16.89J / ESD.352J Space Systems Engineering
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16.89 / ESD 352 Final Design Review

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The 16.89 / ESD 352 Team

<u>Presenting today:</u>

Scott McCloskey

Seungbum Hong

Allan Fong

(Systems Team 3)

Presentation Overview

- Design Challenge
- Executive Summary
- Mobility System Architecture Analysis
- Mobility System Design
  - Approach
  - Assumptions
  - Subsystems
  - Vehicle Selection
- Commonality
- Integrated Dynamic Capability Analysis (MUSE)
- Communication and Navigation
- Conclusions and Future Work

16.89 / ESD 352 Design Challenge

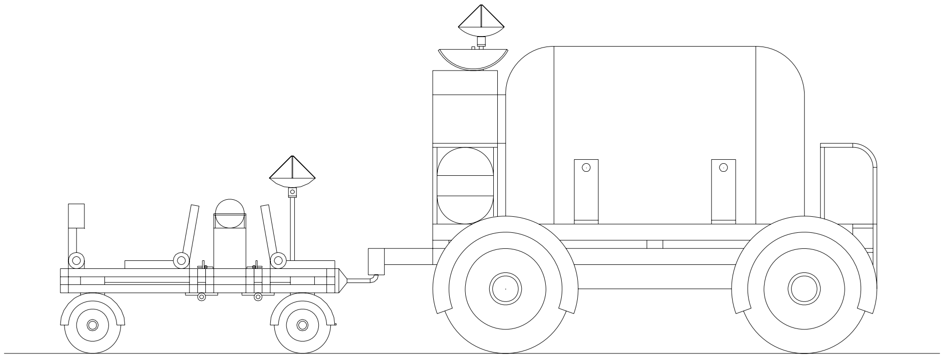
- This year's 16.89/ESD.352 Space Systems Engineering class will engage in the question of how to best architect and design a future, ***extensible planetary surface transportation system***. The system will be designed for the ***Moon*** with considerations for eventual adaptation to ***Mars***. In addition, the class will consider how a terrestrial version of the lunar transportation system can be built for testing in lunar and Mars analog sites on the ***Earth***.

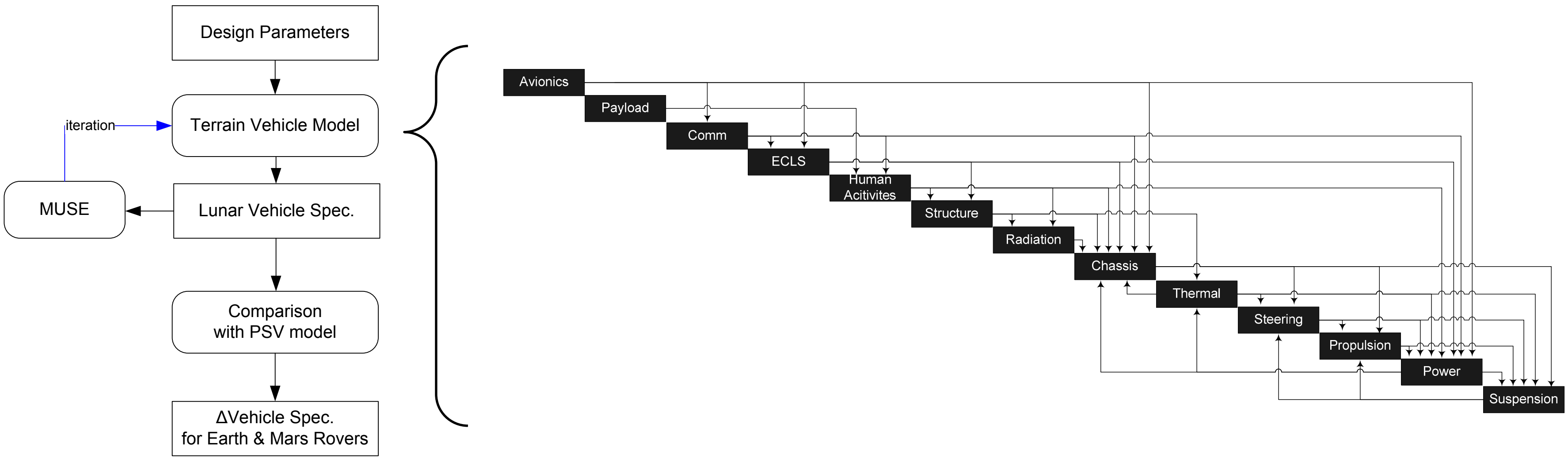
DRMs and Architecture Selection

- Broke down activities into 4 Design Reference Missions (DRM):
  - DRM-1
    - Explore up to 20 km radius on one EVA
    - 60 km range total
  - DRM-2
    - Explore up to 100 (Moon) - 200 km (Mars, Earth) radius over a duration of 5 - 10 days
    - 300 – 600 km range total
  - DRM-3
    - Resupply the base with cargo located up to 2 km away
  - DRM-4
    - Use mobility assets to build and maintain the infrastructure of the outpost
- Architecture analysis:
  - 2 2-person UPVs for short range exploration
  - 3 2-person UPVs and 2 campers for long range exploration

Vehicle Analysis Summary

- **Done iteratively in MATLAB**
- **Lunar exploration:**
  - **3810 kg camper**
  - **374 kg UPV**
- **Commonality**
  - **Camper: Fix chassis geometry**
  - **UPV: Design chassis for Moon and Mars**
- **Dynamic capability analysis done with MUSE**





Earth, Moon, Mars Transportation

- **Earth**
  - **Use of regular ATVs such as those currently present at Mars Haughton (delivered by Twin Otter plane)**
    - **Minimalist solution, possible because no towing required**
  - **Transportation of camper**
    - **Delivery to Resolute Bay using barge, drive to Haughton-Mars over the ice (like Humvee at Haughton-Mars)**
    - **Likely the most cost-effective solution, although time consuming**
    - **Notional schedule: ship during the summer, drive over the ice the following winter**
- **Moon**
  - **Delivery of UPVs and campers with a dedicated cargo launch (1 CaLV, 15-20 mt delivery capacity)**
  - **Alternatively: delivery of campers as re-supply vehicles for a lunar outpost, delivery of UPVs with crew, no dedicated CaLV launch required**
- **Mars**
  - **Delivery of UPVs and campers with a dedicated launch of a CaLV**

Mobility System Architecture Analysis

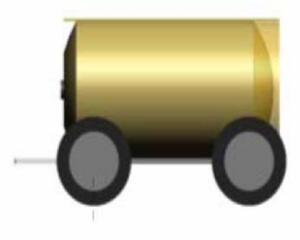
Key Ground Rules & Assumptions

- Earth, Moon, and Mars systems are used for both exploration and operational testing / improvement
- The mobility architecture selection is driven by DRM-1 and DRM-2 operations on the Moon and Mars
- Earth system employs Moon / Mars architecture for operational commonality
- Mobility system masses and geometries have to be within transportation system capabilities for Earth, Moon, and Mars
  - Earth appears to be most stringent if existing capabilities are used
- Crew operates always in groups of at least two
- Worst-case overhead over straight-line distance is 1.5 (3 for round-trip)
  - Derived from Apollo traverses; factor 1.5 for intentional deviations from straight-line (e.g. Apollo 17 EVA-3)

Surface Mobility Element Model

- **Three different types of vehicles can be modeled / sized parametrically on subsystem level:**
  - **Open rover**
    - **Can tow other elements**
    - **Can hold cargo**
    - **Provides accommodations for crew in EVA suits**

  - **Camper**
    - **Provides pressurized environment for crew**
    - **Is not capable of driving without towing vehicle**



  - **Pressurized rover**
    - **Provides pressurized environment for crew**
    - **Is self-propelled**
    - **Can be utilized to tow other elements**

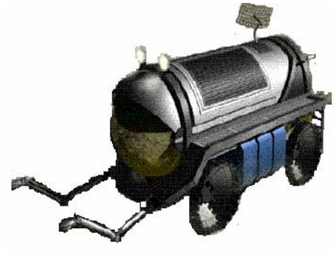
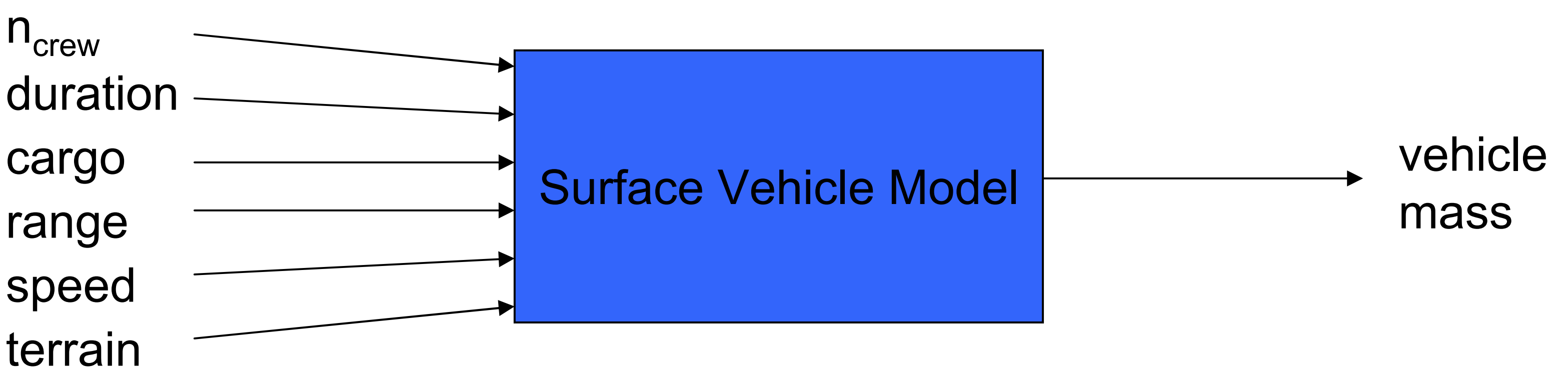


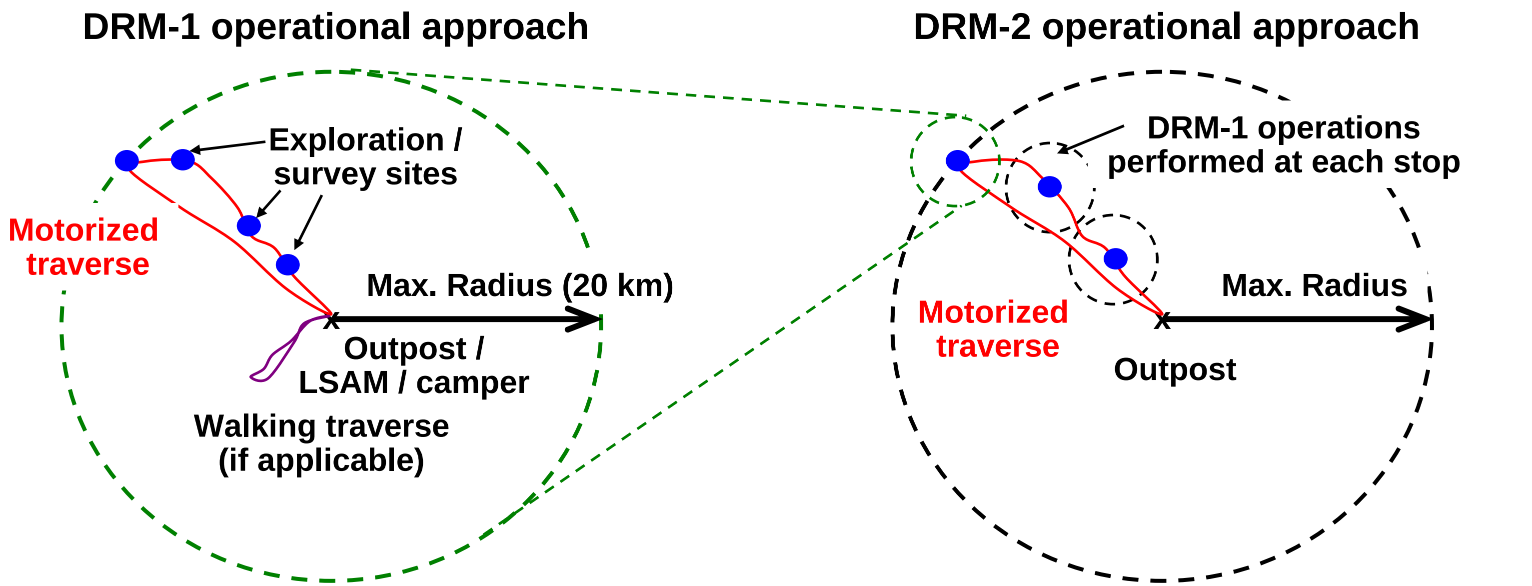
Image credit: from Draper/MIT CE&R report, 2005

Model Flow



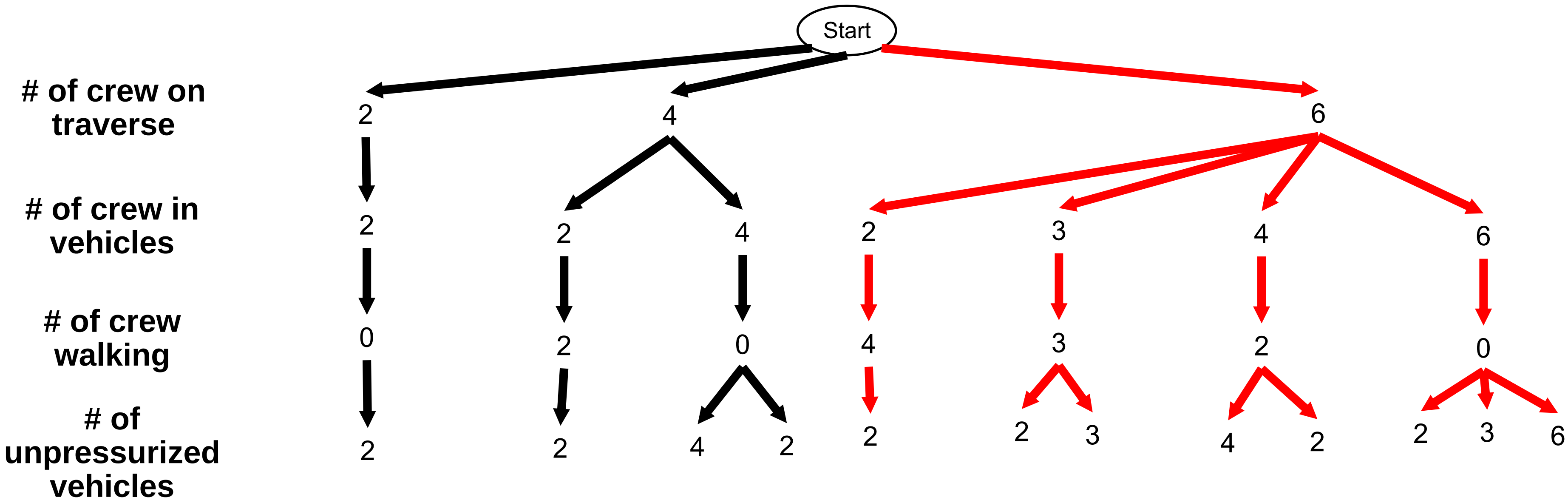
- **Model provided by Afreen and Seungbum**
- **Metrics**
  - **Mobility system mass**
    - **Minimize this metric**
    - **Output from vehicle model**
  - **Number of science sites visited**
    - **Maximize this metric**
    - **Calculated using inputs to vehicle model**
- **Risk, extensibility, performance with loss of asset, and vehicle size were treated as constraints on the architectures**

Common ("Fractal") Operations Approach



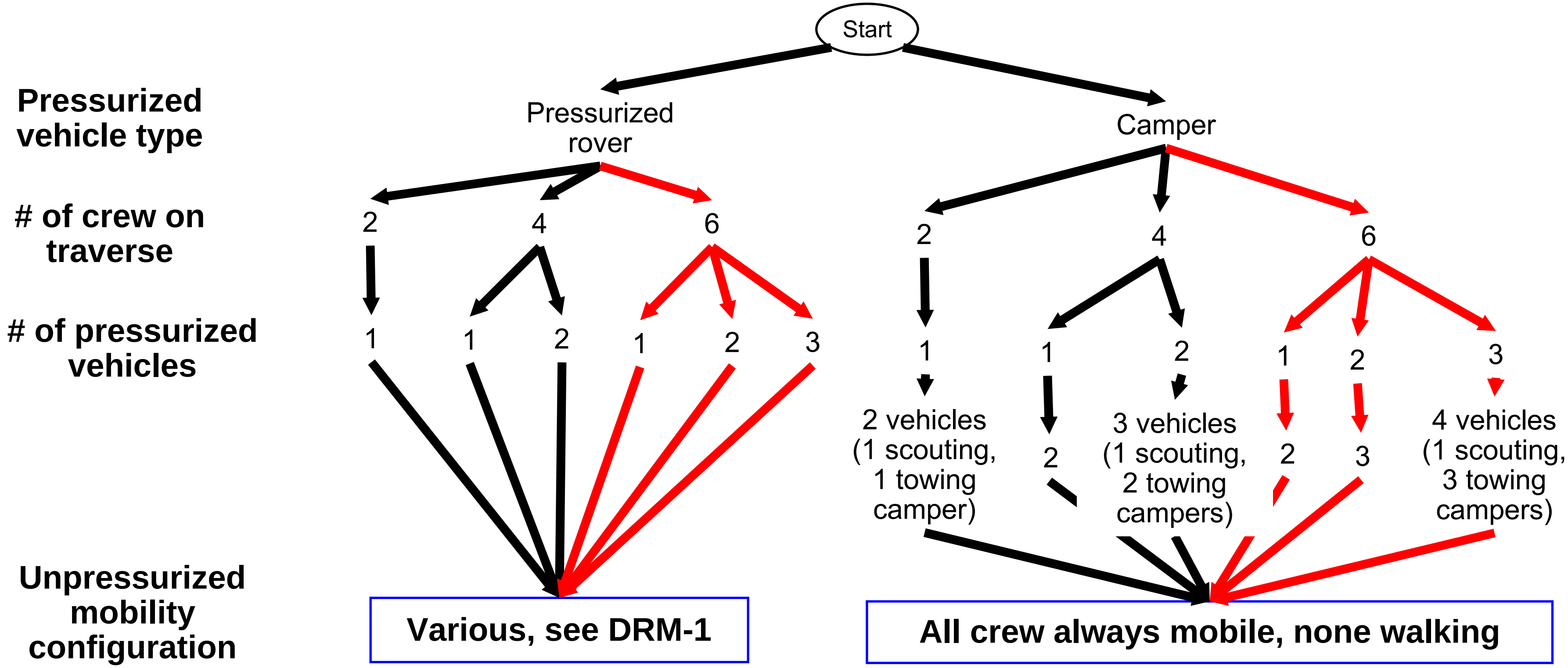
- DRM-1 excursions represent local traverses in the vicinity of a pressurized habitat, not unlike traverses on Apollo J-type missions
- DRM-2 excursions represent long-range excursions 10s to 100s of km away from the outpost and require independent habitation
- Organizing the DRM-2 excursions into traverse days and exploration days provides the opportunity for conducting DRM-1 excursions from the mobile habitat much like from the outpost
  - Potential cost / risk reduction and learning effects from ***operational commonality, reuse of procedures***

