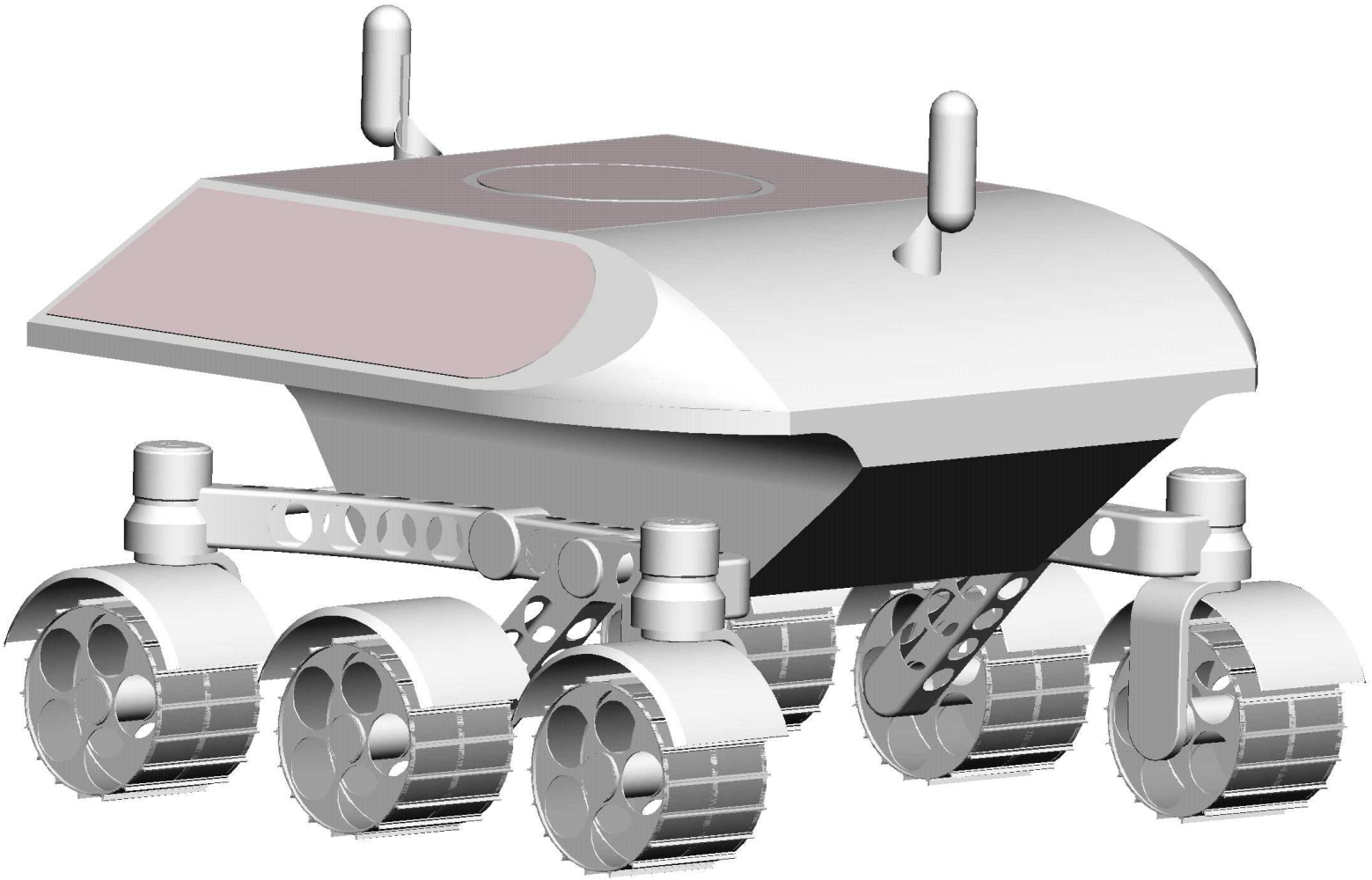


Lunar Rover Design for Commercial Exploration

"To generate technology & methods for lunar rovers and create a lunar rover design to satisfy a proposed commercial mission for mass participation and exploration"

Lalitesh Katragadda(lalit@ri.cmu.edu)

http://www.ri.cmu.edu/LRI

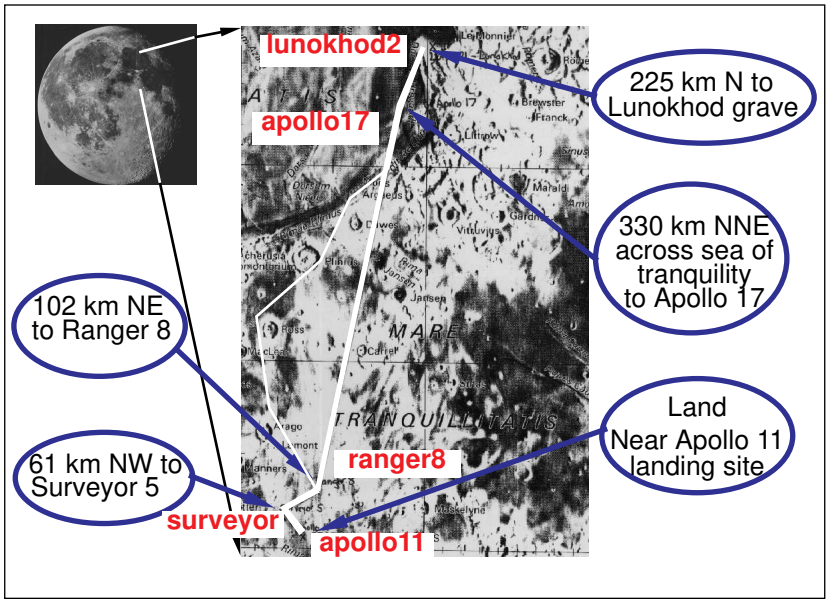
LRI Motivation

- **Pioneering lunar venture for mass exploration**
- **Opens planetary exploration with commerce, science, education and entertainment**
- **Scenario for return on investment**
- **Compelling story of endeavor on the Moon**
- **Immersive video stream enables mass interaction**
- **Long traverse of moderate terrain with short time delay enable unprecedented robotic endeavor**

