolt will be discharged and the ramps will lower to the surface by pivoting about a hinge at the bottom of the ramp, and the rovers will drive down the ramps, which are depressing the flexible collar, onto the lunar surface.

legal issues

Launching the rovers from Russia creates several legal issues which must be resolved. While the cold-war has ended and US-Russia relations are improving, the export of advanced technology from the US is still controlled. This increases bureaucratic overhead since government monitoring is likely to required each time the rover is opened to make adjustments prior to launch. As the rovers are flying Russian plutonium heat sources, the power system must be integrated to the rover in Russia since it is not possible to import the radioactive material to the US. The launch contracts with the Russians would include a guarantee of a second launch in the event that the first lander fails to make a successful landing.

2.4 Programmatics

Getting the rovers to the moon involves significantly more behind the scenes work than just placing the rovers on the Phobos lander and counting down to launch. $200 Million (M) is needed to make the mission happen.

At least three and a half years are required before the launch occurs. As technological and component development is needed before the rovers can be assembled, all budgets must be margined to account for the unknown. Lastly, attention must be paid to lead-times required for component development, legal resolution, etc. to make sure the mission will stay on track.

costing and development timeline

The complete mission costs are estimated at $200 M. $60 M for rover development covers development of components, environmental testing, software development, system integration, the transport of the rovers to Russia and subsequent integration, and personnel costs. This may be reduced by the involvement and partnership of component suppliers in the LRI. The quoted figures for a Proton launch and production of the Phobos lander is $80 M. While the majority of the costs for developing display environments of the mission product fall to the actual customers, $20 M is needed to cover the creation of ground stations around the globe (3 needed for 24 hour line of sight to the Moon), leasing satellite relays for 2 years, employing personnel to assist in the operation of the rover, and construction of a demonstration model operator interface and display environment. Before the rovers arrive on the lunar surface, marketing and coordination of the media events must be underway, and $10 M is allocated for this purpose. $10 M is required for insurance and risk mitigation and $20 M are reserved for contingency.

Following the September 1995 PDR, the terrestrial demonstration will occur in May 1997. This NASA funded program is expected to demonstrate the suitability of the key components for the mission by testing them on a 1000km traverse over lunar-analog terrain such as the American Southwest or Australian Outback. With the commitment of commercial funding for the mission, the Critical Design Review would then be scheduled for July 1997. The CDR presents the complete system design in full detail, ascertains that all technical problems have been resolved, and ensures the design maturity justifies the decision to initiate fabrication, integration, and verification of hardware and software.

With approval at this time, component ordering begins, along with the construction of the engineering mock-up, software verification and subsystem integration. The deadline for delivered, tested, and accepted components would be September 1998. After the final US system testing and preliminary acceptance, the rovers would be ready for shipment to Russia in December 1998. Integrating the power system and performing final systems evaluations would last three months, being completed by February 1999. The final series of acceptance testing would be completed in March 1999. After three months of lander integration, launch can occur in June 1999. This allows one month of slippage in the schedule to still be at Apollo 11 on its 30th anniversary, and six months of slippage to still be on the moon for New Years, 1999.

margins and lead times

Because many design details are not known at this time, margin percentages are added to each component based on the level of technological maturity and overall risk. The contingency factors used in the design are shown in and are based on the NASA-approved contingency numbers. These margins were used for both mass and power figures. In addition to the subsystem contingencies, a system wide contingency was also added to account for any mechanisms which were overlooked.

Contingency values are also based on the criticality of the component. For example, a high contingency is placed on the AMTEC cells. Not only are they still in the development stage, but if the power system was to not deliver the expected power, the mission would have to be altered or aborted. Similarly, the items that drive the mass budget have a high contingency.

The development timeline allows fourteen months between the CDR and the component acceptance deadline. However, there are several items which have longer lead-times. The development of the X-band phased array is likely a 24 month process. Development of high-resolution, rad-hardened color digital cameras with panosphere optics is an 18 month process. Assembling the components for the computing board and creating the

TABLE 2.4 *Mass Margin Details*

Design Maturity	Contingency	
	Mechanical/ Structural	**Electrical Components**
Conceptual Design	30%	30%
Similar Hardware	13%	13%
Prototype Hardware	8%	8%
Actual Hardware	5%	5%
System Margin	5%	5%

MCM is also an 18 month process. Reducing the Micropower Impulse Radar processing electronics to a single chip requires over 16 months.