DRM-1 Architecture Options



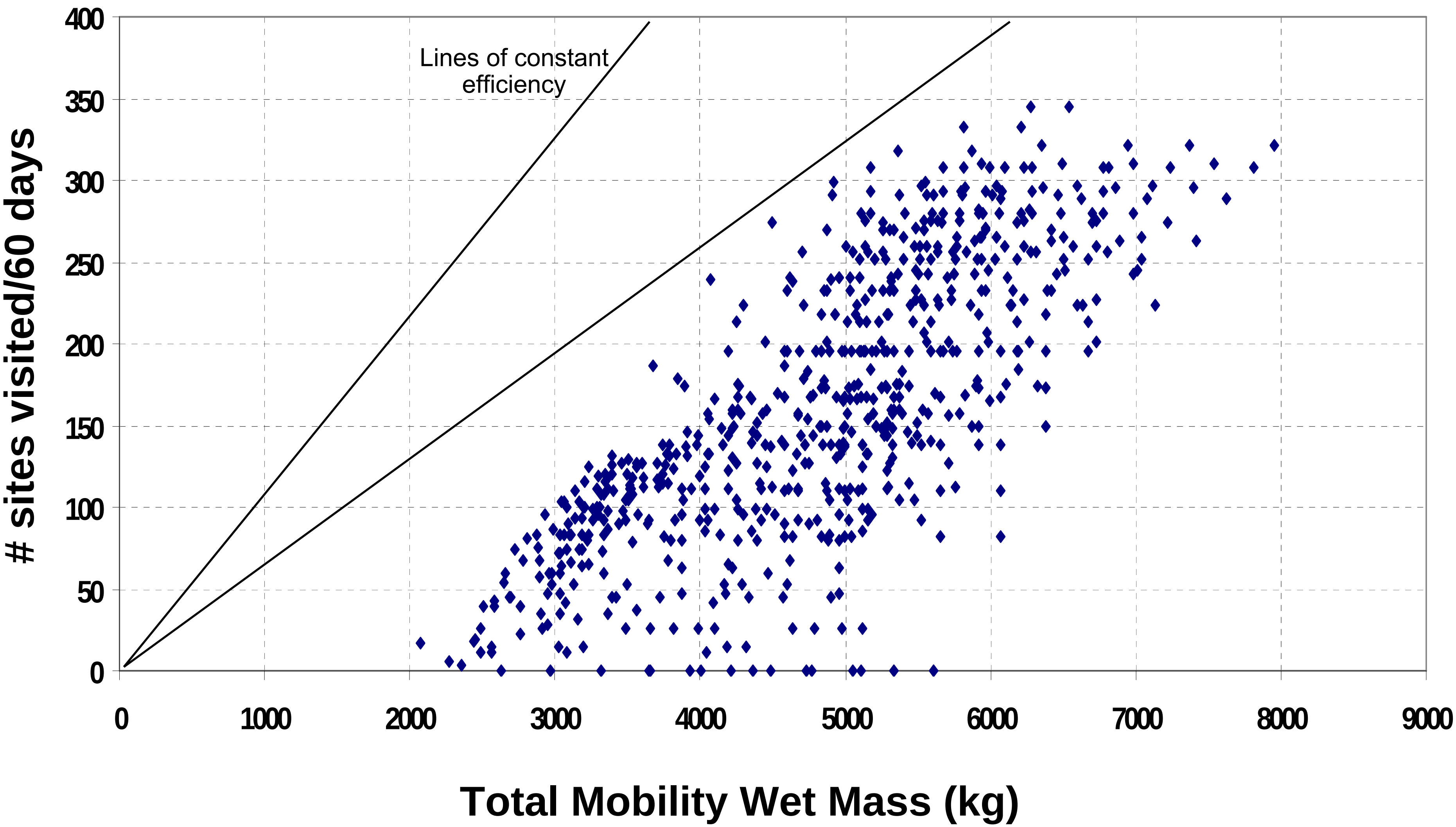
- DRM-1 traverses (60 km range) can be carried out with the entire crew, or leaving behind part of the crew back at base / at the LSAM
- Apart from exploration, DRM-1 traverses are also relevant for accessing the base in case of a long landing (in this case all crew have to be transported)
- All crew on traverse have to be able to return to base in case of an SPE and after loss of one unpressurized vehicle within 3 hours
- For each option, average speed was varied from 10-20 km/h, and different power generation technologies were analyzed

DRM-2 Architecture Options



- Pressurized and unpressurized vehicles drive at 15 km/h average speed
- Unpressurized vehicles are sized such that they can carry excess crew in case of loss of one unpressurized vehicle during DRM-1 type operations
- All vehicles utilize fuel cells (independent of sunshine and solar elevation, more efficient than batteries)
- Pressurized vehicles provide protection and life-support to wait out a SPE

Example Trade Space (Lunar DRM-2)

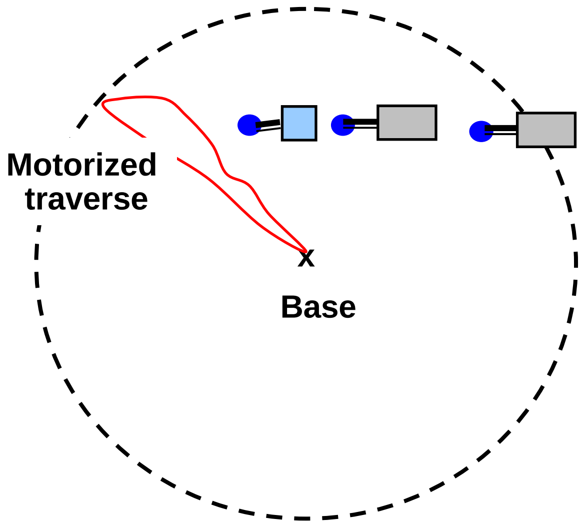


Architecture Sensitivity Analysis

- Examined sensitivity to model inputs:
  - DRM-1
    - Range (30-70 km)
    - Speed (8-18 km/hr)
  - DRM-2
    - Sortie Days (3-10 days)
    - Range (240-360 km for Moon, 480-720 km for Mars)
    - Speed (8-16 km/hr for Moon, 6-16 km/hr for Mars)
- Variation of these parameters had no major impact on the final architecture selection

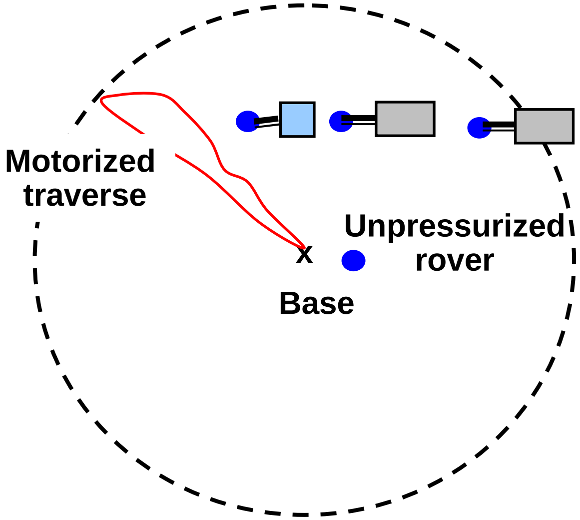
Lunar Architecture Selection

- 2 2-person campers and 3 unpressurized rovers sized for towing a camper
- 2 of the same unpressurized rovers are used for mobility on sortie missions
- Rationale:
  - 1 pressurized vehicle is not acceptable because long-range exploration capability is lost when this vehicle is damaged / permanently unavailable
  - 2 pressurized vehicles provide more safety margin
  - Assumed that the lunar base can be left unattended for short periods of time.



Mars Architecture Selection

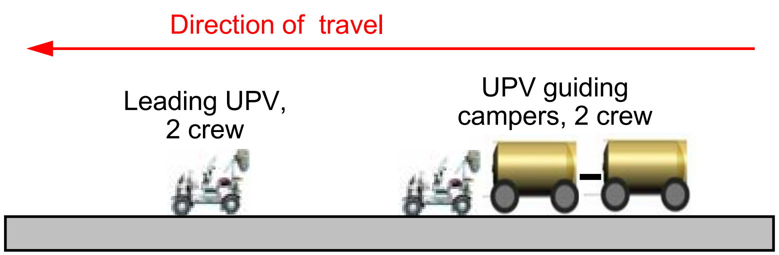
- 2 2-person campers and 4 unpressurized rovers sized for towing a camper
- Rationale:
  - 1 pressurized vehicle is not acceptable because long-range exploration capability is lost when this vehicle is damaged / permanently unavailable
  - 2 pressurized vehicles provide more safety margin
  - It is assumed that the base is never unattended on Mars (2 crew stay behind)
  - 1 additional unpressurized vehicle is left behind at the base during long-range exploration



Camper vs. Pressurized Rover

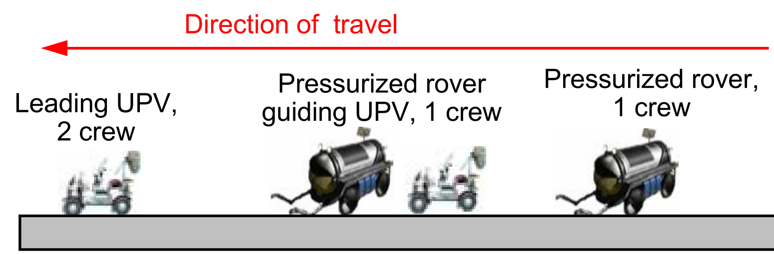
DRM-2 excursion using UPVs and campers

Traverse operations (4 crew):



DRM-2 excursion using pressurized rovers and UPVs

Traverse operations (4 crew):

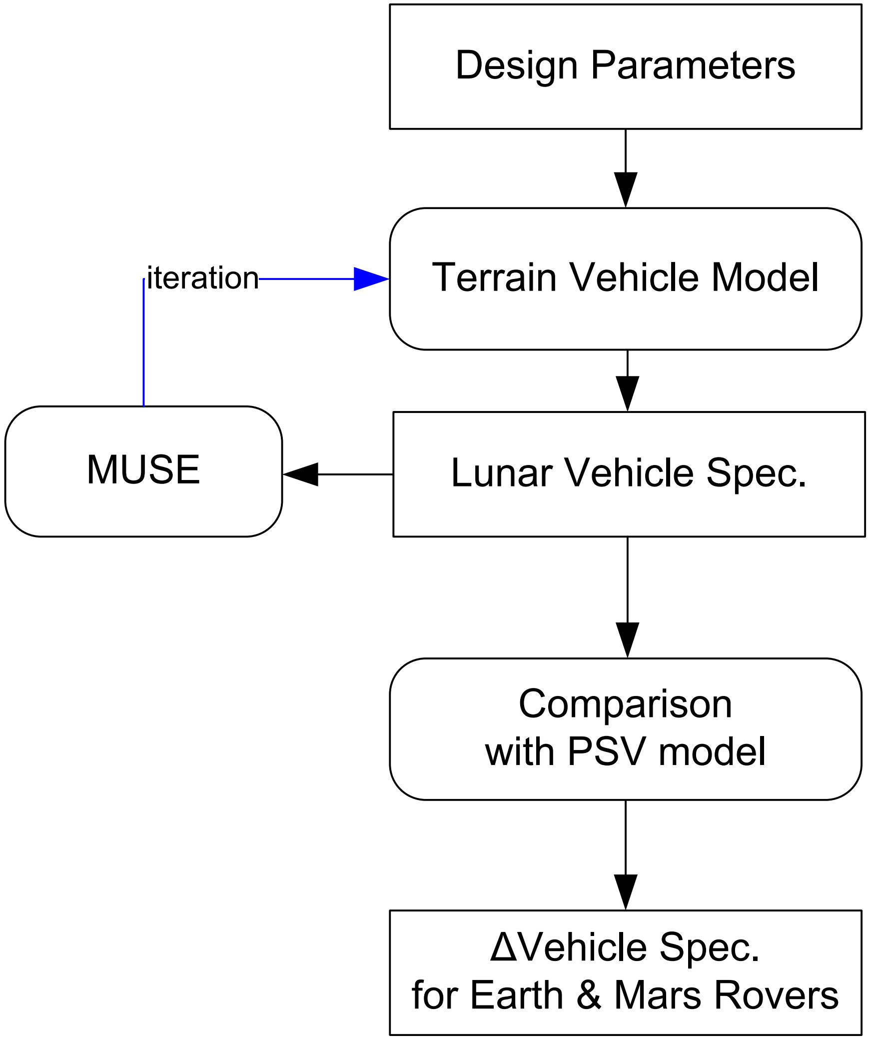


- **Utilizing a pressurized rover in concert with unpressurized vehicles (UPVs) results in duplication of functionality:**
  - **Additional functionality for steering and navigation in pressurized rover (cockpit)**
  - **This additional functionality results in a power, volume, and mass penalty compared to using a camper (excess mass must be transported during the entire traverse)**
- **Using campers that are guided by UPVs represents a minimalist solution to long-range surface mobility**
- **Camper crew compartment is inherently similar to the human lunar lander crew compartment (option for commonality, synergy)**

Mobility System Design

Mobility Design Approach

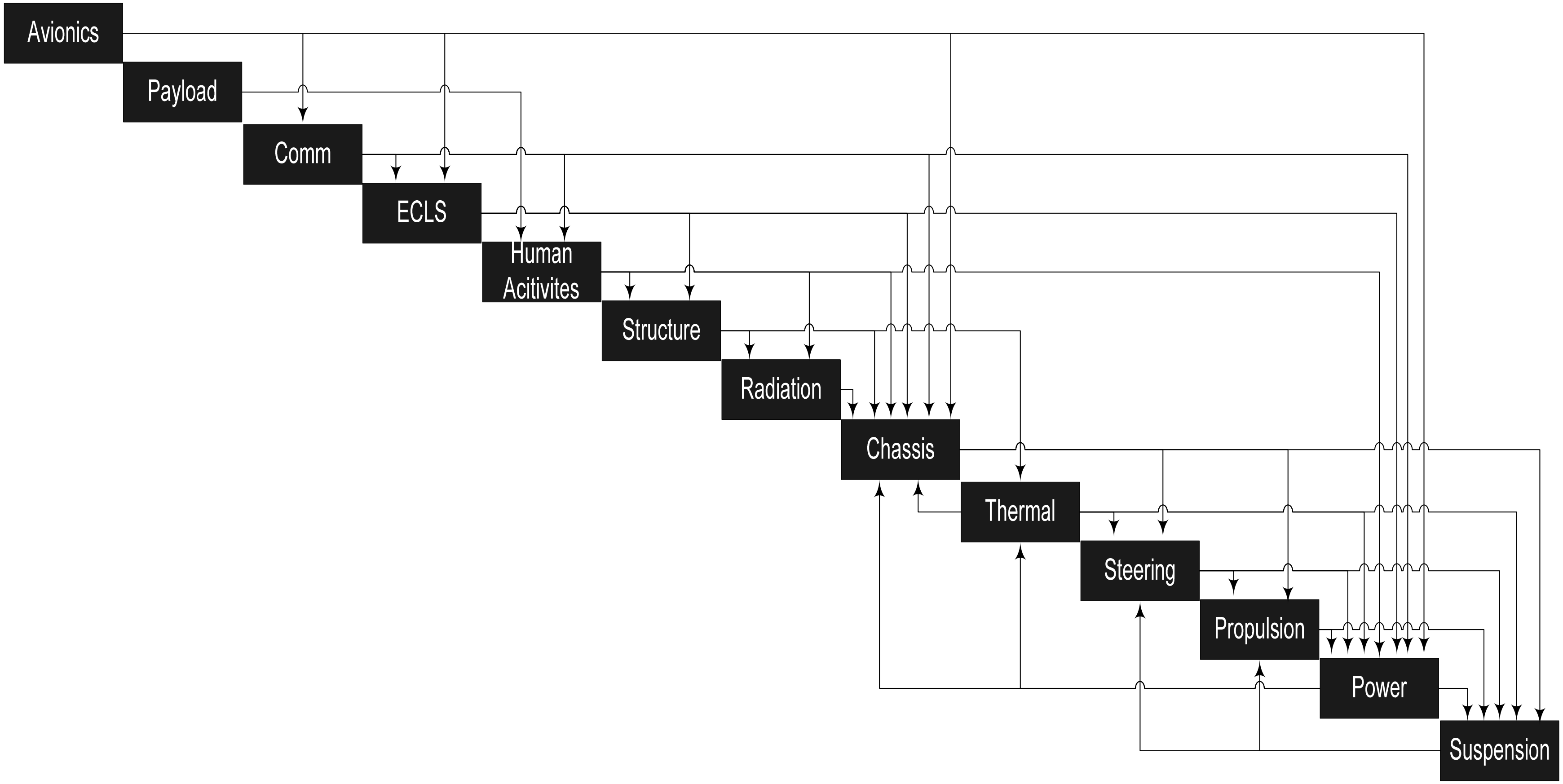
- First design the lunar camper and UPV for DRM 1 & 2, then study the delta to Earth and Mars designs
- Vehicle design is broken down by subsystem and coded into MATLAB modules
- Vehicle characteristics are determined by iteratively running each subsystem module
- MUSE verifies the feasibility of vehicles' design