LRI Mission

Mission
1999 - 2001

2 Years
1000 km
Proton Launch
600 kg mass



-180C to 150C

Dust & vacuum

Long day/night

Radiation

5 sec data loop

Deliverables

Live panoramic video
Rover telemetry
Rover status conversation
Hi quality stills

Value to Customer

Theme park rides, TV shows
Motion platforms, mission hotline
Interact with rover technology
Unique souvenirs, marketing

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Technical Challenges

Achieve high reliability and availability needs

Meet tight cost and time budgets

Operate in extreme lunar environment: Temp, dust, vac, rad

Stream downlink of ~6 Mbps for video & telemetry

Safeguard autonomously during amateur user operation

Locomote uncertain terrain of moderate difficulty

Budgets

2 rovers, 2m x 2m x 1.1m rover, Six wheeled;

Meets mass and volume budgets

Component	Cost ($M)	Power (W)	Mass (kg)
Locomotion	.8+1.45	70	54.2
Communication	3.3+2.7	101.9	17.7
Imagery/sensing	3.95+1.83	63.6	27
Computing	1.55+1.57	197.6	12.3
Power	2.6+5.2	-	59.3
Thermal	.8+3.6	-	40.6
Structure	.4+.45	-	27.1
TOTAL	13.4+15.85	433	238.2
WITH MARGINS	60 (2X)	538	250.7

System margins: Power [5% + 3% regulator loss + 15% DC-DC loss on electronics], Mass [5%], Cost [15% management, 15% contingency]

Design Features

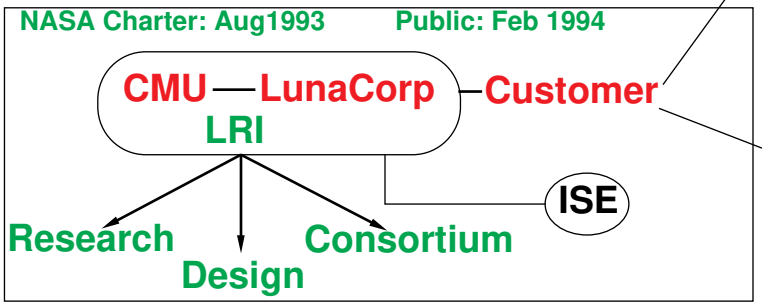
- Rational, driver & analysis based design
- Detail includes primary contractors & budgets
- First glimpses of viable 2 rover scenario and programmatics to build them
- Close to viable budgets

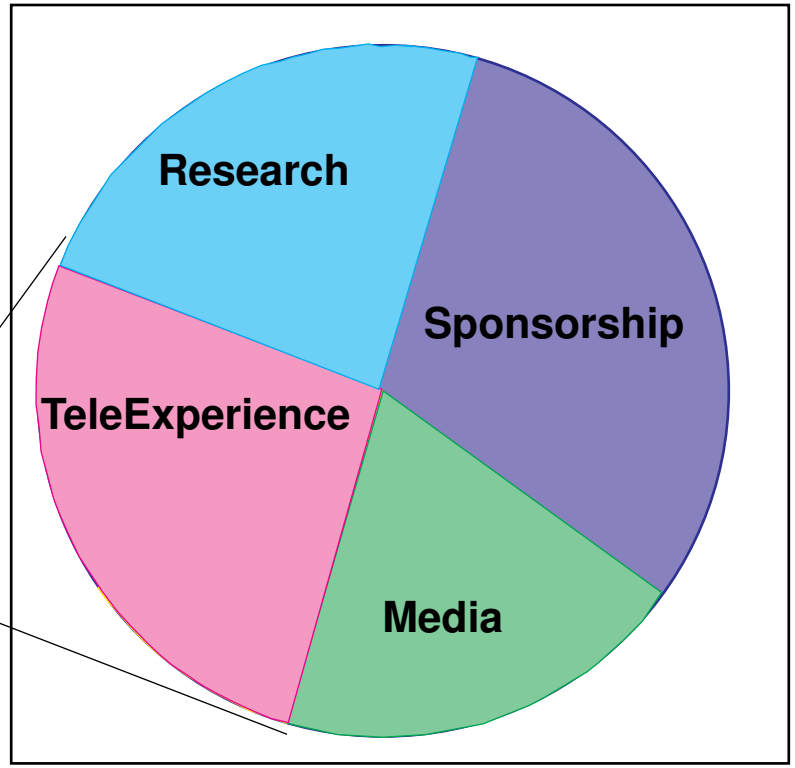
- Power: Plutonium power source & AMTEC cells
- Comm: Phased array only, frequency changed
- Imagery: Panosphere, wavelet compression
- Computing: Adopted new DSP, custom board design
- Locomotion: Detail based on analysis framework
- Safeguarding: Radar sensing technology

“Is there money on the Moon?”

Potential sponsers evaluating the expedition include:

- **AT&T, other telecom**
- **Japanese trading Co.**
- **Universal Studios**
- **Smithsonian at Dulles**
- **Six Flags**
- **Future New Orleans park**





Industry and Media interest is high

Potential sponsers excited and balk at being the first

TV and movie events show massive interest in Apollo & space

Recent Activity

Top down (system) level analysis to identify and solve the design drivers [Power, Comm, Locomotion, Imagery, Computing, Terrain Safeguarding]. The design then followed:

- Driver study & closure
- Requirements analysis and top down derivation
- Mission Environment detail and key issues documented
- Earth traverse rationalized, accepted, proposed
- TRIWG, conferences, media promulgation
- Consortium active: FCB, At&T, Mitsubishi, Universal, ...
- Russia-ISE contacts furthered: Lavochkin, LUTCH, Niitransmaash
- Legal wrangles keyed in: FCC application, RHU launch