In addition to components requiring development leadtimes, there are actual programmatic lead-times. Setting a launch date, and readying the launch vehicle and lander must be started about three years before the intended launch. Gaining access to environmental testing facilities must occur months in advance of the actual testing. Performing searches to obtain qualified personnel must be done in advance to give people time to transition onto the project.

3

Requirements and Drivers

The requirements governing the LRI mission fall into four categories. Customer/Mission based requirements are those requested by the customer or needed for the mission to succeed. Environment based requirements are those which exist as a result of operating on the Moon. Launch/Landing constraints are requirements on the rovers due to the limitations or characteristics of the launch vehicle and lander. Sociological constraints are requirements which stem from having a high profile mission to visit historic lunar sites.

3.1 Customer/Mission Requirements

In the process of selling the mission to commercial sponsors, certain ideas have been promised and are now expected by the customers. The main driving requirements are to deliver a significant exploration capability and achieve a return on investment. One of the main attractions of the mission is the potential for amateur operators to control the rovers. The product returned from the rovers has to be extraordinary for the rovers to be a valuable commodity. Lastly, the stated mission must meet the programmatic constraints.

The intention of the mission is to involve mass audiences in the exploration tele-experience of the Moon, and to achieve this commercially, the mission must generate a return on investment. The delivered experience must encourage repeat business from the audience members, and so the mission must last for an extended duration (proposed as two years). The rovers must also be operational continuously (over 90% rover availability) regardless of time of day, to maximize global participation in exploration, and irrespective of the lunar cycle. This means that operation during both the lunar day and lunar night is of significant advantage and value.

For amateurs to operate the rovers on a consistent basis, the rover must posses extremely capable safeguarding to protect against human error, unforeseen events or deliberate operator mischief. The five second time delay, which is frustrating in a direct teleoperation scenario, must be turned into a selling point of the experience so that the overall driving experience is positive and receives good reviews. The use of semi-autonomous navigation strategies, such as way-point control where the driver chooses a destination point rather than immediate speed and velocity inputs, is expected to be the primary mode of teleoperation. Also, since others will be attempting to enjoy the exploration while an amateur is driving, the interface must be such that progress is made and the experience of the observers also garners positive reviews.

The promised product is high-quality color panoramic video. For this to be truly enticing, the resolution, exposure and framerate must be as good or better than that available on television or laserdisc. To convey the experience of exploration, the video must be processed and displayed in real time. The ability to extract a terrain map of the rover's path as well as of the historic sites is extremely important for generating virtual reality rides and for educational analysis of the mission.

The mission itself must succeed and this means that the rovers must be able to complete their planned route. The locomotion system must be capable enough to prevent getting mired in a crater and to prevent the need for continual backtracking amongst a maze of "barriers". To locate the historic sites, accurate positioning on the lunar surface is required. The rover must be highly reliable, and while ingle point failures are expected, performance should not degrade significantly. As a result, even multiple failures will result in gradual degradation of performance rather than ending the mission.

3.2 Environmental Requirements

Although the lunar environment is highly appropriate for mobile robotic technology due to its barren terrain and freedom from atmospheric effects, it does present some challenges to rover design. The thermal conditions transition between extremes of lunar noon and lunar pre-dawn. The ambient radiation is similar to conditions found in low-earth-orbit. The extremely fine lunar dust creates hazards as an abrasive and as soft and slippery soil. The main features of the lunar environment and their effects on the rover are shown in Table 3.1.

TABLE 3.1 *Lunar Environment and Effects*

Environment	Effects
Dust	Surface Coating Abrasion of Mechanical Components
Radiation	Single Event Upsets Optical Coating Degradation
Vacuum	UV Degradation Outgassing
Thermal	Vehicle Heating
Terrain	Terrainability Trap Vehicle
Micrometeorite	Impact Damage
Sun Earth Moon Geometry	Long Day/Night Cycle Fixed View of Earth

The thermal environment around the rover consists of direct solar flux, reflected lunar albedo flux, and direct infrared radiation direct from the lunar surface. The maximum solar flux on the Moon during lunar daytime is 1358W/m^2. The mean lunar surface temperatures during day are 107C (130C max) and during night are -153C (-180C min). Electronics cannot operate at these extremes, and so they must always be thermally insulated from the environment. Components which must be in contact with the environment (cameras, radiators, phased array, wheels) must have individualized thermal regulation solutions to maintain operability. The thermal design of the wheel is of considerable difficulty since while rolling in and out of shadows and over different terrain compositions it will experience continual changes in the external contact temperature.