Basic Assumptions

- 2 crews for camper, 2 crew for UPV
- Total excursion days: 7 days
- Number of driving day: 4 days
- Number of consecutive driving days: 2 days (?)
- Driving or working time per day: 12 hr/day
- Number of EVAs per excursion: 7
- Number of traverses over the lifetime of the vehicle: 125
- ECLS regeneration on camper
- Number of wheels: 4
- Driving system on Camper & no steering system on Camper
- UPV guides Camper, not tows
- Al structure and chassis

Interface


Avionics
Payload
Comm
ECLS
Human Acitivites
Structure
Radiation
Chassis
Thermal
Steering
Propulsion
Power
Suspension

Comparison of TVM & PSV

TVM	PSV
Power storage on camper	Power storage on UPV
Driving motor on camper	No driving motor on camper
UPV GUIDEs a camper	UPV TOWs a camper
Radiation protect system	No radiation protect system
Consideration of terrain roughness	No consideration of terrain roughness
More detail model on thermal, comm	Simple model on thermal, comm
Consideration of living space	No consideration of living space

Human Activities Module (1)

- **Assumptions**
  - **No Kitchen – MRE's (American)**
  - **No Bunks – Astronauts kip on hammocks spanning width of living space**
  - **Living space is rectangular**
  - **Ceiling is the curved interior wall of "can"**
  - **All space outside living space is usable for storage/supplies**
- **Basis**
  - **HSMAD**
  - **PSV Model**
  - **Personal Experience RV'ing across USA while growing up**

Human Activities Module (2)

- **Function**
  - **Volume**
    - Living space volume determined by summing volumes of things needed per person per excursion that exist in living space
    - Storage space volume determined by summing volumes of things needed per person per excursion that may be stored
  - **Mass**
    - HA mass determined by summing volumes of things needed per person per excursion
  - **Power**
    - Power determined by summing items that draw power for living, EVA’s, and interior work

ECLS System Model (1)

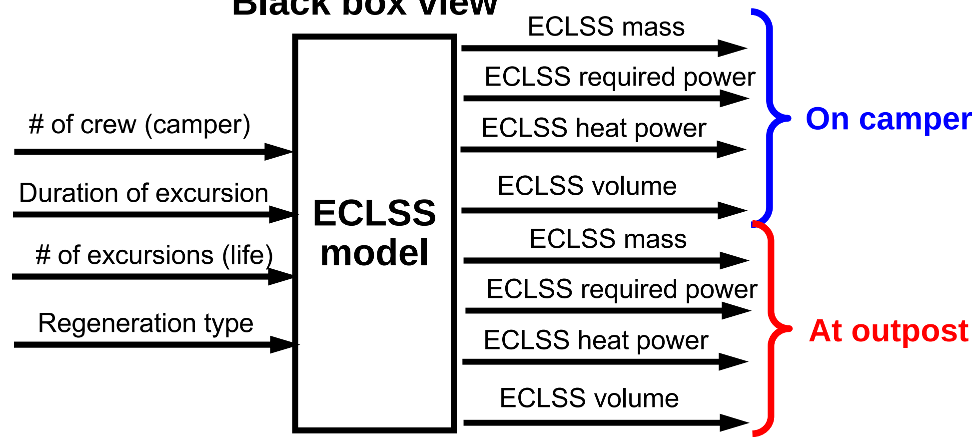
Assumptions, ground rules:

-ECLS is only required on the camper

-The camper is continuously operated for excursions of 1-2 weeks duration

-Over the lifetime of the camper, on the order of 100 such excursions can occur

Black box view



Mathematical model is based on equipment parameters provided by HSMAD [1]

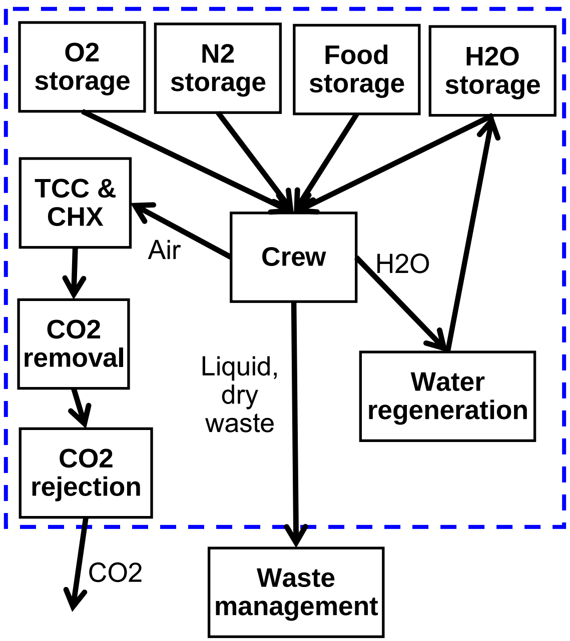
ECLS functionality:

Provide O2 & N2 storage
Provide O2 & N2 feed and control
Provide trace contaminant control
Provide CO2 filtering
Provide CO2 drain and storage
Provide CO2 rejection
Provide food to crew
Provide water storage
Provide water filtration and regeneration

- **Major ECLS system interfaces:**
  - To human factors / accommodations: waste management
  - To power generation + storage (required power)
  - To thermal control (waste heat)
  - To structure (mounting, structural integrity)
  - To astronauts, cabin atmosphere
  - To avionics (control, crew interfaces)

ECLS System Model (2)

Baseline ECLS system design:



ECLS functionality for different use cases / planetary surfaces:

Planetary surface	Earth	Moon	Mars
Provide O2 & N2 storage		X	X
Provide O2 & N2 feed and control		X	X
Provide trace contaminant control		X	X
Provide CO2 filtering		X	X
Provide CO2 drain and storage			X
Provide CO2 rejection		X	X
Provide food to crew	X	X	X
Provide water storage	X	X	X
Provide water filtration and regeneration	X	X	X

Example legacy hardware:

Shuttle condensing heat exchanger

ISS cabin fan

ISS water multi-filtration device (hardware)

- **ECLS system extensibility:**
  - **Mars use case requires most functionality due to difficulty in CO2 rejection**
  - **Food and water management are common for all three use cases**
  - **Platform should be lunar design with scarring for Mars CO2 drain, storage and rejection**
  - **Design should be modular so that atmosphere management components can be removed for Earth use case**

Thermal Module (1)

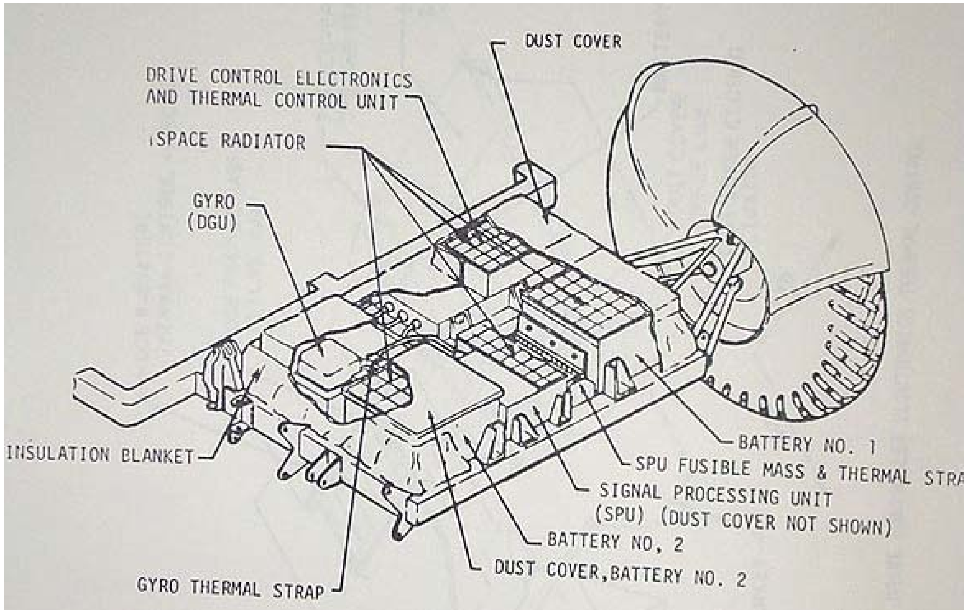
- Environmental Inputs
  - Solar energy from sun
  - Albedo effects
  - IR emission from surface
- Vehicle Inputs
  - Driving heat produced
  - Sci. time heat produced
  - Surface area of vehicle
    - Average environment heat flux
  - Vehicle type
- Sizing
  - Heat flow problem: need more heat dissipation or retention?
  - Based on HSMAD parametric values
- Trade
  - Vertical radiator
    - Bi-directional heat radiation
    - Additional structural mass
  - Horizontal radiator
    - Less structural mass
    - Uni-directional heat radiation
- Outputs
  - Total thermal volume
  - Thermal mass on chassis
  - Thermal pressurized mass
  - Thermal driving power
  - Thermal science time power
- Verification
  - LRV (for upv only)

Thermal Module (2)

- **Assumptions**
  - Paint absorptivity: 0.2
  - Paint emissivity: 0.8
  - 1.2 factor on heat inputs
  - Radiators on top of camper for better heat dissipation
- **Heat dissipation**
  - Radiation only on Moon
  - Radiation, convection on Mars
  - Convection on Earth
  - Size radiator and support structures to dissipate higher value of heat
  - "Delta" between environments can be found, but no redesign of internal fluid paths

- **Components**

MLI	fluids
Heat pumps	plumbing
radiators	louvers
controls	Structural support



Apollo LRV Thermal components, including Space Radiators (courtesy NASA: LRV Bible)

Radiation Module (1)

- Environmental Inputs
  - Average GCR
  - Solar Particle Events
- Vehicle Inputs
  - Surface area of airlock
  - Vehicle type
- Sizing
  - Keep under NASA radiation requirements
    - 50 REM per year
- Trade

Water	Aluminum
Lithium Hydride	Polyethylene
Liquid hydrogen	Liquid methane

- Process
  - Iterates thickness of shielding until less than yearly value
- Outputs
  - Total radiation volume
  - Radiation mass
- Verification
  - HSMAD
    - States 10 g/cm^2 is reasonable areable density for solar particle event protection

Radiation Module (2)

- Assumptions
  - Use additional shielding provided by airlock structure, vehicle structure, other components to stop radiation
  - SPE protection sized based on the 6 solar particle events in 1989
  - Worst case scenario with GCR at solar minimum plus these events
  - Astronauts sleep in airlock, which is also the safety vault, so no need to place shielding elsewhere
    - Large reduction in mass

- Major questions to answer
  - How much radiation is stopped by Mars atmosphere?
  - How much lead time will astronauts have before an SPE hits?
    - Technology improvement (SOHO, etc)
  - Long-term effects of GCR on cancer risks?
  - Verification of materials for effectively stopping GCR
    - Polyethylene proved ineffective on ISS at stopping GCR cascading effects

Structures (Crew Compartment)

- Assumptions for the model
  - Shell thickness will be sized based on pressure difference
  - Does not assume different dynamic failure modes
- Inputs
  - Human activity dimensions (width and length)
  - Internal crew stations dimensions
  - Environment conditions
- Outputs
  - Structure mass
  - Structure volume
  - Surface area for radiation system
  - Surface area for thermal system

Structures (Crew Compartment) (2)

- Interfaces
  - Human activities
  - Thermal
  - Radiation
  - Chassis
- Description
  - Skeleton frame material is Al-2219
  - Shell material is Al-7075
  - Internal pressure kept at 10.2 psi or 0.694 atm
  - Frame includes 6 horizontal supports and 4 cross-section ribs
- Reference
  - Framework and thickness of skeleton based on airplane specifications
- Earth, Moon, Mars Extensibility?
  - Major factors that will change
    - External pressure: size the thickness of the shell
    - Gravity: loading forces

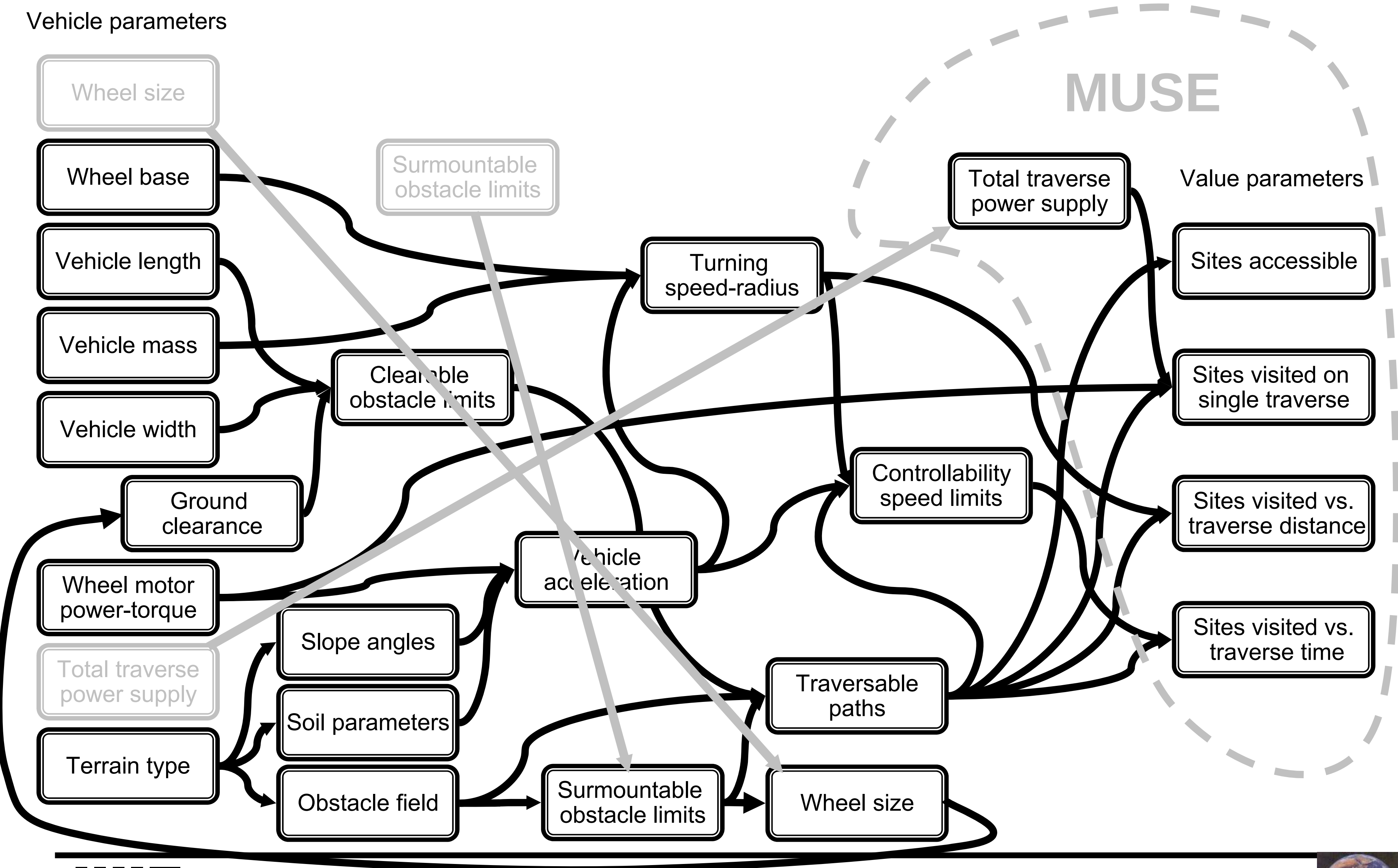
Chassis

- **Assumptions for the model**
  - Ladder chassis
  - Uniform vertically distributed load
  - Calculated for an allowable maximum deflection of 0.02m
- **Inputs**
  - Structure dimensions (length and radius)
  - Wheel diameter
  - Total mass needed to be carried by the chassis
  - Environment conditions
- **Outputs**
  - Chassis dimensions (wheelbase, track, height)
  - Chassis mass
  - Free chassis volume