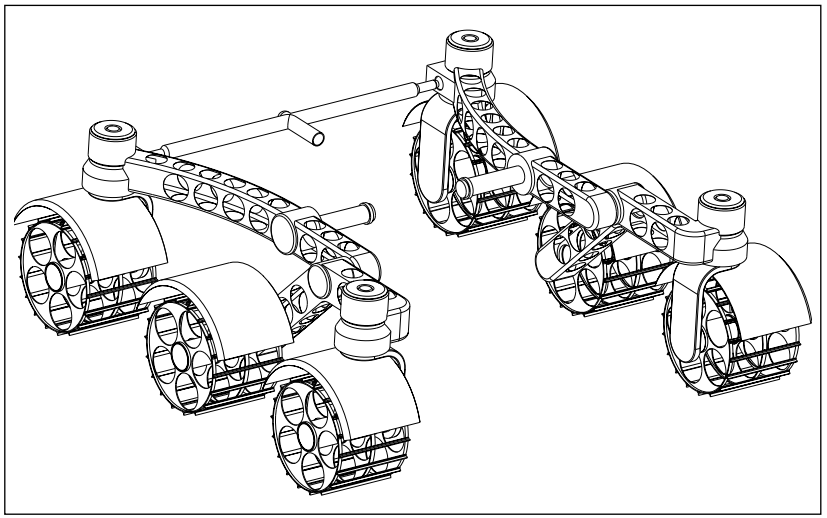
1995 Accomplishments

- Generated and reviewed viable design of flight article
- Increased industry/media interest in planetary exploration
- Identified key technologies to enable capable lunar mission
- Formulated Synergy: for mobile robot simulation, design
- Formulated LocSyn: robotable locomotion design tool
- Formulated PanoSphere: tele-experience design tool
- Formulated PreciComm: beam steering from mobots
- Formulated ROSE: for system analysis & code generation
- Published at four reviewed conferences

Locomotion

Unique Mission Challenge:

- 1,000 km, 10^6 wheel revolutions, 10^8 motor revolutions
- vacuum < 8.10^{-9} Torr
- electrostatic dust
- -150°C < T < 130°C, solar flux
- galactic & cosmic rays, IR from the lunar surface
- diverse soil properties



Design

- six wheels with wire mesh rim and grousers
- independent drive actuators on each wheel
- explicit steering of corner wheels, alternative steering schemes
- pivot arm suspension, linkage for averaging body pitch

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Locomotion (2)

- 55 kg for locomotion (20% of total mass)
- rover negotiates 25 cm high obstacles and is stable on a 35 deg slope
- wheel geometry provides good contact profile, mitigates resistance to steering, and is efficient
- brushless DC motors are reliable (electronic commutation), have good efficiency and favorable torque-speed characteristics
- harmonic drives have good weight/size ratio, compact design, and achieve high reduction ratios in a single stage unit
- no active cooling of the actuator
- thermofoil heaters are used to warm the actuator enclosures at night

Issues to be addressed:

Motion control design, heat regulation in actuator unit, wire routing and insulation of wires, design of vehicle positioning in payload fairing, design of vehicle attachments to the landing ramps

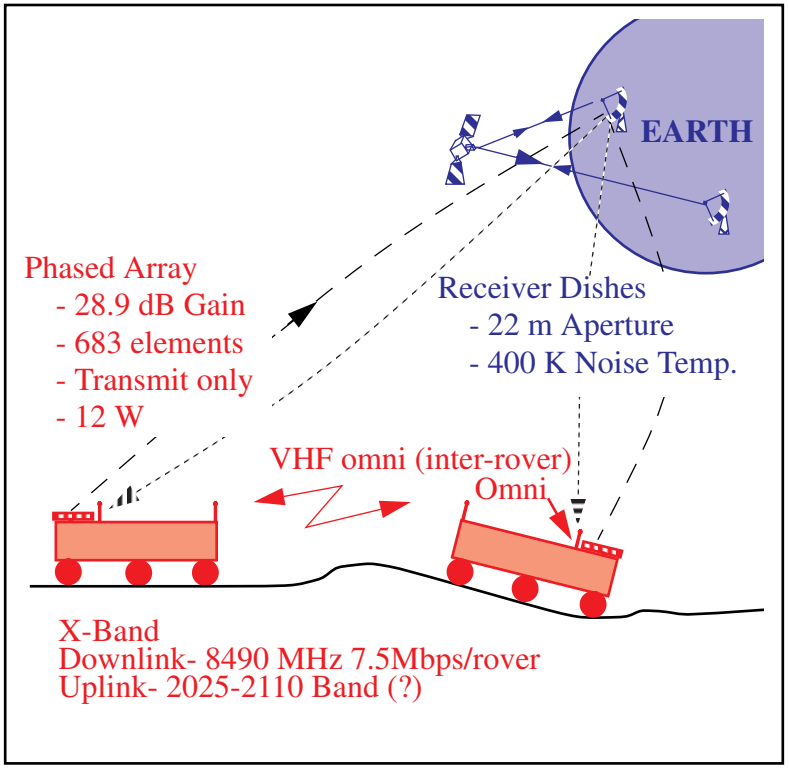
Communication

Requirements:

- Uninterrupted communication between Earth and rovers.
- Minimum 6 Mbps downlink
- Power < 100 W; Mass < 20 kg

Design

- High gain phased array transmit antenna on each rover.
- Omni-receiver to receiver commands from Earth.
- Omnilink between two rovers.
- 3 receiver dishes to ensure continuous coverage.
- 60% excess bandwidth root raised cosine pulse shaped QPSK.
- Rate 2/3 turbo code for error correction.



Communication (2)

Features:

- Reliable; Backup modes; Efficient use of bandwidth; Believable: Day and Night Operations

The communication system can transmit at 7.5 Mbps (BER 10e-6) in X-band with a link margin of 4.7 dB.

Component (#)	Cost ($M)	Power (W)	Mass (kg)	Margin used	Vendor
Phased Array (1)	3.13 + 1.64	94.5	12.6	5%	Ball Aerospace
Transmitter (1)	0.50	5.3	1.0	5%	Motorolla
Omni receiver (1)	0.25	-	1.0	5%	E-Systems
Inter-rover Omni (1)	0.25	1.0	1.1	5%	E-Systems
Receiver Dishes (3)	2.0	-	-	-	TIW Systems, Inc.
Satellite Links (2)	1.7	-	-	-	Comsat

Primary issue to be addressed:

Uplink frequencies; Wavelet Compression; Cost/Complexity of real time Turbo decoder; Cost/Complexity trade off for constant envelope & class C amplifier vs. Nyquist QPSK vs. class A amplifier.

Error Correction and Modulation

Requirements:

- 10 MHz occupied BW
- Bit Error Rate of 10^{-6}
- As low power as possible
- As high a data rate as possible, on order of 5 Mbps

Error Correction:

- Rate 2/3 turbo code
- Achieves BER of 10^{-5} at S/N of 2dB

Modulation:

- 60% excess BW Nyquist QPSK
- Achieves 0.8 Hz/bps

Error Correction and Modulation (2)

Subsystem Highlights:

- Turbo codes are a newly discovered random interleaving of multiple recursive convolutional codes, which achieve performance near the Shannon limit.
- Requires simple hardware for modulation & encoding (on robot).