The radiation experienced on the lunar surface is a large amount of low-energy solar wind particles, smaller amounts of high-energy galactic cosmic rays, and occasional intense particle bursts emitted by solar flares as detailed in Table 3.2. Soft x-rays and ultraviolet light are also present in significant quantities. Solar wind particles are the most numerous of the radiation striking the rover, but are of less concern than the other fluxes. Solar flare fluxes can last from several hours to several days and emit a large number of high-energy particles. These particles can damage the rover's structural integrity and electronic components. Especially damaging is their ability to ionize optical materials and create defects throughout the bulk of the materials. Galactic cosmic rays are infrequent, but their high energy can damage electrical components. A single particle can cause component failure through energy transfer and elastic/inelastic scattering. The soft x-rays and UV rays are sufficiently energetic to induce defects in optical materials and can cause darkening throughout shallow depths.

Due to its unusual properties, lunar dust is expected to be problematic. The particles are very fine and highly abrasive, and will erode bearings, gears, and other mechanisms which are improperly sealed. Lunar dust also carries an electrostatic charge which enables it to cling to all non-grounded conductive surfaces. The

TABLE 3.2 *Major Types of Radiation in Lunar Environment*

Type	Solar Wind	Solar Cosmic Rays	Galactic Cosmic Rays
Nuclei Energies	~0.3-3 keV/u*	~1 to > 100 MeV/u	~0.1 to > 10 GeV/u
Electron Energies	~1-100 eV	<0.1 to 1 MeV	~0.1 to >10 GeV/u
Fluxes (protons/cm^2sec)	~3 × 10^8	~0- 10^6 †	~2-4

* eV/u = electron volts per nucleon

† Short-term SCR fluxes above 10 MeV. Flux above 10 MeV as averaged over ~1 m.y. is ~100 protons/cm^2sec

accumulation of dust on optics and radiators is a concern since even a few grains could increase stray light scattering onto the image. A thin layer of dust on the thermal radiators is unlikely to cause problems, but thicker accumulations will degrade the radiator performance to the point of failure. The dominant source of dust being lifted from the surface is the rover interaction with the soil. However, without atmospheric effects, the path of lifted dust is nearly parabolic and falls back to the moon fairly quickly.

3.3 Launch/Landing Constraints

Although other launch vehicles are possible, the Russian Proton C launch vehicle is the preferred choice due to low cost, availability, large payload capacity (mass and volume), successful flight history, and the availability of a compatible lander design. In addition to size constraints dictated by the payload volume available above the lander, the loads felt by the rovers during the launch process will exceed any load achieved while operating on the Moon. While earlier Proton launches to the Moon utilized the less constraining Luna lander, the Phobos lander is well analyzed, believable, and available. For the LRI mission, the deployment strategy and launch integration issues need to be addressed.

The launch vehicle imparts 6 g's of axial acceleration and 3 g's of lateral acceleration during the lift-off and stage separations. The worst vibration occurs in the low frequency range (1500-5000 Hz) and is approximately 2500 g's.

The deliverable payload of the Proton/Phobos combination to the lunar surface is 600kg. Some of this mass must go toward designing the attachment and deployment strategy, and so each rover must be less than 265kg. The usable diameter inside the payload fairing is 3.8meters. The lander loads are less than the launch loads, and thus are not drivers. The accuracy of the lander is approximately 4.5km CEP error from the intended lunar coordinates. The maximum landing velocity is 2m/s vertical and 1.2m/s horizontal. The center of gravity of the payload is expected to be within 1m of the universal payload adapter interface, but this constraint can be mitigated by adjusting the lander.

3.4 Sociological Issues

In addition to the technical constraints, some of the design drivers are more intangible. Many people express concern about a commercial lunar mission for fear of the tarnishing the memory of the Apollo missions. Even if the mission is a complete technical success, the aesthetics and apparent personality of the rovers are important for creating the appropriate mood surrounding the project. Positive relations with foreign nations must be maintained if the interest in the project is to grow outside the US.

While mapping and investigating the historic sites on the mission traversal route, it is extremely important not to alter these sites. Many positive memories exist of the Apollo landings, and with the mission occurring near the 30th anniversary of these events, were the LRI rovers to damage this history, it could create enough adverse publicity to jeopardize the entire mission. In the same vein, turning the mission into an opportunity to leave advertising logos or operator initials or other graffiti on the lunar surface may generate antipathy towards the mission.