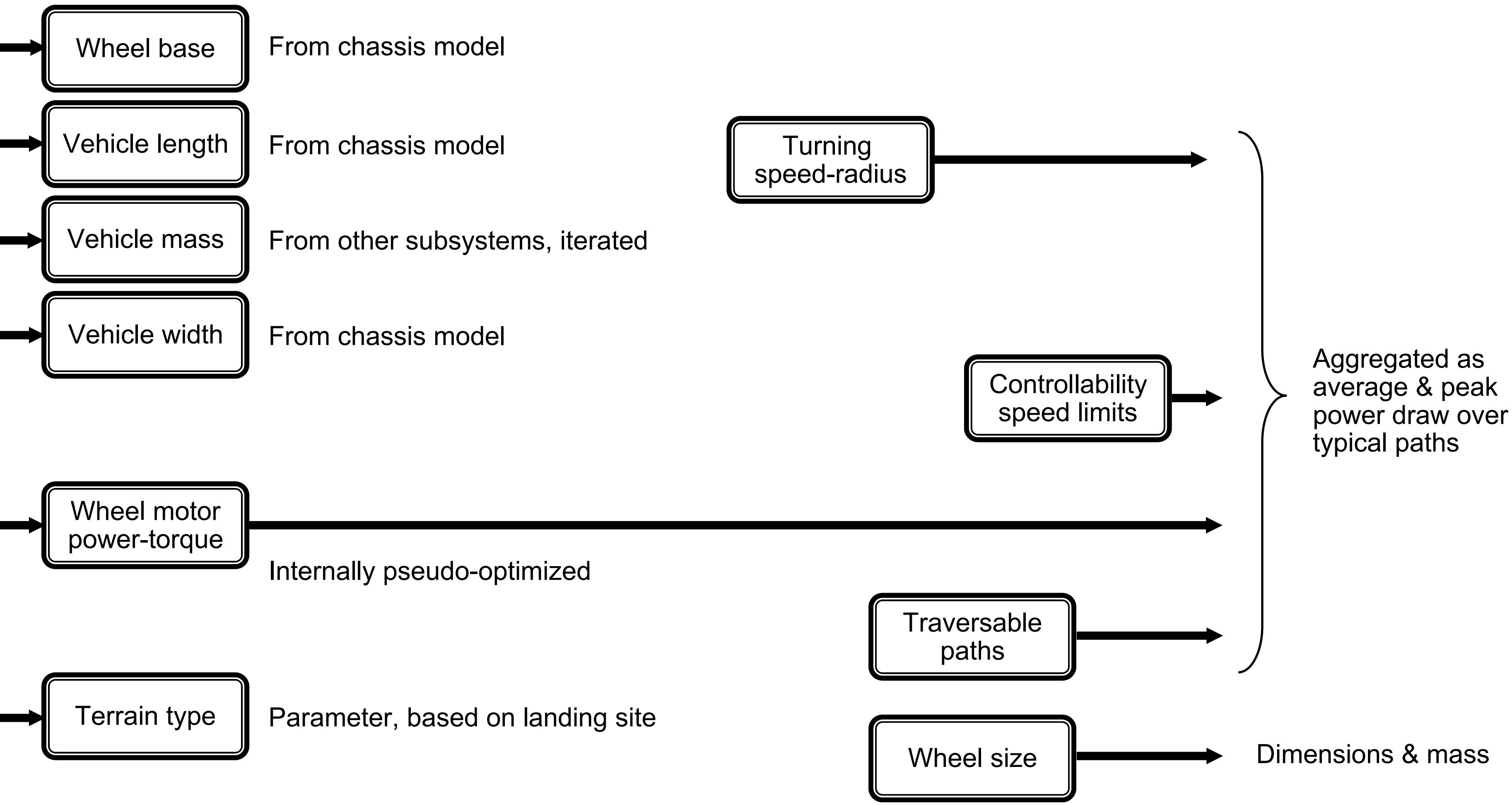
Chassis (2)

- Interfaces
  - Human activities
  - Payload
  - Structures
  - Propulsion
  - Various other subsystem volume and masses
- Description
  - Beams have square solid cross-sections
  - 2 side rails and 3 cross bars
  - Free chassis volume calculated includes volume between the chassis and the crew compartment
- Reference
  - Based off ladder model and PSV assumptions
- Earth, Moon, Mars Extensibility?
  - Major factors that will change
    - Gravity: loading forces

Propulsion: A Few Changes …



Propulsion: Inputs and Outputs



Terrain Characterization

Sample terrains for simulation generated from relationships in Apollo and post-Apollo geological literature

TABLE 2. PHYSICAL AND MECHANICAL PROPERTIES OF LUNAR SOIL SIMULANTS

Soil Condition	G (MN/m³)	e	D_r (%)	ρ (g/cm³)	ρ_L (g/cm³)	k_c [(lb/in.)$^{1+n}$]	k_ϕ [(lb/in.)$^{2+n}$]	n	ϕ_b (deg)	c_b (kN/m²)	ϕ_{PL} (deg)	ϕ_T (deg)	c_{TR} (kN/m²)
Yuma Sand													
S_1	0.54	0.77	32	1.51	1.75	0.54	6.01	0.72	13.8	1.65	29.8	37.1	0
C_0	0.21	1.02	0	1.32	1.53	2.61	2.46	0.73	21.6	0.83	28.1	34.6	0.28
C_1	1.26	0.94	14	1.38	1.60	0.21	8.03	0.67	23.5	0.97	29.0	36.0	0.55
C_2	3.17	0.83	52	1.46	1.69	4.96	10.08	0.52	15.2	2.14	31.2	38.4	1.10
Crushed Basalt													
LSS_1 – (Loose-Air Dry)	0.2	0.90	31	1.52	1.63	0.42	4.32	0.90	29.0	0.97	34.0	38.5	0
LSS_2 – (Intermediate Density-Air Dry)	0.6	0.83	42	1.58	1.69	0.13	5.34	1.15	29.0	1.03	35.0	39.0	0.3
LSS_3 – (Dense-Air Dry)	1.8	0.74	52	1.66	1.78	-1.58	8.83	1.48	28.8	1.03	35.5	40.0	0.6
LSS_4 – (Loose-Moist)	1.0	0.90	31	1.52	1.63	1.76	5.04	1.18	29.0	0.83	34.0	38.5	0.8
LSS_5 – (Dense-Moist)	6.4	0.69	59	1.71	1.83	(Not Available)					36.0	41.5	2.9

G – Penetration resistance gradient

e – Void ratio

D_r – Relative density

ρ – Dry bulk density (specific gravity of solids: Yuma Sand – 2.67; crushed basalt – 2.89)

ρ_L – Equivalent bulk density of lunar soil (specific gravity of solids – 3.1), based on the same void ratio

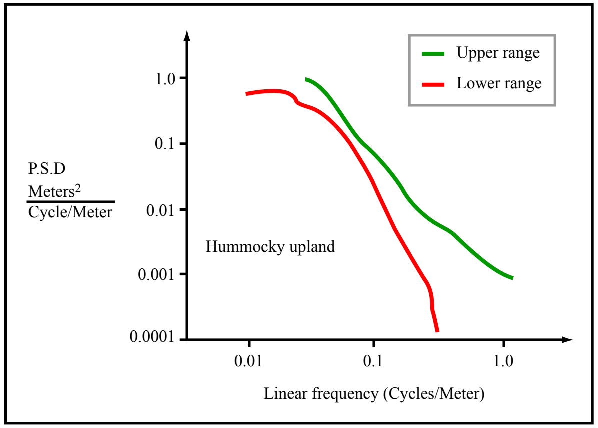
k_c, k_ϕ, n – LLL soil values obtained by standard plate Bevameter tests

ϕ_b, c_b – Soil friction angle and cohesion obtained by standard Bevameter ring-shear tests

ϕ_{PL} – Soil friction angle obtained from in-place plate shear tests

ϕ_T – Soil friction angle obtained from triaxial compression tests

c_{TR} – Soil cohesion obtained from trench slope stability analysis and triaxial compression tests



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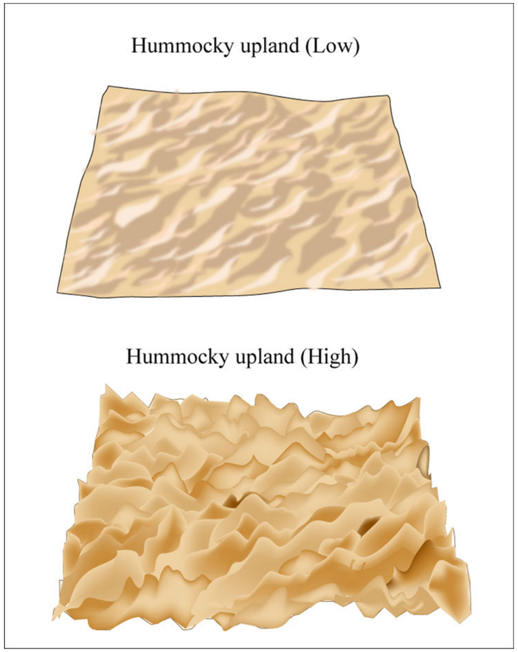

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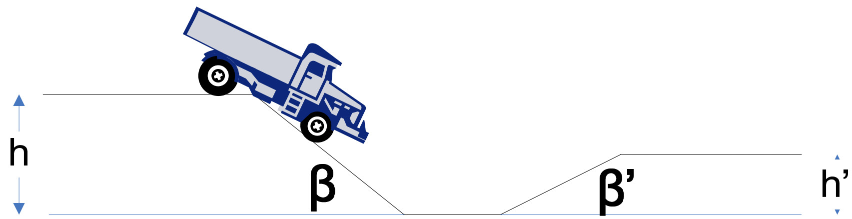
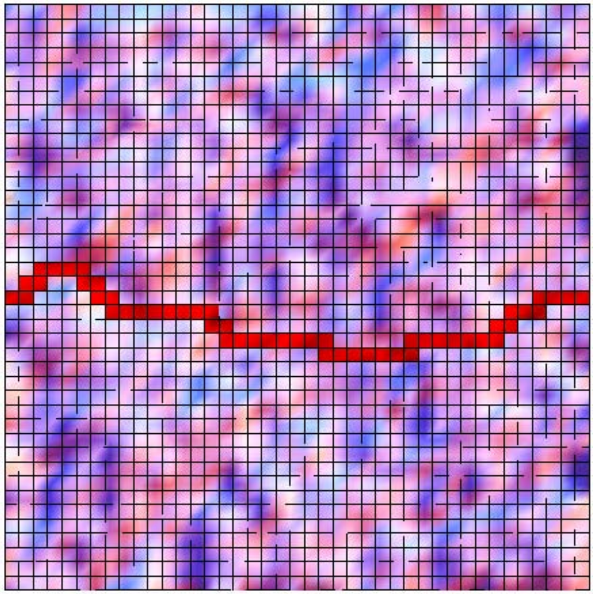
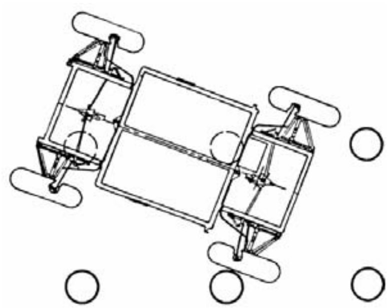
Terrain type → Slope angles, Soil parameters, Obstacle field

Traverse Performance



$$h \leq 0.5\left((D_W + D_O) - \sqrt{(D_W + D_O)^2 - b^2}\right)$$





Clearable obstacle limits

Wheel motor power-torque

Slope angles

Soil parameters

Obstacle field

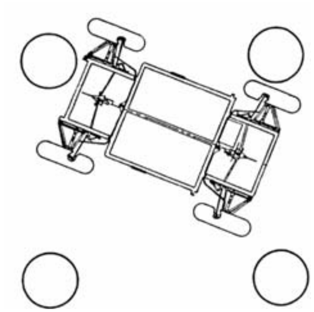
Vehicle acceleration

Surmountable obstacle limits

Controllability speed limits

Traversable paths

Based on geometric navigability of obstacle field, combined with path planning constrained by vehicle geometry and dynamics



Steering

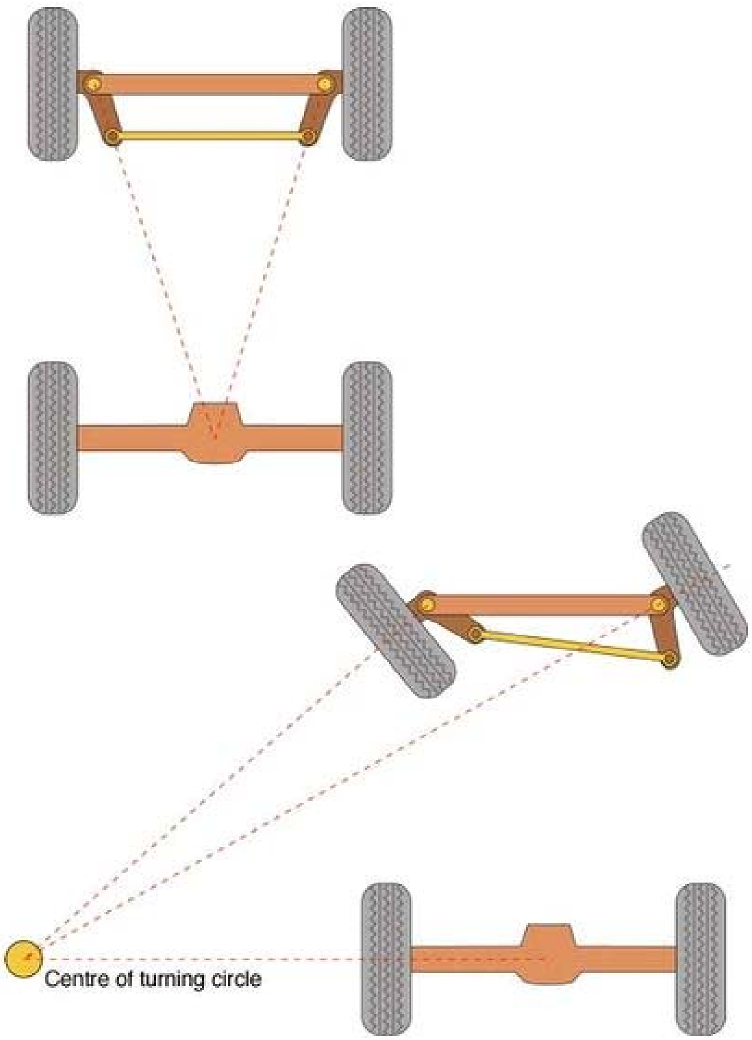
- **Assumption**
  - Electronic power steering
  - Wheel turning angle is 50°

- **Inputs**
  - # of steered wheels
  - Sprung mass
  - Wheel base, track

- **Outputs**
  - Steering mass
  - Turning Radius

Steering (2)

- **Interfaces**
  - **Chassis**
  - **Various other subsystem masses**
- **Description**
  - **Ackerman steering model**
- **Reference**
  - **Motor Truck Engineering Handbook, pg 326**



Power Module

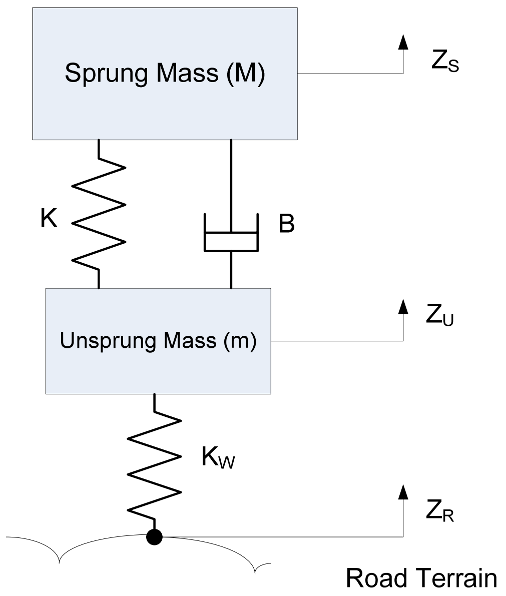
- **Inputs**
  - **Power levels for various power modes from each subsystem**
  - **Traverse duration**
  - **Energy needed for UPV science traverse**
- **Outputs**
  - **Power subsystem mass and distribution**
  - **Thermal power to dissipate**
  - **Amount of water produced**

Power Module (2)

- Power is stored in primary fuel cells
- From the power usage and times, calculates energy and sizes the fuel cell reactants
- From the peak power, sizes the distribution and conversion components
- Based largely on the PSV code and adapted for our TVM
- Extensible to Earth and Mars

Suspension

- **Assumption**
  - Quarter-Car Model
  - Passive Control
- **Inputs**
  - Sprung mass
  - Wheel mass
  - Tire Stiffness
- **Outputs**
  - Spring Stiffness
  - Damping Coefficient
  - Suspension Mass

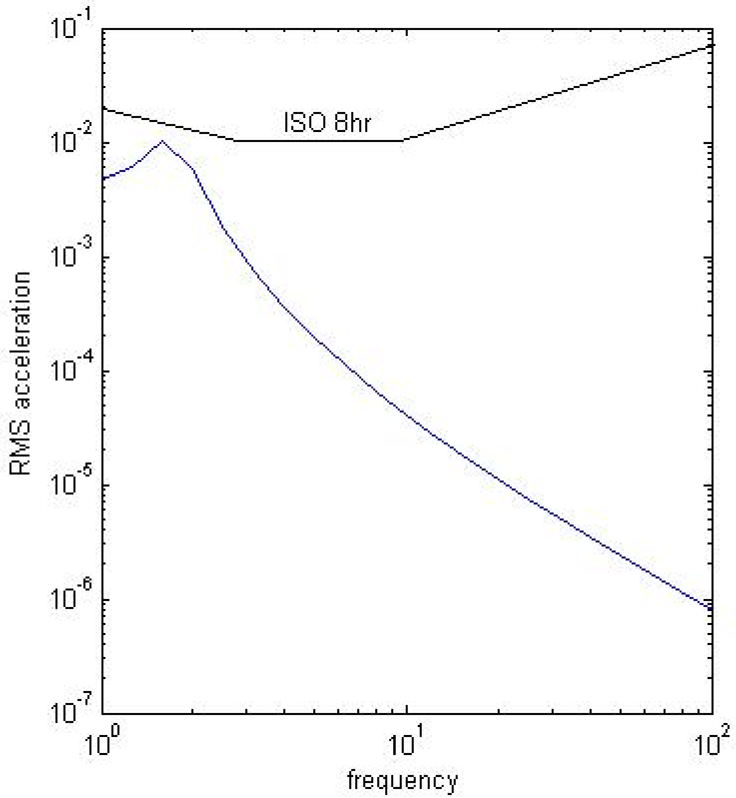


Suspension (2)

- **Interfaces**
  - **Propulsion**
  - **Various other subsystem masses**

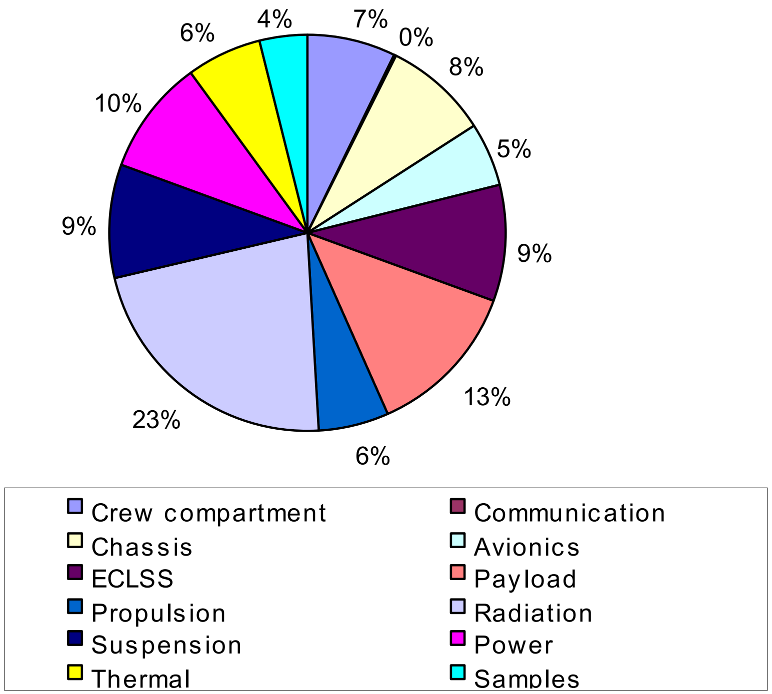
- **Description**
  - $$a_{RMS} = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt}$$
  - **Evaluate the vibration of the vehicle against ISO 2631-2 criteria**