Primary issue to be addressed:

Complexity and cost of Turbo decoder.

Trade-off between constant envelope modulation and class C power amplifier.

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Visualization

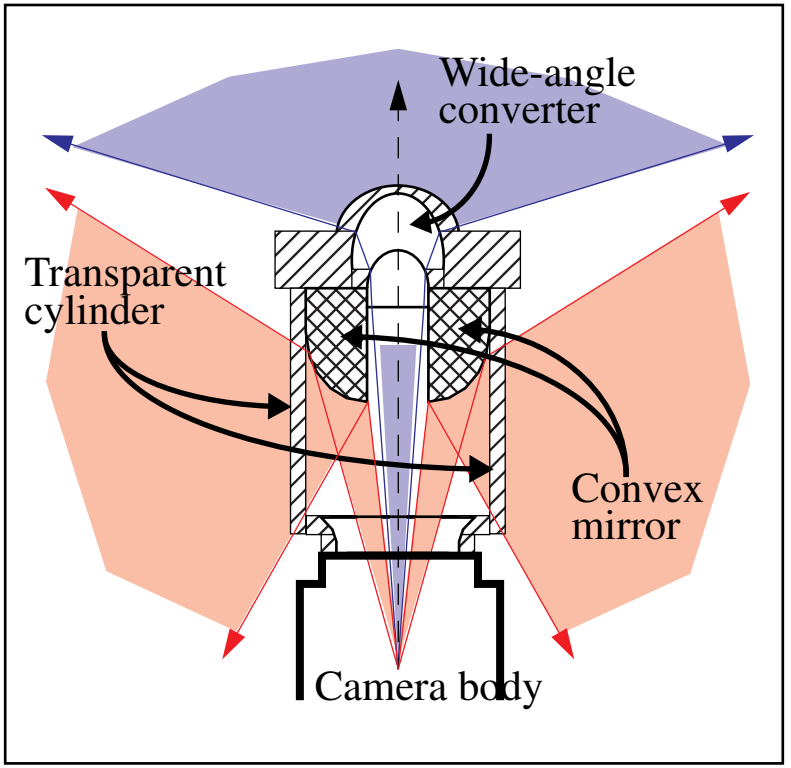
3 redundant pairs of cameras, located at front, back and bottom of rover

Front/back pano-sphere cameras for 360° color panorama (+20 to -60 from horizontal) - 2k x 2k image at 10fps

Belly fish-eye camera (140° FOV) for color safety views of wheel position on the terrain - 1k x 1k image at 0.3fps

Dynamic range packing (12->8 b/pixel) and image dewarping done in software

Video displayed on domed theatre



Subsystem Highlights:

- Optics coated with thin-film diamond for scratch resistance and thin-film gold to allow grounding (dust)
- Entire sphere about rover is capable of being imaged at any time
- Omnidirectional video allows multiple users to choose where they want to look and when
- Stereo ranging possible from side views of front/back pano-spheres

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Visualization (2)

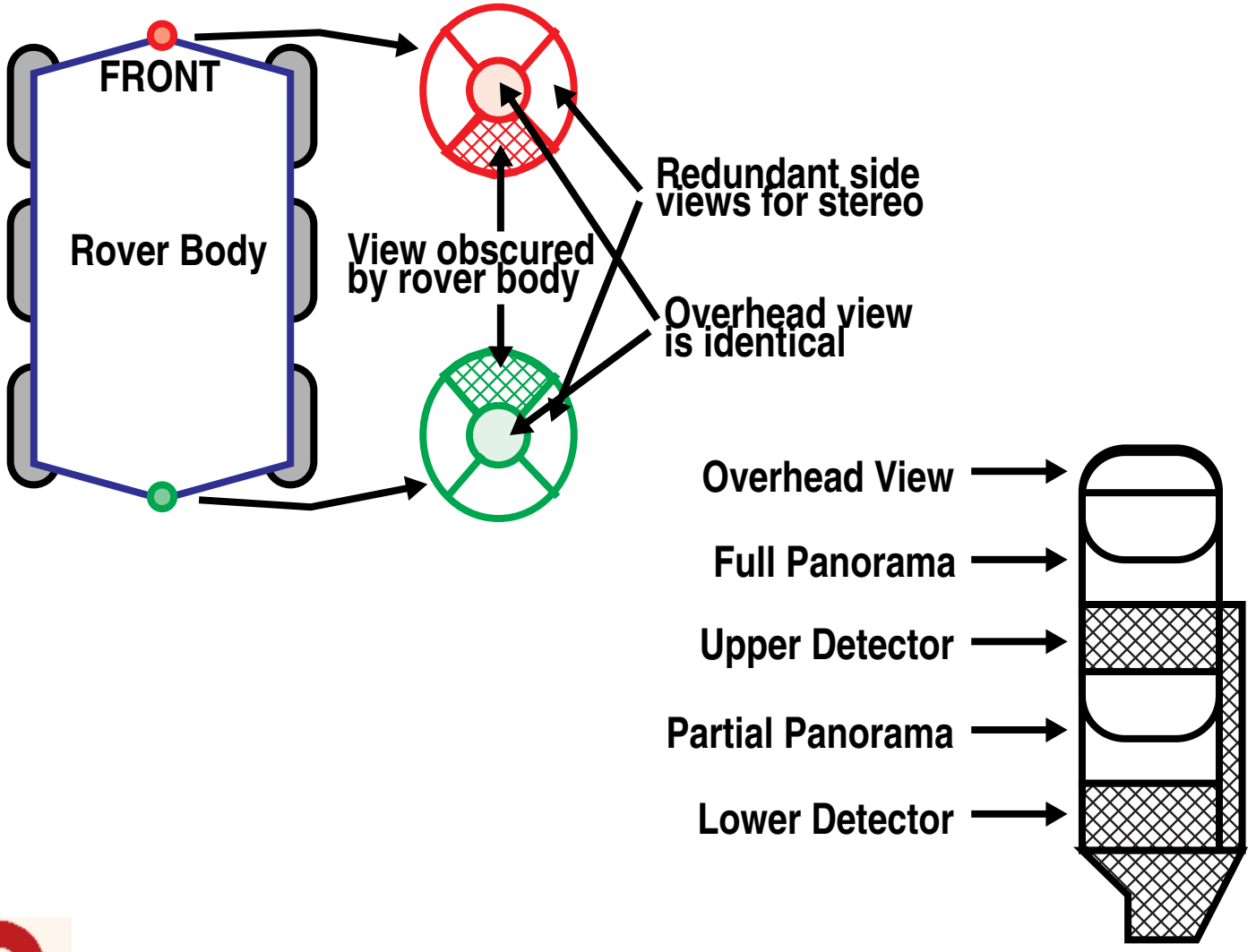
The main risks are the development of a rad-hardened high-res color digital camera, turning 2k x 3k @ 10fps (the max datarate) into an exciting product, and porting processing algorithms to the rover computing environment.