Selling the journey and the LRI mission to the mass audiences will be significantly easier if the rovers themselves are interesting. A vehicle which appears to be alive and intelligent is much more interesting to interact with than a simple tool. Amateur drivers will also likely be less offended and frustrated and more involved and committed if the rover itself is offering driving tips and route suggestions. Giving the rovers a personality with a voice, name, and unique appearance makes them interesting for interactive experiences like theme park rides, educational programs, etc.

To simplify the pointing requirements of the communication system, the transmitted beam of returned imagery is sized to cover the entire earth. With the 24hour continual operation of the mission, this implies that the X band frequencies of every nation in the world will be interfered with by the low-level rover broadcasts. As a result, the allocation of frequencies must be accomplished not just from the FCC, but from the analogous international licensing agency, ITU.

4

Risks, Open Issues and Future Work

For the LRI to reach the level of a Critical Design Review (CDR) several risks must be addressed, and significant design and development must occur. There are several risks at the mission level, which could alter the overall requirements as well as the programmatics. In addition, there are open technical issues which have yet to be addressed with in-depth analysis and testing.

4.1 Mission Risks

To realistically have a chance of being operational from the lunar surface on December 31, 1999 the influx of commercial funding must begin by Spring 1996. With this date only six months away, and funding from entertainment-based corporations not yet achieved, it is possible that government funding, in the form of a Discovery Proposal for example, could be won for a mission occurring after 2000. If the commitment to launch is not obtained in the next few months for the edutainment mission, a refocusing of the mission goals could be in order.

In order to achieve operation during the lunar night, radioactive thermal sources were added. The use of radioactives had previously been frowned upon by the LRI due to fear of possible notoriety and activism against the customers. However, the use of radioactives is the only known way to generate power during the 14 Earth day lunar night. Without this power, the rovers must hibernate until daybreak and the customer is left without a “live tele-experience” for two weeks out of every month. It remains an open issue whether the customers object to the rovers carrying radioactives.

With the influx of commercial funding, the design freeze must be achieved no later than Summer 1996 to allow for the fabrication of long-lead-time components. This means that vendors and components must be identified before the terrestrial traverse demonstrations are completed. Without the opportunity to test the configuration performance, a choice must be made between the trade-off of low-risk and high-performance.

Once components are identified, significant testing is required to achieve believability for the lunar environment over the mission duration. Such tests include vacuum, temperature, radiation, and shock for components, assemblies, subsystems, and finally the entire vehicle. Access to NASA test facilities is expected at this time, although scheduling and cost could result in failing to hold the testing portion of the development budget to initial specifications. In addition, CMU members of the LRI are not familiar with space operations, and deciding what tests to perform, on what components, how many times, etc. are issues for which experts will have to be found.

With launch and integration occurring in Russia, a primary risk is the legal issue regarding the exporting of advanced technology. Not enough is known about such issues at this time to truly understand how much lead time is required to settle this issue. This naive assumption that the post cold-war environment has lessened the bureaucracy surrounding US/Russia relations should be evaluated more deeply. In addition, the accessibility of Russia facilities is dependent upon continued amicable US/Russia relations, which is certainly not yet an obvious and predictable state.

At this time, there is very little customer feedback into the design process. Once commercial resources are obtained, it is likely that customer ideas will be suggested into the design process. Knowing how to address these issues, and understanding the effects of change (for example, adding a manipulator arm to the vehicle or carrying a 15kg science payload) will be required if the project is to remain on schedule.

4.2 Technical Issues

The thermal survivability of the locomotion subsystem, and especially the wheel design, is still without a true solution. Since the wheels are separated from any thermal enclosure and since the wheel is in contact with the lunar surface (150C to -180C range) keeping the wheel actuator at a viable equilibrium temperature requires an innovative solution.

While the communication subsystem is fairly well developed, the major risk is still the licensing of uplink and downlink frequencies. Current plans are to utilize bands allocated for space research, however with these bands reserved for government use and the mission being primarily commercially funded there is a potential conflict. The allocated frequency is required to proceed with a believable mission, but may require a funded mission to obtain.