- **Reference**
  - **Theory of Ground Vehicles, Wong, 1978**
  - **ISO 2631-2**

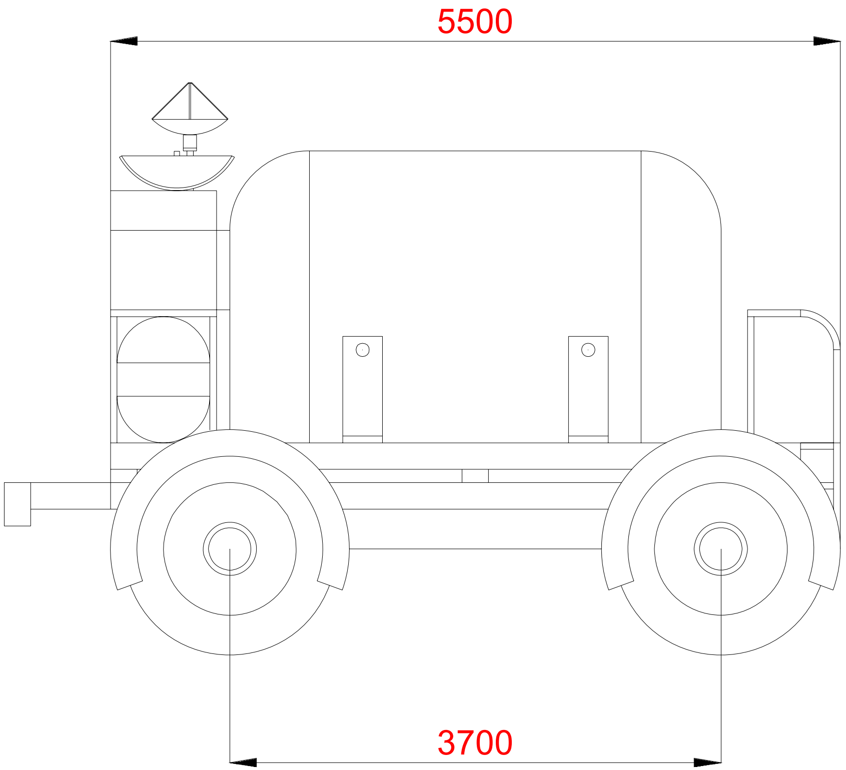


Camper Design Specifications

CAMPER	dimensions (m)		vol (m^3)	mass (kg)
Crew compartment	radius	1.63		275
	length	3.11		
Comm.	antenna height	1		10
Chassis	wheel base	3.64		321
	wheel track	3.49		
	height	0.076		
Avionics			0.248	200
ECLSS	O2N2 tanks		0.0966	358
	H2O tanks		0.1428	
Payload	equipment		0.53	482
Propulsion	Wheel dia.	1.6		229
	Wheel width	0.5		
Radiation	around shell		0	840
Suspension				355
Power	total		0.27	364
	water		0.151	
Thermal	vert. radiator		0.5281	226
	MLI		0.55	
	pump		0.06	
Samples			1	150
		Total Mass (kg)		3810

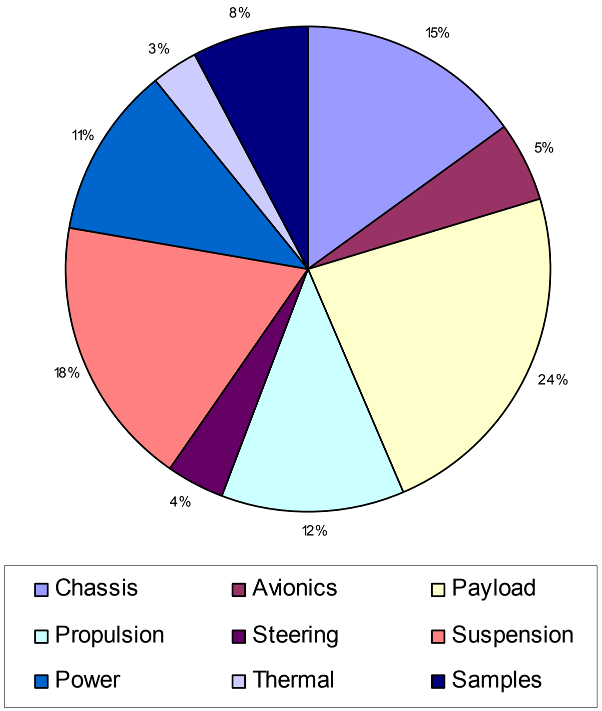


Camper Design Concept

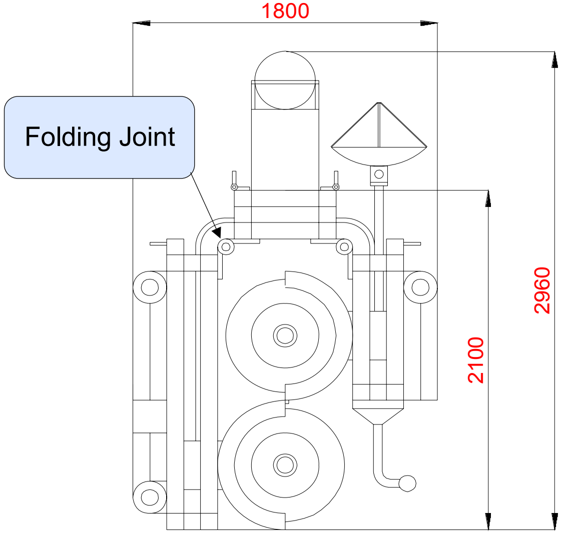


UPV Design Specifications

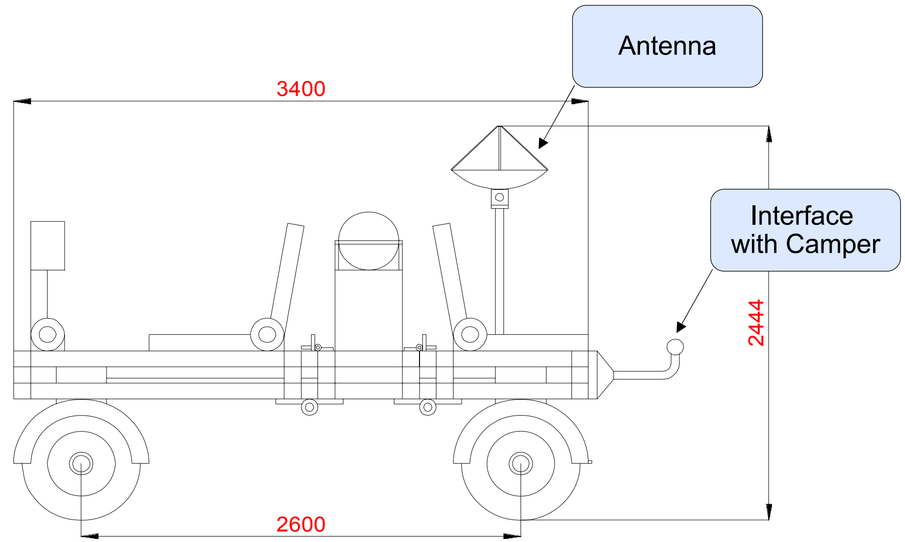
UPV	dimensions (m)		vol (m^3)	mass (kg)
Chassis	wheel base	2.6		58
	wheel track	1.7		
	height	1.4		
Avionics			0.248	20
Payload	equipment		0.21	90
Propulsion	Wheel dia.	0.7		48
	Wheel width	0.23		
Steering				15
Suspension				69
Power	total	0.27		44
Thermal	total			12
Samples			0.1	30
		Total Mass (kg)		386



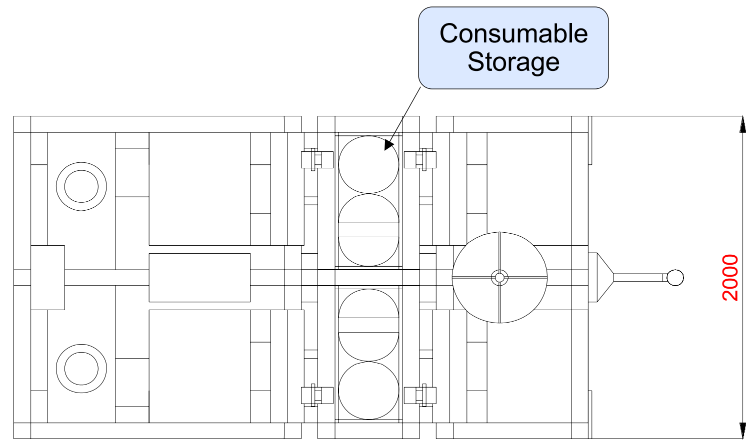
CAD Model - UPV



<Packaging View>



<Side View>



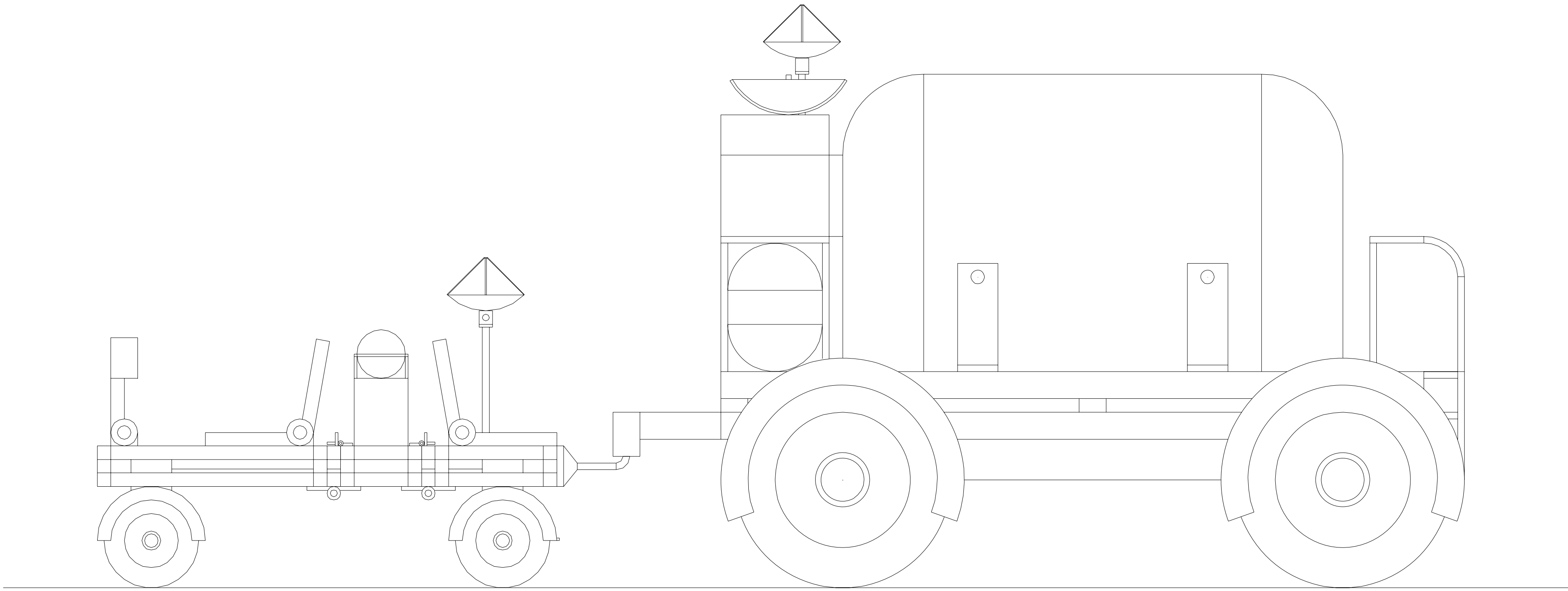
<Top View>

Power Distribution

Camper (Watts)	**always**	**driving**	**science (day)**	**night**
Propulsion		1205		
Thermal		73	87	87
Avionics	300	300	400	
Comm	96	96	96	96
HA			150	150
ECLSS	80	80	900	900
Payload (Science)			100	
Steering				
sub Total	476	1754	1733	1233
Total with 15% margin	547.4	2017.1	1992.95	1417.95

UPV (Watts)	**driving**
Total with 15% margin	852

UPV –Camper Combination



Vehicle Analysis

Commonality, Sensitivity, and Extensibility for Different Environments

Vehicle Sensitivity Analysis

- Used PSV model to determine effects planet has on the design
- Analyze mass of subsystems on different planets, multipliers, and absolute differences
- Important scaling factors

System	Earth	Mars
Chassis	gravity (9.8 m/s^2)	gravity (3.3 m/s^2)
ECLSS	breathing-air ventilation	CO2 control
Human activities	no airlock	similar to Moon
Propulsion	terrain and gravity	terrain and gravity
Radiation	None required	thickness, environment
Shell structure	external pressure	external pressure
Power	Temperature difference	Temperature difference
Thermal	Heat absorb, convection	Heat absorb

PSV Camper Sensitivity to Surface Environment

- **Mass variation from the Moon design:**
  - **Earth: crew station, chassis, propulsion**
  - **Mars: chassis, propulsion, power**
- **Subsystems are predominately most massive in Mars design**

PSV Camper	Mass (kg)			Ratio		Absolute Difference	
	Moon	Earth	Mars	Mars/Moon	Earth/Moon	Moon-Earth	Moon-Mars
crew station mass	1239	816	1238	0.999	0.659	423	1
communication	32	32	32	1.000	1.000	0	0
chassis	109	268	219	2.009	2.459	-159	-110
wheel	44	91	102	2.318	2.068	-47	-58
suspension	160	150	190	1.188	0.938	10	-30
drive system	28	107	62	2.214	3.821	-79	-34
power	113	136	207	1.832	1.204	-23	-94
thermal	75	67	87	1.160	0.893	8	-12
steering	22	20	23	1.045	0.909	2	-1
TOTAL	**1822**	**1687**	**2160**	**1.186**	**0.926**	**135**	**-338**

PSV ATV Sensitivity to Surface Environment

- **Mass variation from the Moon design:**
  - **Earth: chassis, propulsion, power, thermal**
  - **Mars: chassis, propulsion, power**
- **Design for system for Moon and Mars**

PSV ATV	Mass (kg)			Ratio		Absolute Difference	
	Moon	Earth	Mars	Mars/Moon	Earth/Moon	Moon-Earth	Moon-Mars
communication	**16.21**	**16**	**16**	**0.987**	**0.987**	**0.21**	**0.21**
chassis	**32.74**	**194**	**65**	**1.985**	**5.925**	**-161.26**	**-32.26**
wheel	**11.16**	**54**	**63**	**5.645**	**4.839**	**-42.84**	**-51.84**
suspension	**11.23**	**39**	**23**	**2.048**	**3.473**	**-27.77**	**-11.77**
drive system	**10.73**	**47**	**21**	**1.957**	**4.380**	**-36.27**	**-10.27**
power	**20.52**	**43**	**39**	**1.901**	**2.096**	**-22.48**	**-18.48**
thermal	**4.78**	**16**	**7**	**1.464**	**3.347**	**-11.22**	**-2.22**
steering	**9.2**	**11**	**10**	**1.087**	**1.196**	**-1.8**	**-0.8**
				2.10	**3.62**		

Commonalities

- Camper
  - Shell Structure
  - Power
  - Thermal
  - Suspension
  - Propulsion
    - Motors
    - Wheels
  - Radiation
  - Payload
  - Steering
  - ECLSS
  - Chassis
  - Communications
  - Human Activities
    - Airlock

- UPV
  - Power
  - Thermal
  - Suspension
  - Propulsion
    - Motors
    - Wheels
  - Chassis
  - Payload
  - Steering
  - Communications

Changes for Earth

Changes for Mars

Changes for Both

- Highlights major varying subsystems
- 2 design options

Vehicle Commonality Conclusion

- Fix chassis geometry
  - Common chassis design for different environments
  - Vary beam profiles to account for different loads
  - Allows for swappable subsystem modules
  - Reduce multiple chassis design cost
- Crew station, wheels and propulsion need to be modified based on terrain and external environments
- UPV design for Moon and Mars
  - Customize existing ATVs for Earth operations
- Over-designed UPV chassis can be beneficial to DRM 3 and DRM 4 operations on the moon