Component (#)	Cost ($M)	Power (W)	Mass (kg)	Margin used	Model and Vendor
pano-sphere cameras (4)	1.5 + 0.5	24.0	7.3	5%	derived from DALSA's CA-D9 MegaSensor
under-body cameras (2)	1.0 + 0.25	5.4	3.2	5%	derived from DALSA's CA-D9 MegaSensor
image processing algorithms	0.4 + 0.1	N/A	N/A	N/A	iSight's dynamic range, PVSI's dewarping
17' domed display & driver interface (1)	0.2 + 1.3	N/A	N/A	N/A	based on Evans and Sutherland's VistaView

Primary issue to be addressed:

To achieve full night operations, the cameras must be able to return high-quality video during lunar night. The actual lighting conditions from Earthshine must be identified and modelled to test exposure and dynamic range algorithms.

Pano-Sphere Placement and Schematic



Computing

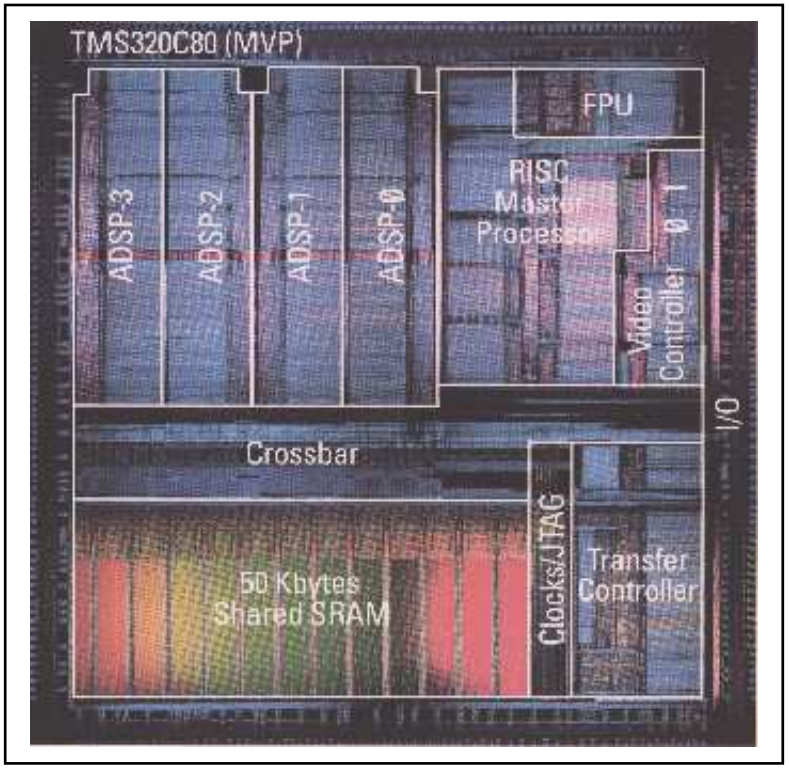
Compression drives needs

Radiation primary concern

DSP needed for compression

Programmatics suggest MCM

- C80 DSP (2 BOPS), can be hardened to 100 krad
- R3000 (Rad Hard)
- 6 x 3U VME cage



5 identical boards: Each with a R3000 central processor, 3 DSP modules (DSP + VRAM + direct camera interfaces), DRAM and I/O. 6th slot occupied by radar electronics. Sufficient to handle sensor fusion for terrain and position.

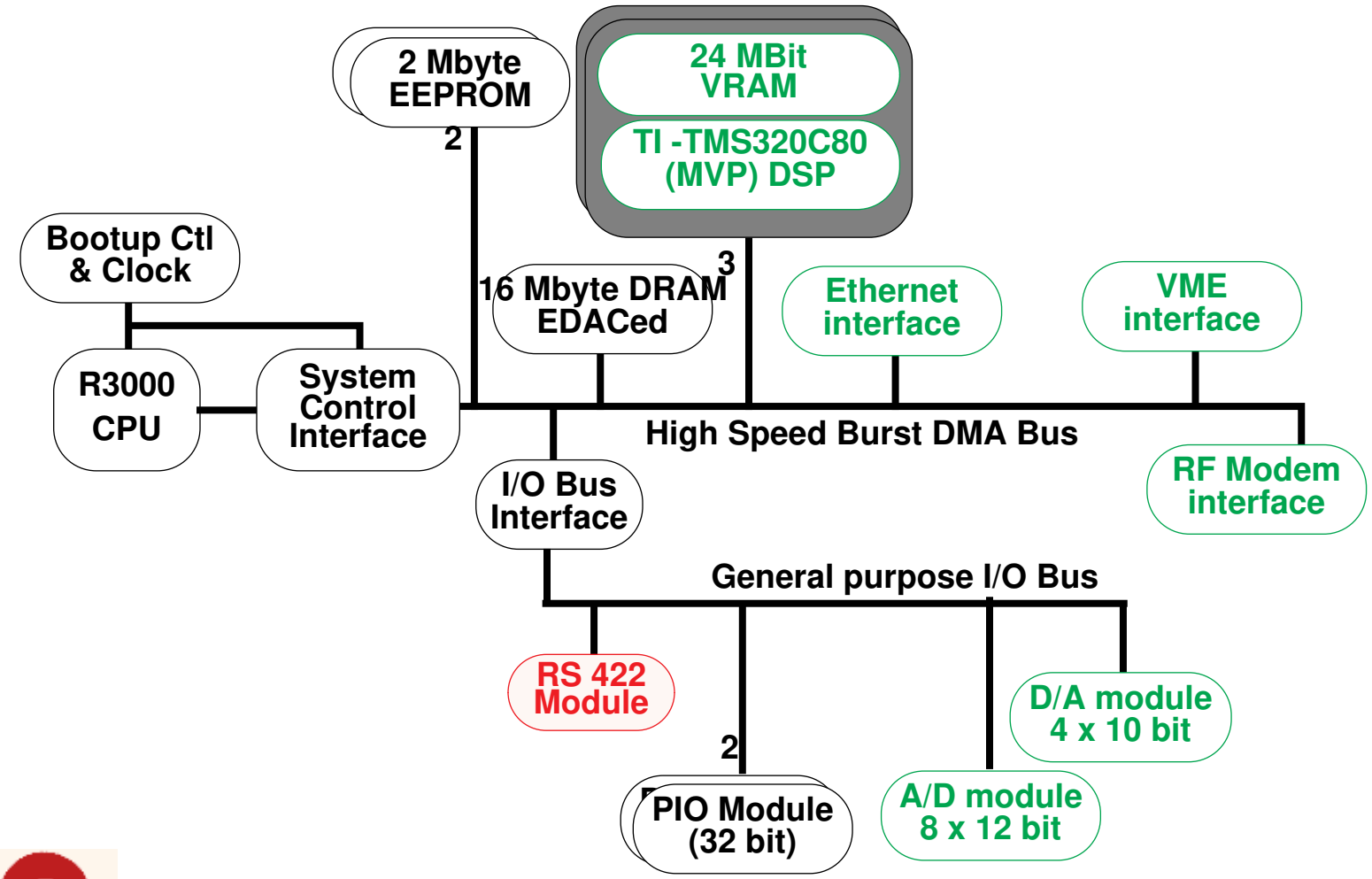
Computing (2)