Assuming the locomotion system can handle the extreme low temperatures during night operations, the imagery system must be able to return usable imagery during that time. Early research indicates that the Earthshine will be sufficient during 10 of the 14 night time days, and that image intensifiers might be needed for the four days during lunar dawn and dusk. Deeper understanding of the lunar lighting conditions as well as the camera capabilities are required to resolve these issues.

Displaying 360 degree imagery to large audiences has generally been done in the past using a circular array of CRT style projectors. It is possible that the resolution allowed by the compression scheme will be insufficient to appear visually impressive when projected onto a large screen due to pixel visibility. For small audiences, creating a motion platform/display system which fits within the budget could be difficult. Understanding exactly what the LRI development must provide in terms of displays must be resolved soon.

Direct teleoperation (controlling speed and direction) while experiencing a five second time delay is known to be difficult and frustrating. At this time, waypoint navigation is the operator interface method of choice, but this method must be evaluated in terms of excitement and enjoyment along with overall performance to decide whether it is suitable as the base operational scenario for amateur drivers.

Twelve DSP's are currently specified to compress the panoramic imagery using the MPEG 1 standard. As a result, the computing system accounts for almost half the total rover power budget. Unfortunately, the amount of raw imagery which this compresses does not take advantage of the resolution captured by the cameras. Wavelet and fractal methods are being investigated, but so far no algorithms have been found which are a significant improvement. Without such a significant improvement, the mission is in jeopardy of failing to return high-quality panoramic video.

Due to the demands of the computing/compression system, the power required by the rover is over 500W. Through the use of 14 Plutonium-based general purpose heat sources (GPHS) and AMTEC thermo-electric conversion, the required power is generated. At the conservative efficiency of 15% heat->energy conversion, the rover does not have enough power. However, at the expected efficiency of 18% heat->energy conversion, the rover has a surplus. Other power gains could be achieved if the DC/DC conversion could be made more efficient, or if power to the computing and locomotion subsystems could be directly provided by the power regulator.

Although heat pipes have considerable flight history in space, the current design involves extremely high temperatures. It is not known whether a heat-pipe can survive the 600K temperatures involved with the AMTEK converters. Also, the weight of the heat-pipes and the total length needed were determined more from guesstimating than analyzing.

The weight of the rover body is fairly high compared to the weight of the internal components. Determining how much structure is needed to ensure strength and not have excess weight requires better knowledge of the components. However, use of composite materials may be required to make the mass budget more believable at the expense of raising the cost of the rovers.

4.3 Future Work

Identification of components, reliability and system analysis, technology development, and software generation are the four primary thrusts of the future work.

As often as possible, potential vendors and comparable components have been identified to justify the assumptions being made in the design. However, to move toward a CDR, all the major components must be identified. While some components must be developed from scratch, most are slight modifications to existing products currently available. To obtain quotes and specifications for components, the preferred vendors will be chosen and will become part of the LRI development team.

Once components are identified, a complete design can be performed. The lead times, cost, mass, power draw, and other programmatics will be assessed. In addition, reliability analysis will be done to ensure that no unexpected single point failures exist, and that suitable redundancy has been included to ensure the rovers remain available during the two year mission.

Several key tests must be performed early to keep to the proposed schedule. A single wheel and joint to the rocker-bogie needs to be evaluated in vacuum, dust, and heat/cold. The radiators need to be evaluated to verify reflectivity and emissivity. Dust tests must be performed on all the surfaces to understand the effects of accumulation, creep, electrostatic charge and removal techniques.

As part of the terrestrial traverse, key technologies will be developed for demonstration. The locomotion chassis, phased array communication, impulse radar, panoramic imaging and immersive display will be evaluated to ensure that the technology meets the expectations obtained from simulation and analysis.

Compiling a list of required algorithms is the first step toward generating the rover software. Currently, each subsystem is being modelled to determine the software connections between components and to aid in the simulation of the rover system. The on-board computing for the terrestrial traverse will utilize as much of the actual rover flight software as possible, and all software generated for the terrestrial traverse will be portable to the computing platform on the flight vehicle. It is likely that evaluation of various image processing algorithms and compression techniques will be tested to see how they fare in approximate lunar conditions.

Deeper information in general is needed regarding integration for launch and rover deployment, adjustment of the CG requirement of the lander, development of the rad-hardened TI-C80, creation of the MCM's and identification of all the on-chip components, specifications of thermal components, understanding the legal issues regarding rover export, and confirming frequency licensing.