DRM 3 and DRM 4 Briefly Revisited

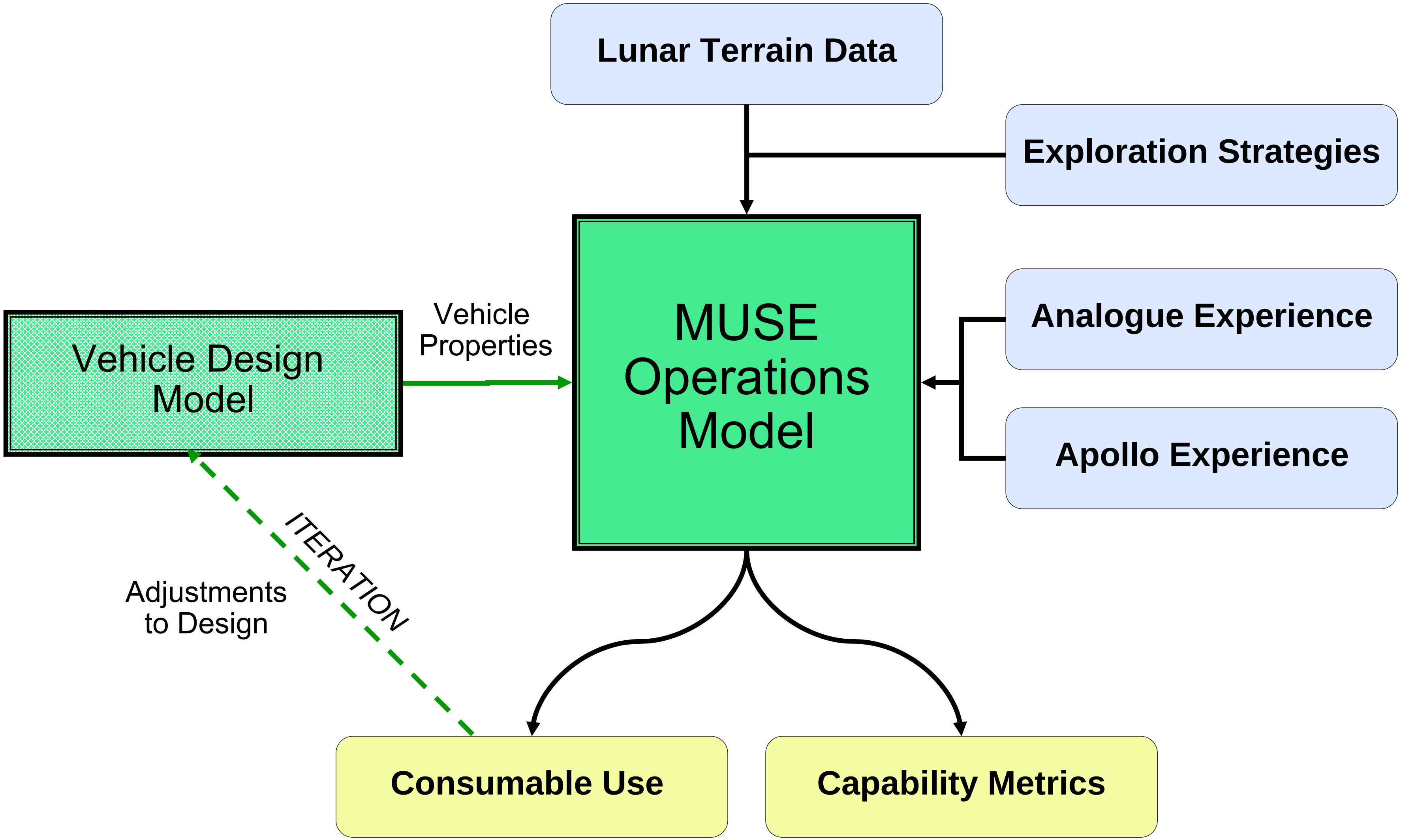
- DRM 3
  - Resupply within 3km
  - Move cargo from lander to base (lifting, towing)
    - Astronaut manipulable “briefcases” (~100 kg)
    - Medium-size modules that need manipulation assistance (~500 kg)
    - Large pallets with built-in mobility (~2 mt)
    - Moon outpost mission: 7.3 mt for consumables
- DRM 4
  - Infrastructure buildup within 3km
  - Move regolith to provide blast protection, radiation/thermal shielding, initial ISCP
  - Deploy small equipments
  - Connect base modules with wires, etc.
  - Light surface construction
    - Cable bundle estimate: 300 kg and 0.3 m3
    - Large science instruments are ~25 kg
    - Estimated mass: 250-300 kg for backhoe, 150-200 kg for dozer blade

Extensibility DRM 3 and DRM 4

- Approximate horizontal force ~ 6x10^6 N
- Approximate digging/lifting force ~2,296 N
  - Plowing ~6x10^6 N
  - Lifting capacity ~ 1,408 kg
  - Bucket Capacity ~ 0.04 m^3
- Average regolith density ~ 1,250 kg/m^3
- Moon gravity ~ 1.63 m/s^2

Integrated Dynamic Capability Analysis (MUSE)

Mission Utility Simulation Environment (MUSE)

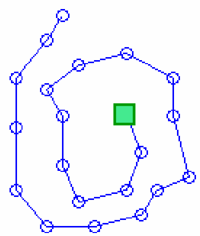


Roles of MUSE

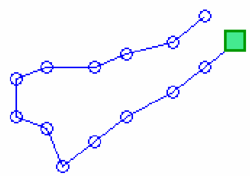
- Validation tool of vehicle capabilities
  - Vehicle architecture design ("static" model)
  - MUSE ("dynamic" model)
- Iterative design
  - Enables debugging of vehicle model and MUSE simulation
  - Enables convergence to overall design
- Identification of consumable modularity opportunities
- Environment incorporating all the key components:
  - Terrain
  - Vehicle design
  - Logistics (consumables, human activities)

DRM-1 & DRM-2 Exploration Strategies

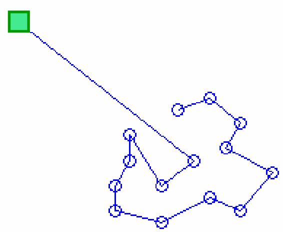
- **Four DRM-1 exploration types**



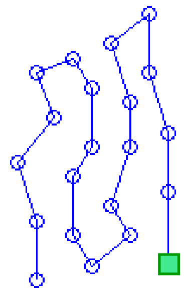
Spiral
Search in expanding circle around origin



Loop
Travel out and come back on different path



Area Search
Travel to distant site and explore sites in vicinity

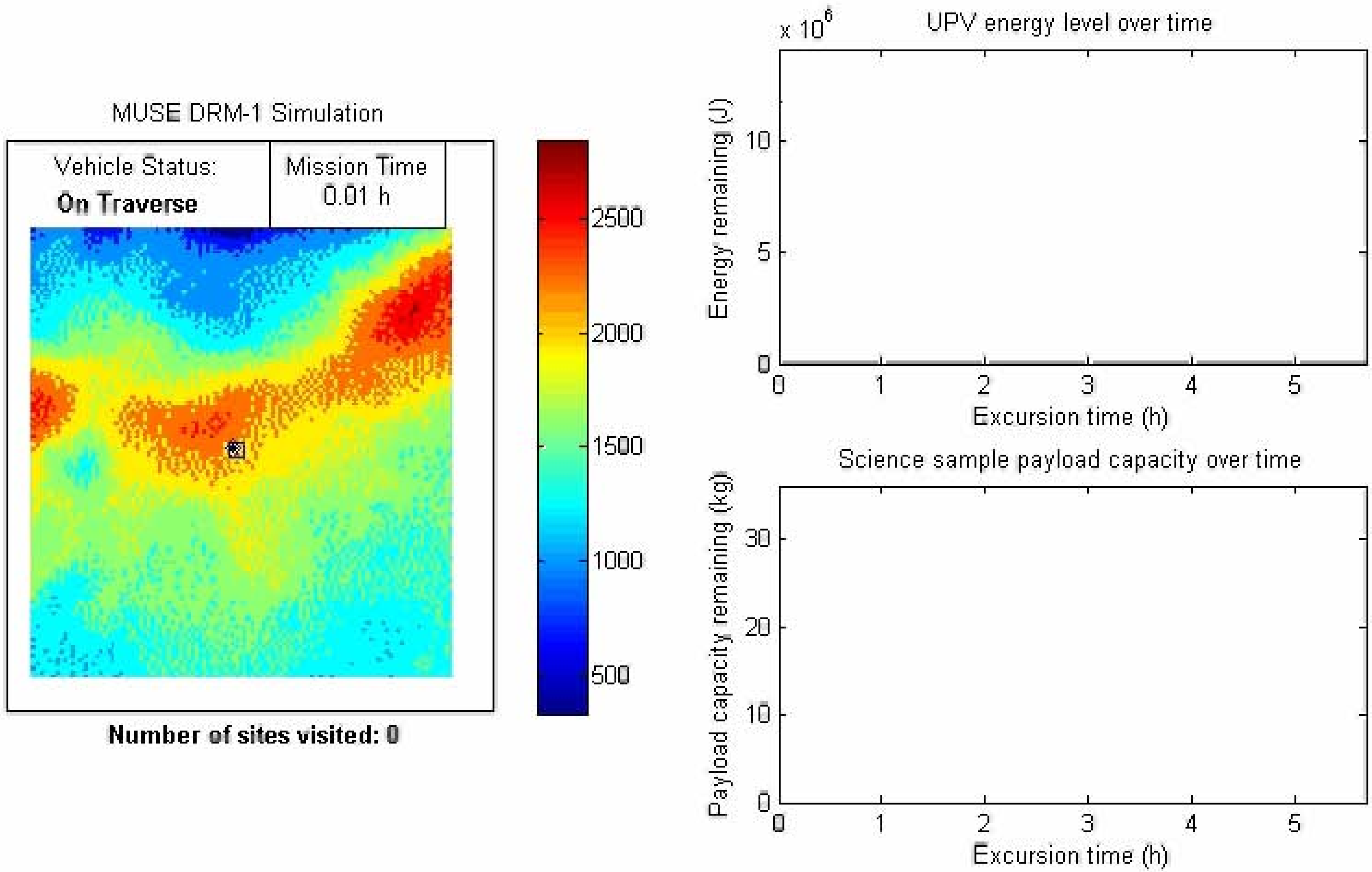


Grid Search
Travel to sites along survey grid lines

  - Each location is either a “site” or a “region” (collection of four closely-spaced sites)
  - Locations of interest are ~3km apart (from Apollo)

- **DRM-2: drive directly to camp site, perform DRM-1’s**

DRM-1 Simulation
Tsiolkovsky Crater



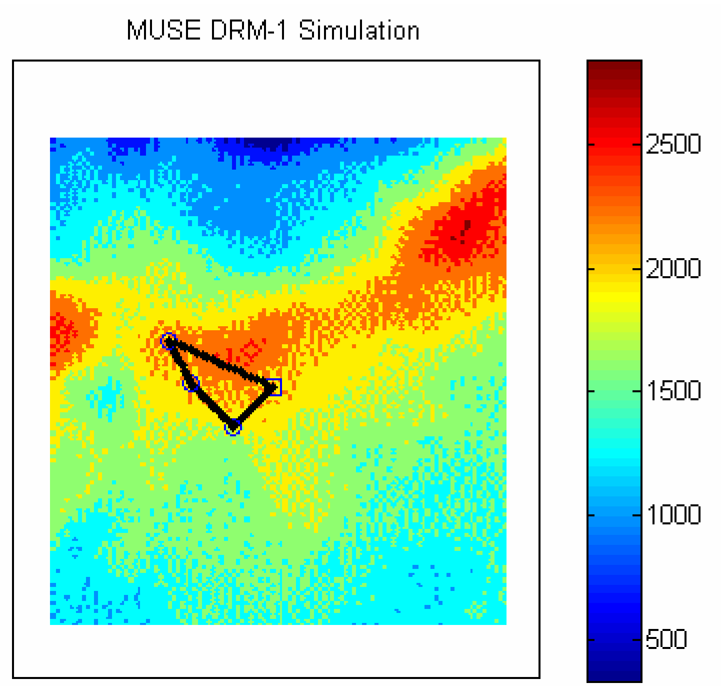
Modeling DRM-1

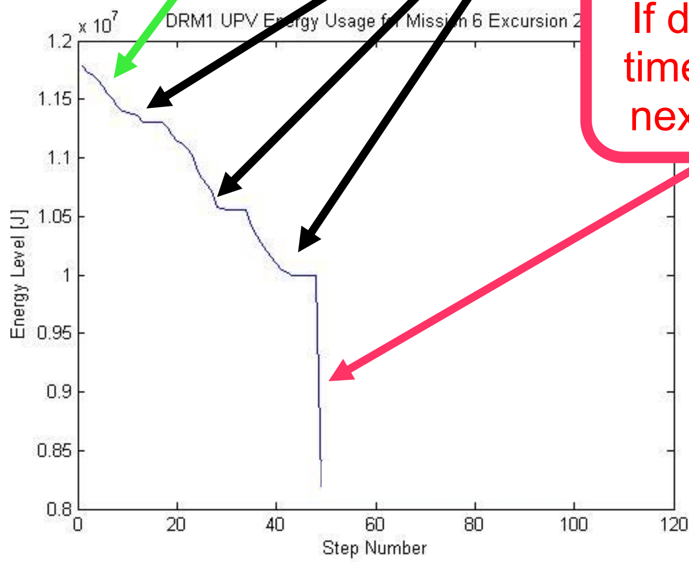
Traverse

Propagate over Terrain
Decrement energy
Increment time

Site

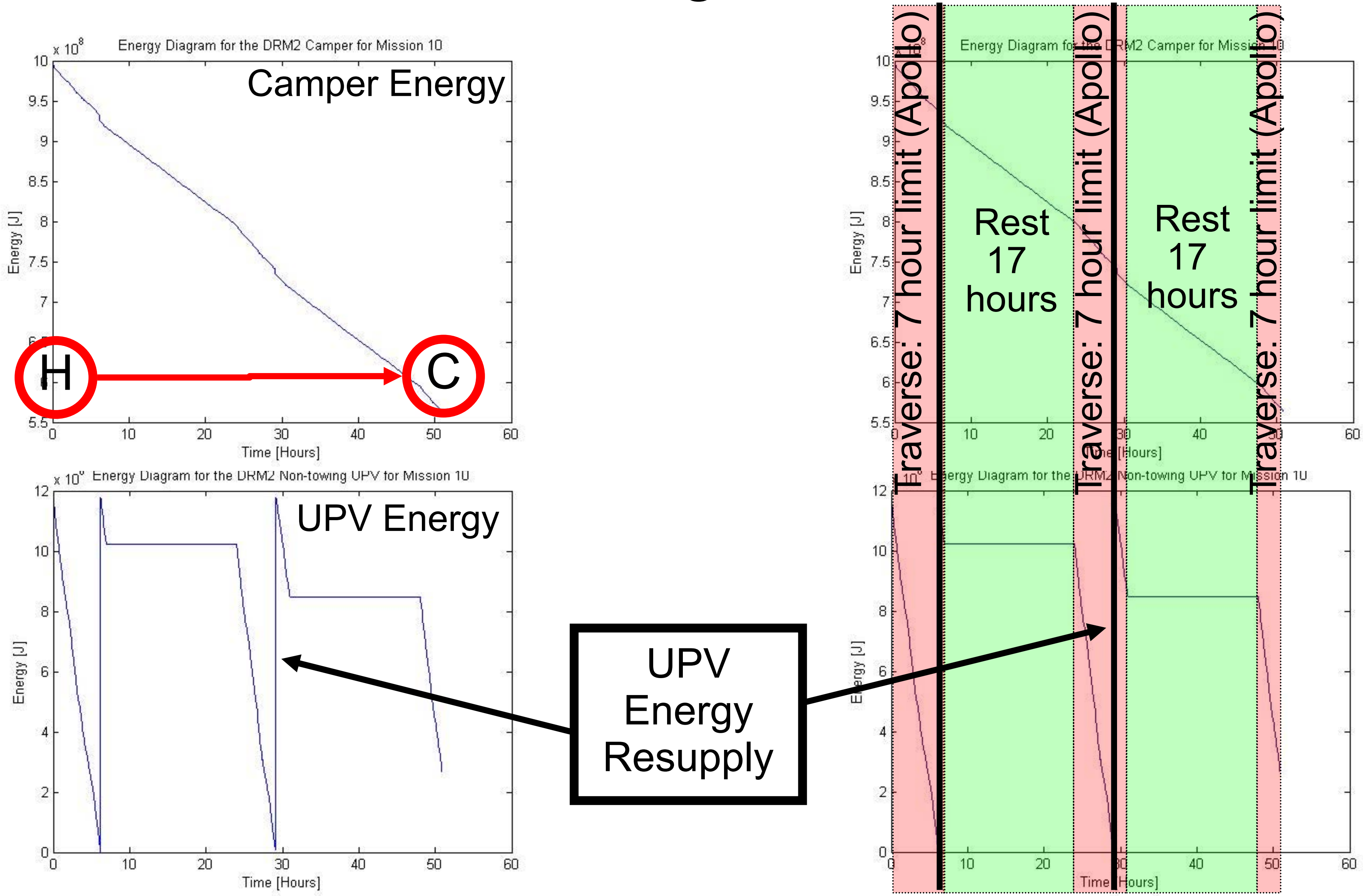
Spend time at site/region
Increment payload
Increment time