Component (#)	Cost ($M)	Power (W)	Mass (kg)	Margin used	Model and Vendor
VME cage	.1+.2	16.2	3.5	8%	
MCM (5)	1.4+.3	181.4	7.3	8%	TI, Anders., DDI, Harris
Cabling to power	.05+.075	-	.5	8%	

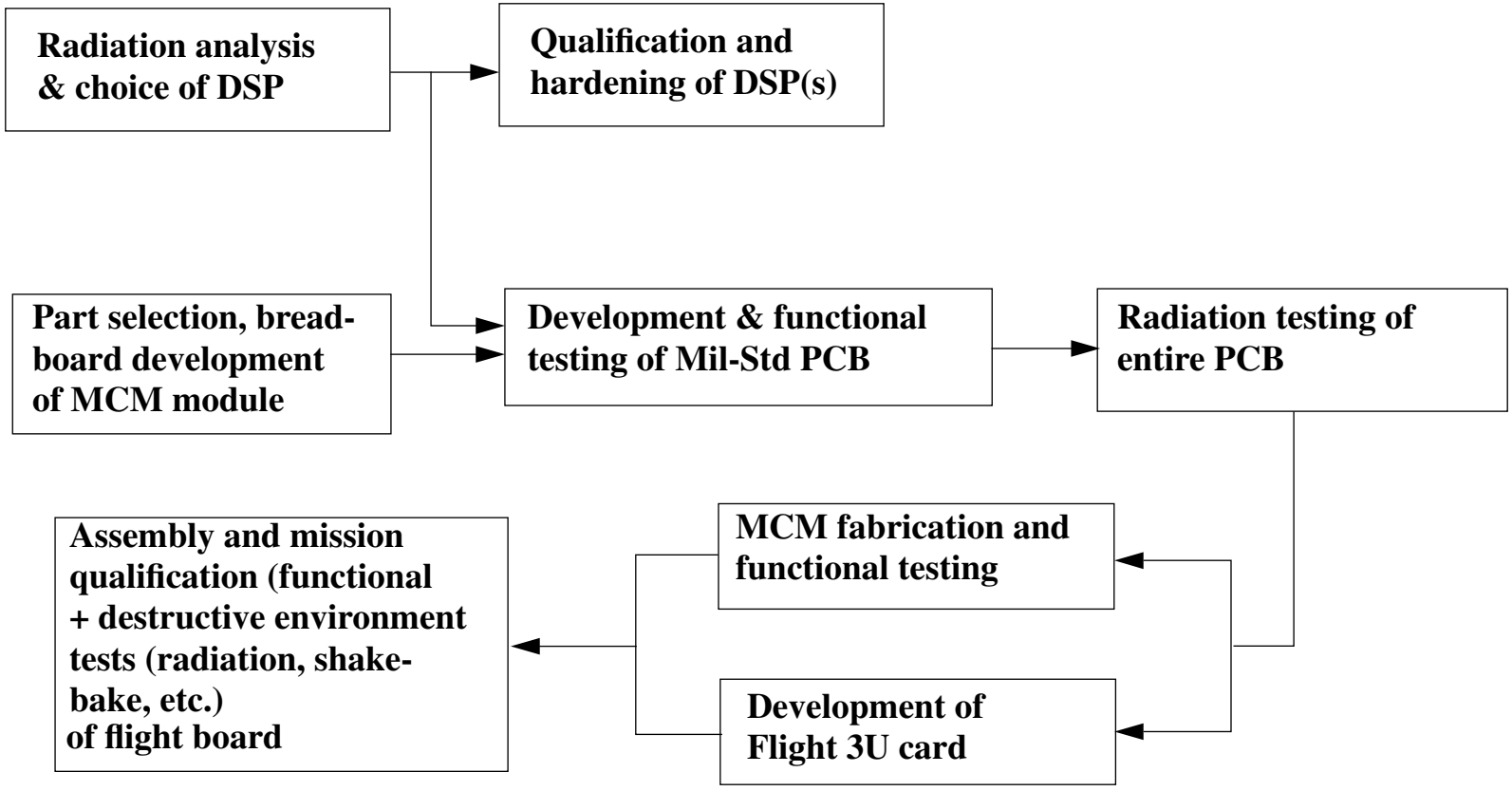
Primary issues to be addressed:

- Reducing computing needs w. focus on algorithms
- Designing from MCM block dia. to detail and rule checks
- Complete radiation tolerant/qualified parts list
- Quick PCB prototype for reality check
- Strategic alliance/enterprise to reduce mission cost

Computing Board Design



Computing Board Development

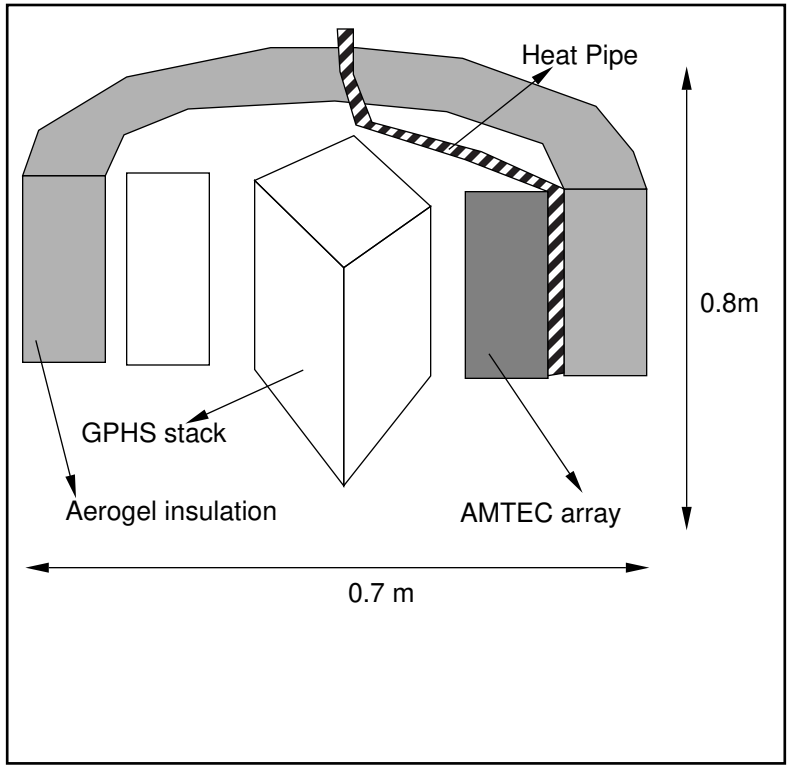


Power

Generate ~500W day+night

Meet thermal requirements

- 3500 W Plutonium RTG
- 18% AMTEC conversion
- Radiative transfer to AMTEC
- Heat pipes to low cost black body radiator
- Radiator temp [500, 600k]
- Size = 0.7m dia x 0.8m long



- Highly reliable, no moving parts
- Legal issues reportedly of low significance
- Possibility of upgrade in AMTEC efficiency

Power (2)

Plutonium has a half life of 78+ yrs, performance is ~constant

Component (#)	Cost ($M)	Power (W)	Mass (kg)	Margin used	Model and Vendor
GPHS (14)	1+2	-	21.3	5%	LUTCH, Russia
AMTEC converter	1+2	-	14.7	5%	AMPS
Switching Regulator	.4+.4	-	4.3	8%	Matra Marconi
DC/DC (10)		-	1.1	8%	Interpoint
Capatteries (20)	.1+.2	-	2.3	13%	Evans
Cabling (59m)	.25	-	5.5	13%	

Primary issues to be addressed:

- Co-development initiative with JPL for leverage
- Integration scenario with LUTCH and D of Commerce
- Viability of heat pipes & aerogel at 600k & 1300k
- Detailed design, modeling, FEA (Str,Thr,Vib) and testing

Thermal

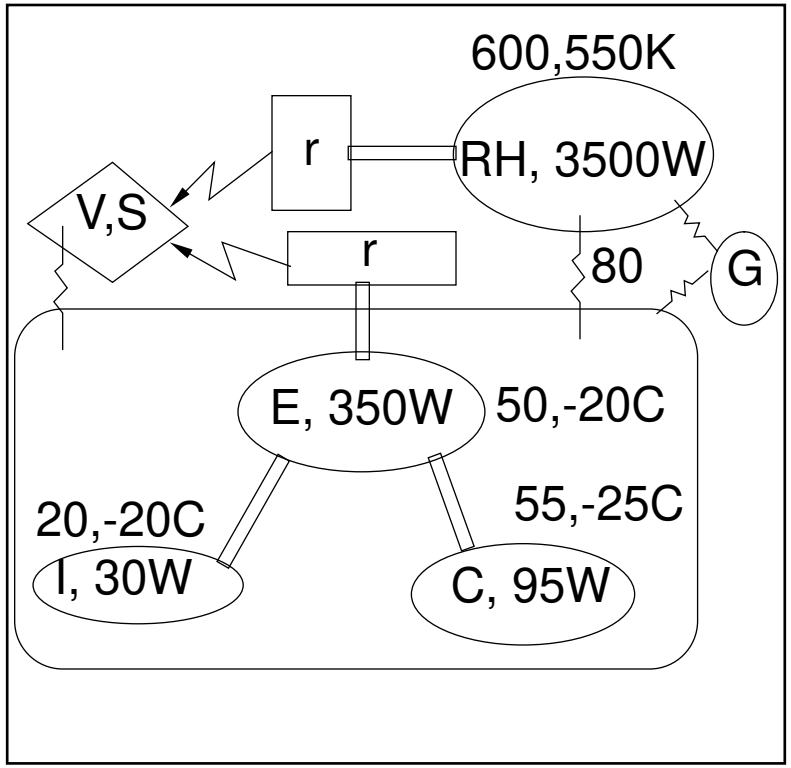
Electronics T [-50C,80C]

Comm T [-50C, 80C]

RTG T [400K,700K]

Camera T [-50C, 20C]

- •Aerogel 0.02 W/k/m
- •Heat pipes 100 W/k
- •MLI, 0.1 - for integrity



The thermal control is mostly passive, requiring electronic heating/cooling for imagery hardware and constant heat at night into the Comm system. The electronics radiators are louvered using bimetallic strips that close at 0C, -20C

Thermal (2)

Component (#)	Cost ($M)	Power (W)	Mass (kg)	Margin used	Model and Vendor
Radiator (1+2)	.2+.9	-	5.4	8%	
Heat pipe	.2+.8	-	14.7	13%	Noren
Carbon Aerogel	.1+1.45	-	4.2	5%	JPL/BMDO
MLI	.1+.3	-	3.4	13%	Therm Electron Tech.
Joints	.2+.15	-	6.8	13%	