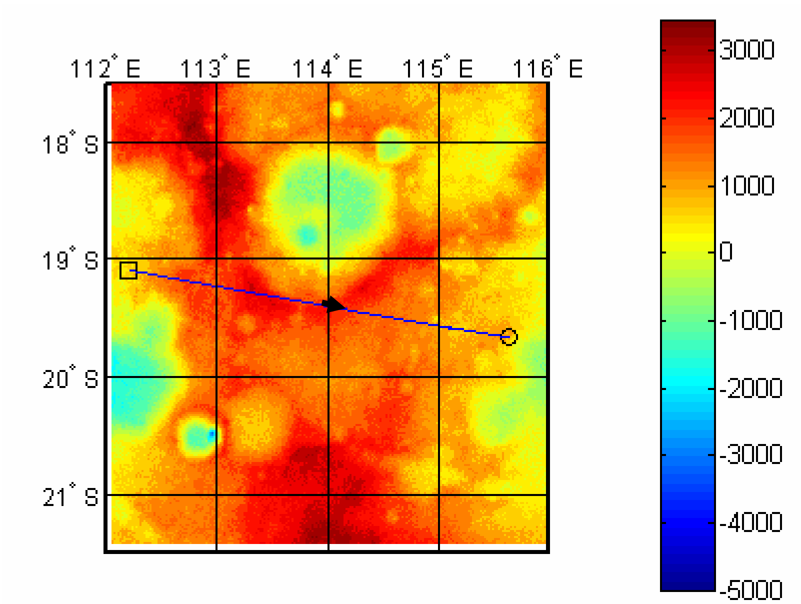


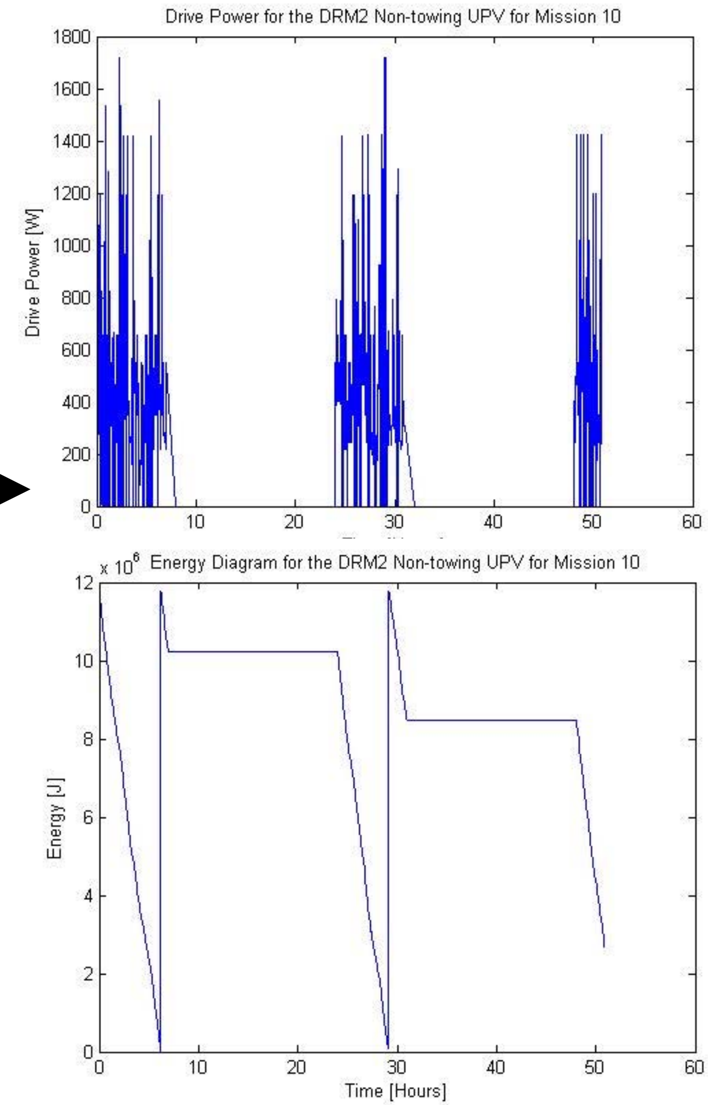
Check constraints:
If don't have enough time/energy to get to next site, drive back

Modeling DRM-2



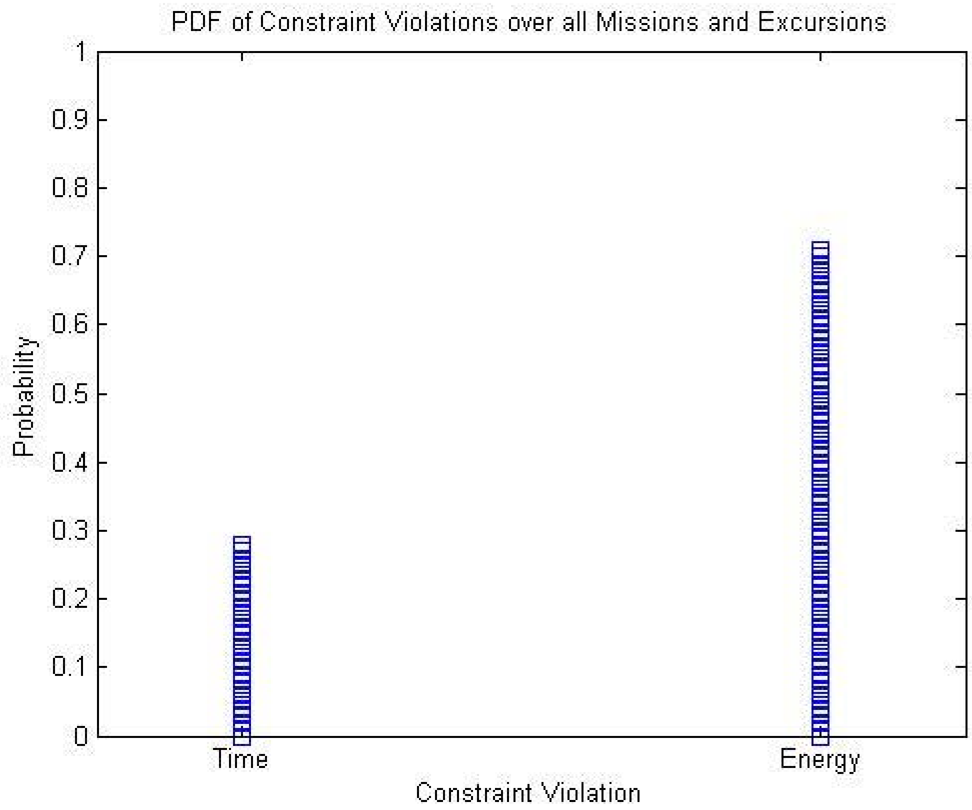
Modeling Propulsion-Terrain Interaction





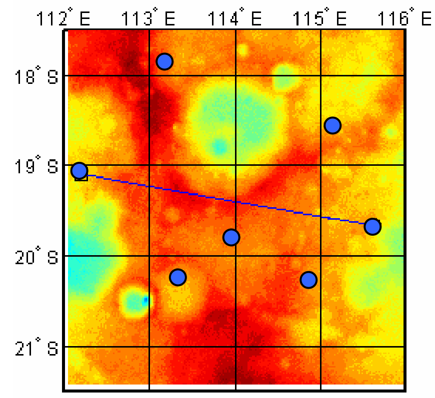
Constraints

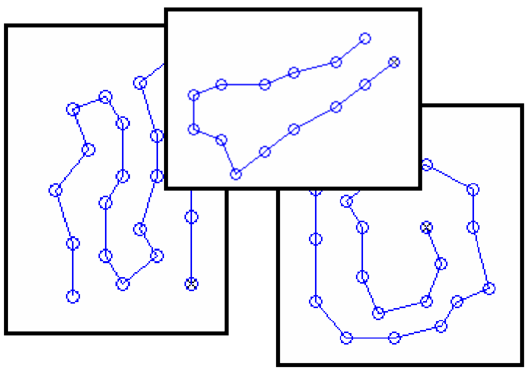
- MUSE guarantees vehicles always return to base
- Enforce time and energy capacity constraints



Statistics of Excursions in MUSE

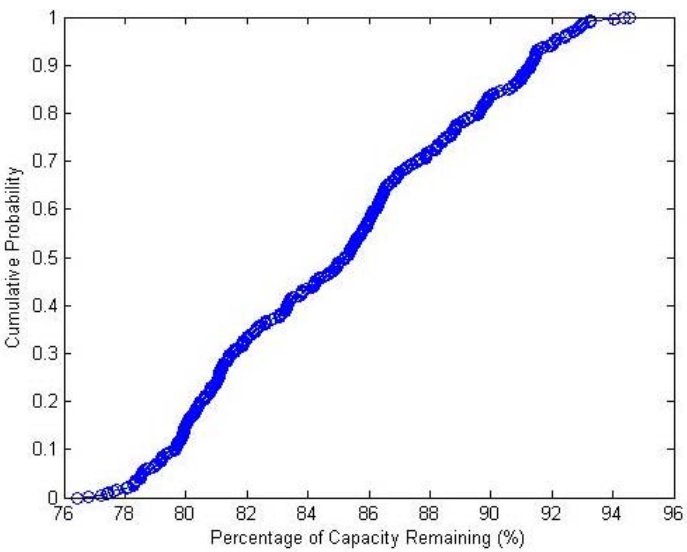
- Run the DRMs with multiple different parameters
- Can get statistical sampling of excursions
  - Try to abstract out site selection / terrain as much as possible
- Changed the following parameters
  - Exploration Types (search patterns)
  - Science site types (site vs. region)
  - Operations at science sites
  - Origin locations (DRM-1)
  - Hab & Camp Locations (DRM-2)





Design Iterations: Vehicle Model ↔ MUSE

- **Results of first iteration**
  - UPV energy storage was far too high
    - Used only 10-25% of energy stored onboard
  - Camper had insufficient power to reach camp (no exploration possible)



CDF of remaining energy capacity onboard at end of DRM-1 excursion

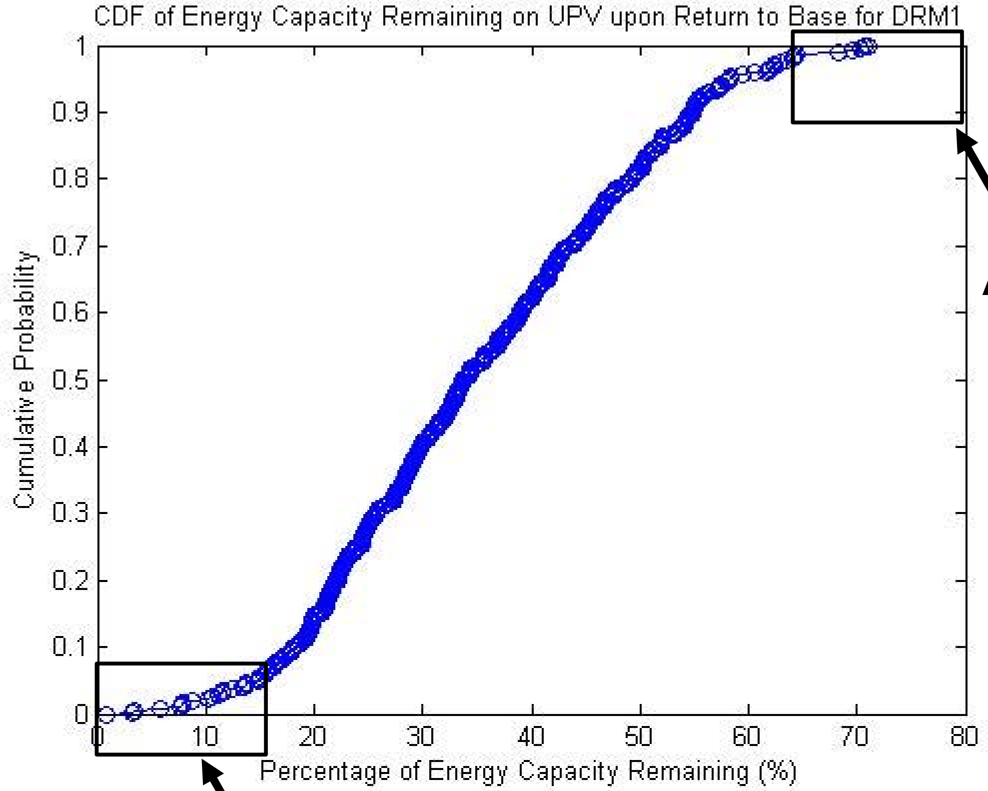
Min remaining: 76%
Max remaining: 95%

- **Feedback to vehicle design team**
  - Reviewed power consumption strategies
  - Verified propulsion model
  - Modified design selections
    - Removal of some power consuming items
    - Lowered energy capacity on UPV

- **2nd iteration design input into MUSE for final results**

Results: Energy on DRM-1

At the end of a DRM-1 excursion…

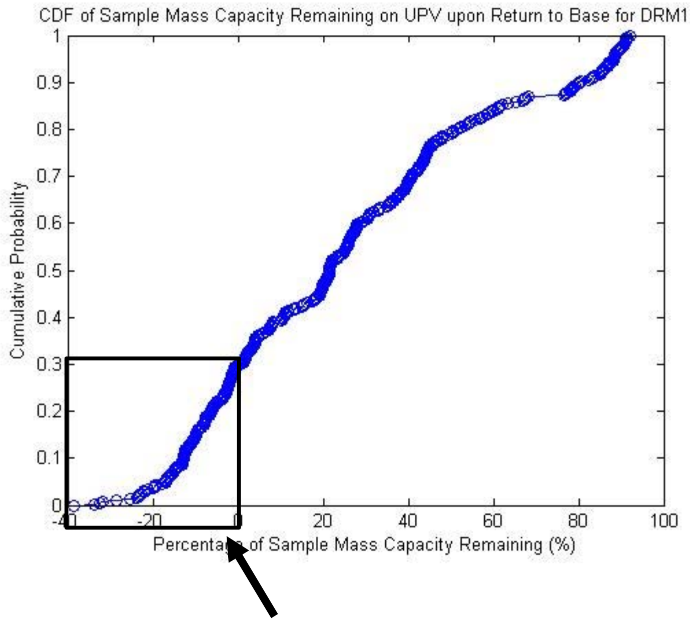


Always use ~30% of capacity

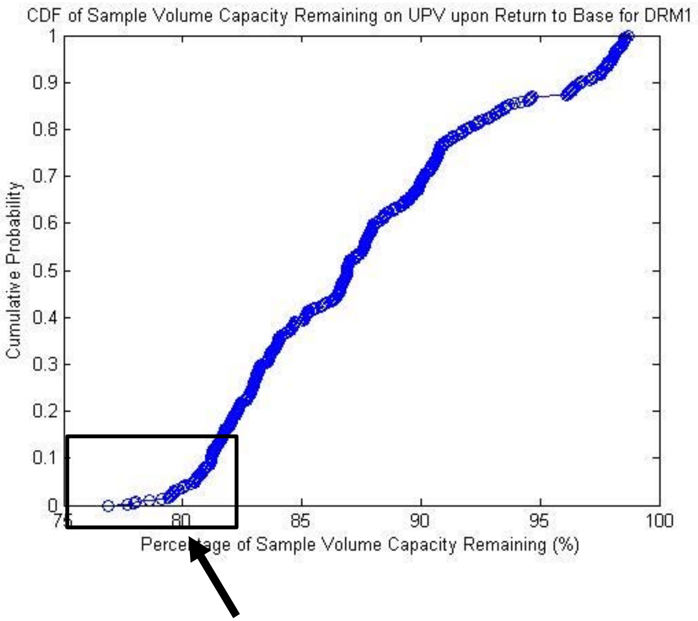
6% chance of using some of the 15% safety margin

Results: Sample Collection on DRM-1

At the end of a DRM-1 excursion…



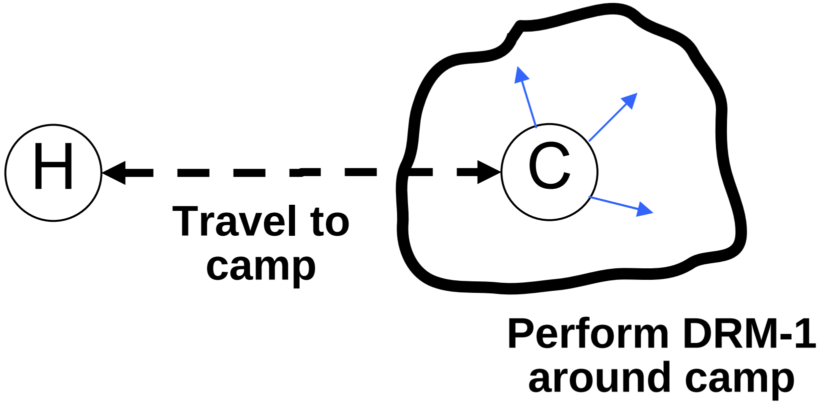
30% probability of running out of sample mass capacity