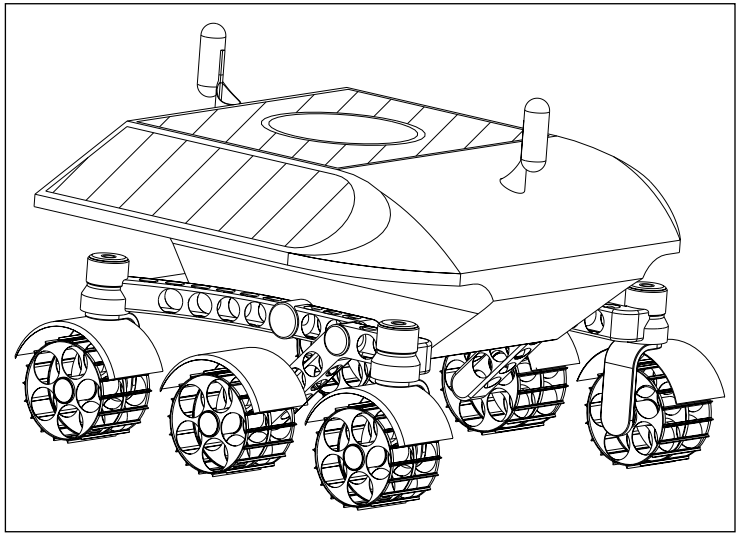
Primary Issues to be addressed:

- Locate vendors & verify component specs
- Analyze construction methods to detail the design
- Test radiators performance w/wo dust to improve model

Structures

Requirements:

- protection from the environment
- interface to locomotion & lander
- structural support to subsystems
- mounting location for sensors and antennae
- area for heat dissipation
- CG position according to spec
- appealing to the customer



Design:

- three compartments: RTG+AMTEC, axle housings+camera mounts, computing+electronics+comm+power distribution enclosure (E-box)
- power generation and E-box are fully enclosed
- side panels radiate excess heat from the RTG unit
- top panel consists of the phased array and the E-box radiator

Structures

- 27 kg for structures (10% of total mass); supports 70% of rover mass
- base plate: aluminum honeycomb which is filled with aerogel insulation
- body shell: Kapton sheets (MLI) covered in Kevlar
- vertical structural plates: carbon-carbon composites
- epoxies and rivets connect the structural members

Issues to be addressed:

- RTG mounting and insulation
- heat paths & radiator performance
- launch & transfer load analysis
- body design for dynamic impact & vibrations
- environmental effects on structural materials

Structures (3)

Component	Cost ($K)	Power (W)	Mass (kg)	Margin used	Model and Vendor
base plate	5.0 + 200	-	9.5	13%	Hexcel
internal vertical panels	2.0 + 60	-	5.5	13%	CMU, DuPont
E-box panels	0.8 + 20	-	2.0	13%	CMU, DuPont
gussets	1.0 + 50	-	3.0	13%	CMU
body shell panels	20.0 + 170	-	4.5	13%	DuPont, Thermo Electron
axle housings, flanges	0.2 + 20	-	1.2	13%	Rexnord, CMU
pyrotechnic disconnects	10.0 + 150	-	1.4	30%	?

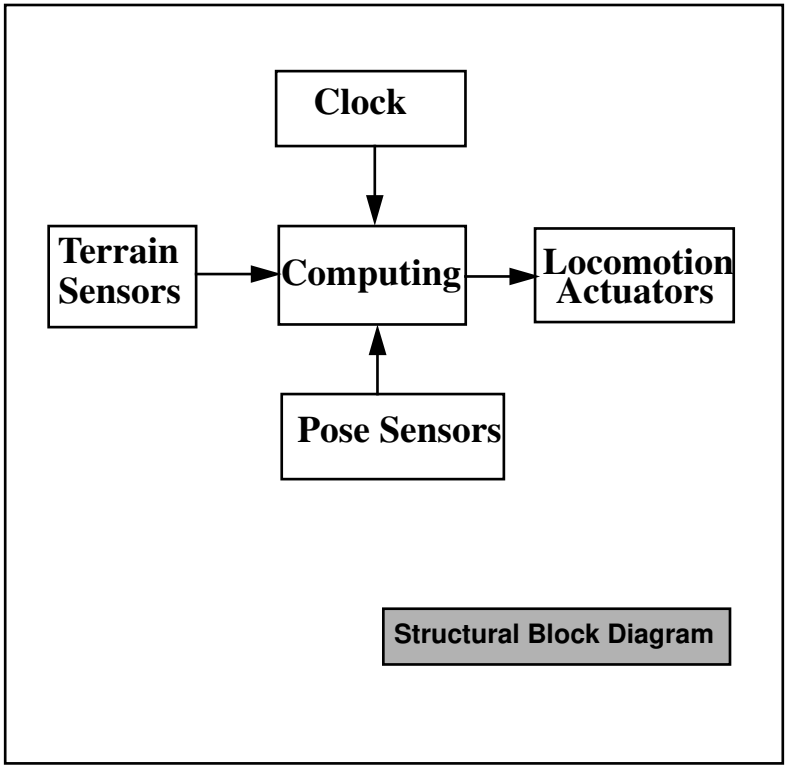
Terrain Safeguarding

Terrain sensing needs:

- •4cm grid
- •2cm accuracy
- •range > 1m at pose of actuator commands
- •Robust in lunar environment

Micro impulse radar sensing technology meets needs

C80 DSP for processing



Only sensor with environmental compatibility (heat, rad, dust)
Can cut through material/dust, enables mechanical shielding
Calibration of individual sensors needed due to analog nature

Terrain Safeguarding (2)

- Array of 60 sensors at each end, 10 spread along each side & bottom as well
- Each sensor provides range vs. intensity at 40 Hz
- Multiple sensors help localize range values & detect hazards
- C80 DSP used to process and generate local hazards

Primary issues to be addressed:

- Nascent technology, needs to be hardened for space
- Analog electronics; careful noise engineering needed
- Possible conversion to VLSI to save mass & power
- Radiating elements are large, need to find a way to create sensor banks

Software

- Software generation strategy developed:
  - Develop hardware & functional models using OOA,
  - State models and transitions using Cadre teamworks
  - Analyze using ROSE - state model simulator
  - Translate to verified object stub code & headers
  - Generate code using “case” tool & algorithm library
- Analysis reveals 90% of system software for station keeping and exception handling
- Correctness important for reliability & availability
- Real time control & operating systems identified to be consonant with Cadre

Launch Landing Scenario

- ~50kg for non-rover interfaces
- 3 point mounting of rovers on ramps
- Ramps connected to each other and center structure
- BBQ rotation of craft during translunar stage
- Flexible, springy “raft” protects rovers during landing
- Pyro disconnect of rovers from ramps on deployment
- Pure mechanical interface between lander-rover
- Lander/Earth activate rovers via omni
- Electronics turned on by timer after LEO injection

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