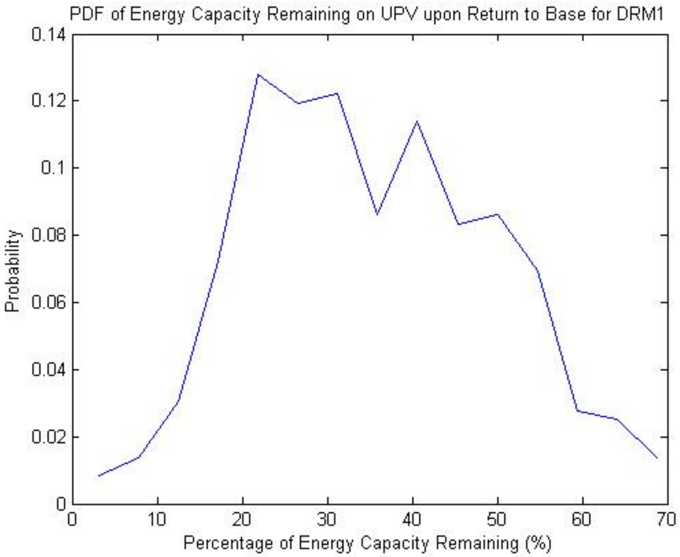


Always have at least 77% sample volume capacity available

Results: Exploration Capability on DRM-2

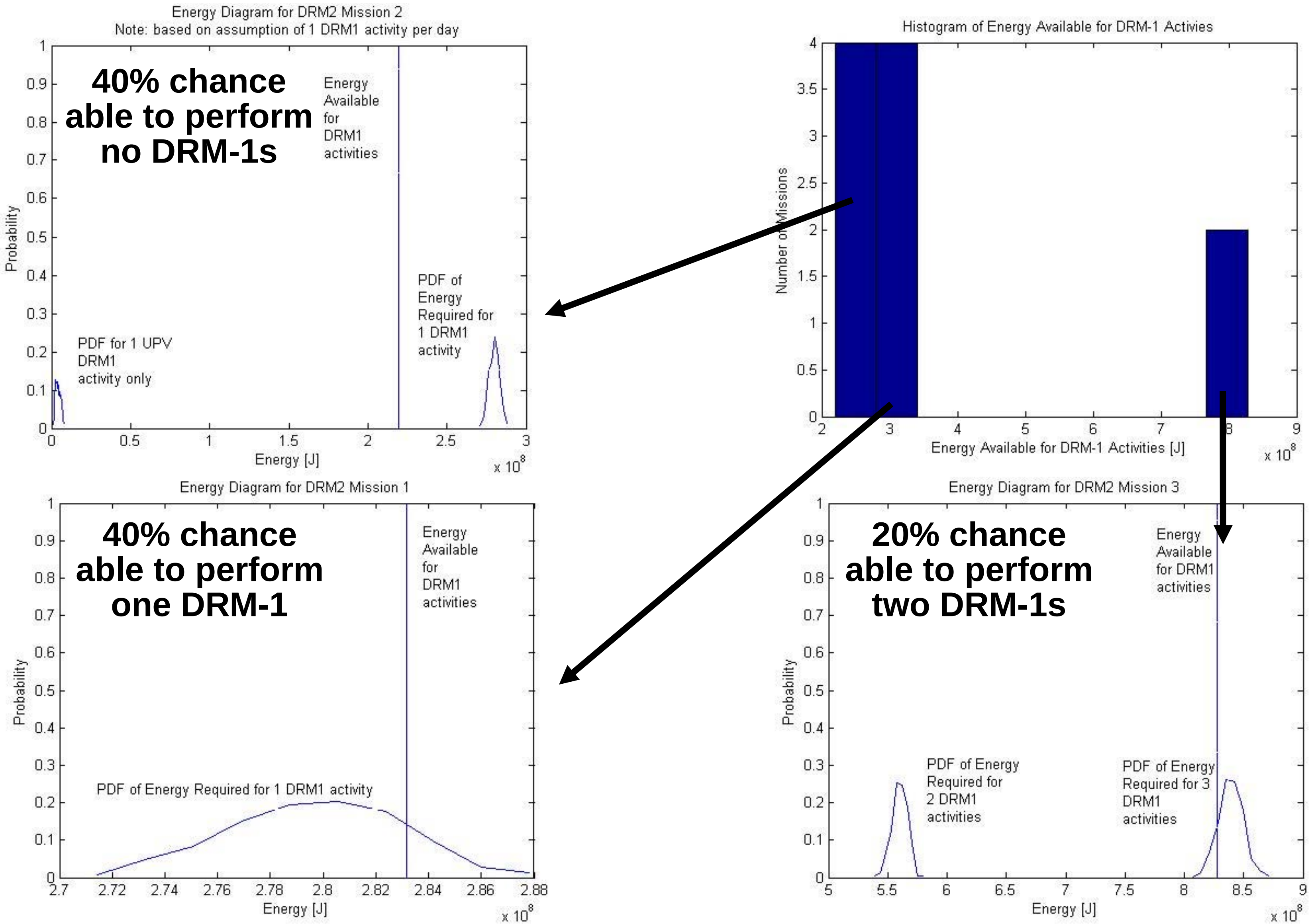
Once at the camp during DRM-2…



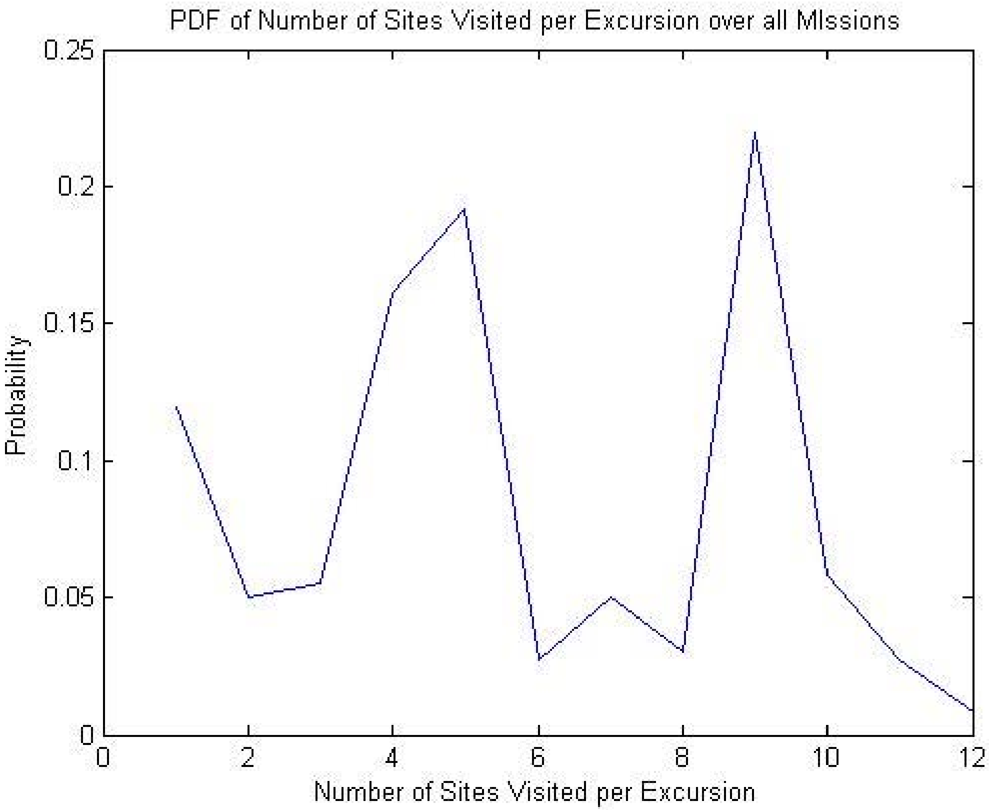


- **Evaluate remaining resources after the camper travels from hab to camp**
- **Find the number of DRM-1 excursions that are possible at the campsite using resources on camper**
  - Assume all consumables for DRM-2 are on camper
  - No additional supplies brought specifically for exploration

Results: Exploration Capability on DRM-2

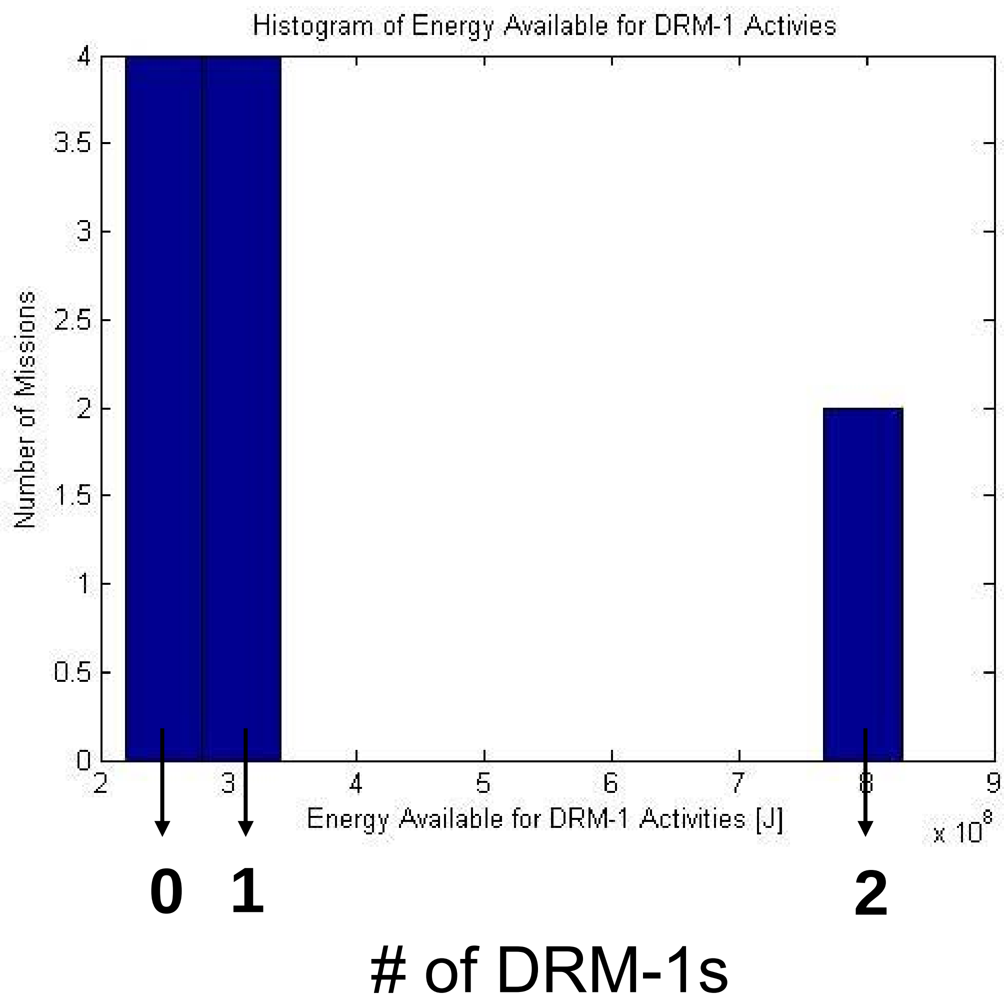


DRM-1 Capability Metric Results



- **Metric: number of sites per excursion**
- **Expectation: 5.71**
- **Standard Dev: 3.02**

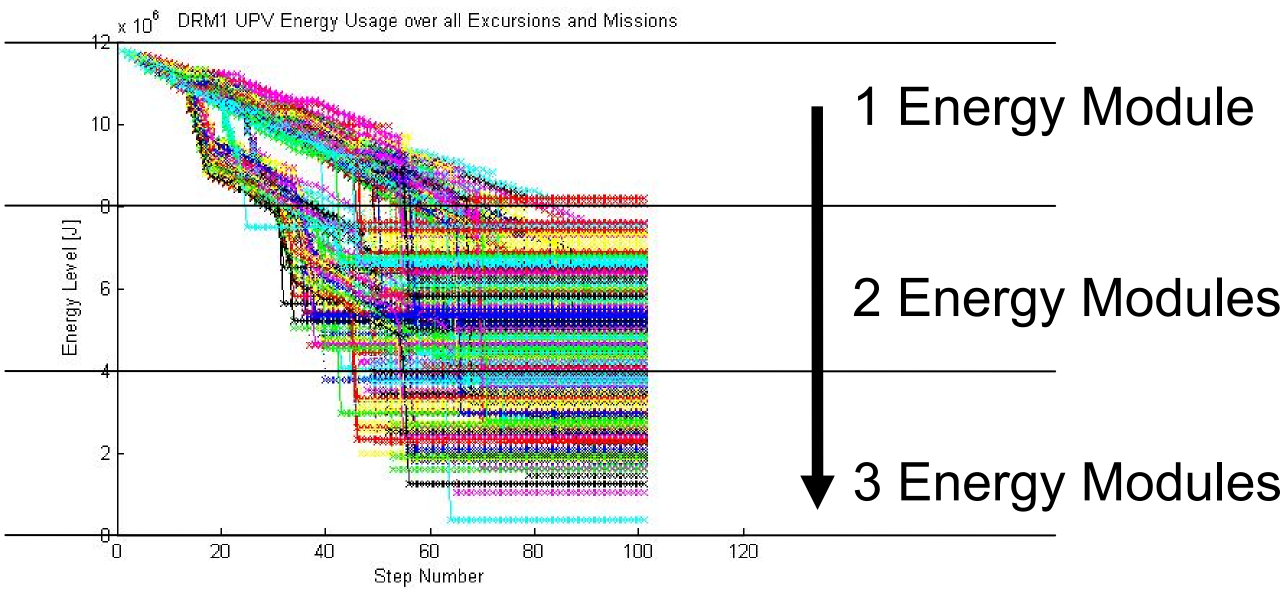
DRM-2 Capability Metric Results



- **Metric: number of DRM-1s per DRM-2**
- **Expectation: 0.80**
- **Standard Dev: 0.75**
- **Next camper design iteration should have more energy onboard**

Consumable Modularity Comments

- **Modularity of vehicle energy supply**
  - Improves matching energy requirements to DRM-1 excursions
  - Also an area of potential commonality among vehicles/planets



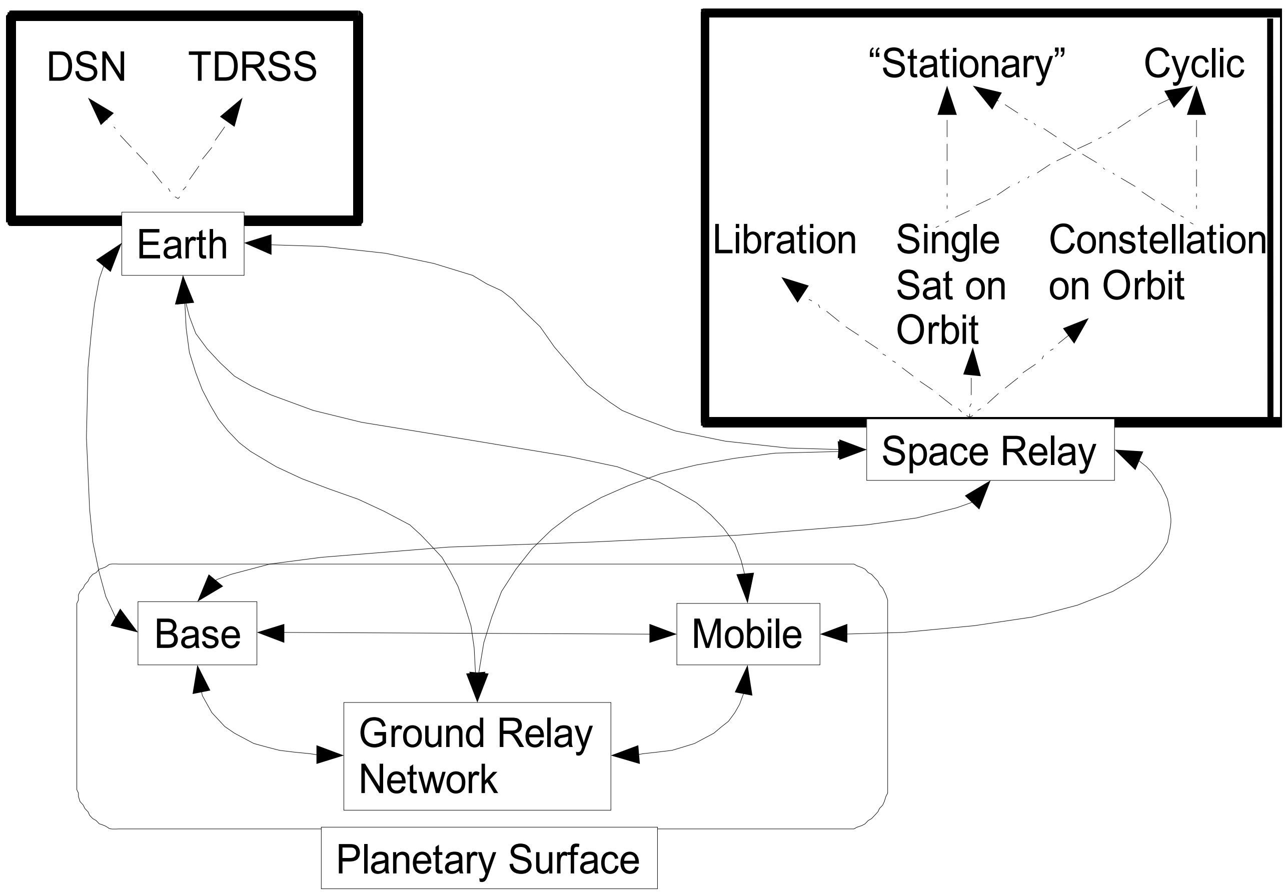
- **Modularity of ECLSS supplies**
  - May extend excursion capabilities in some instances
  - Reallocate supplies as necessary (nominal and contingency ops)

Communication and Navigation

Comm / Nav Architecture Review

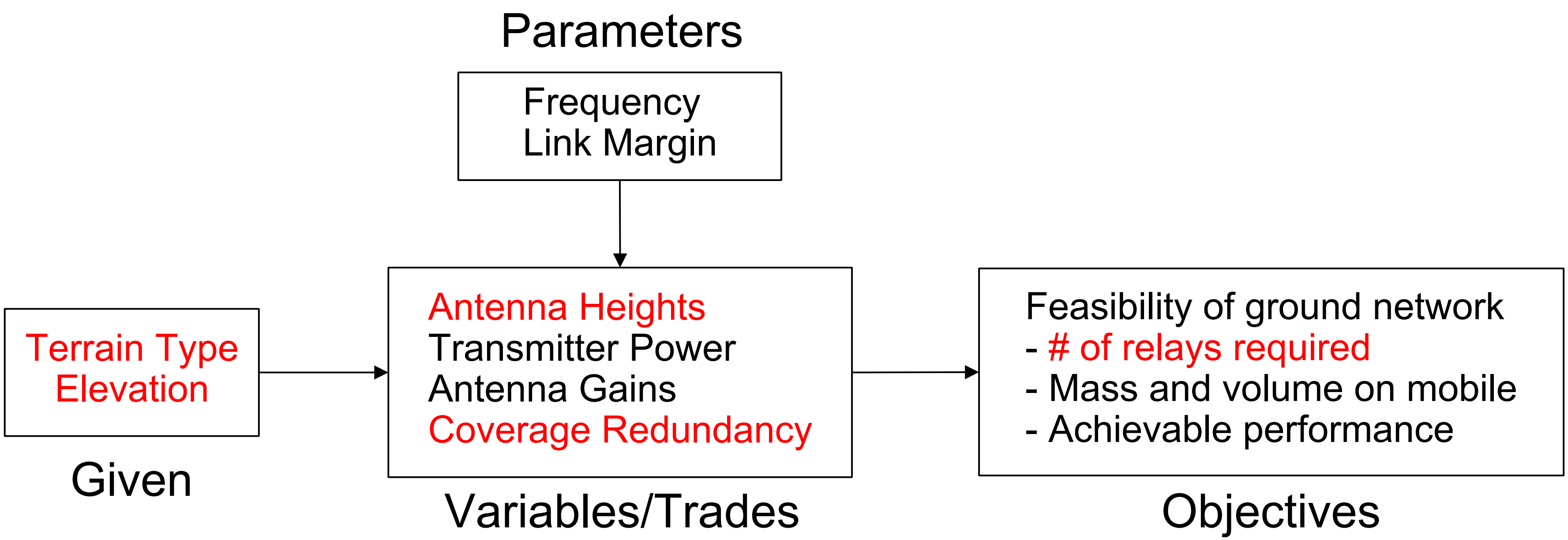
- **Communication strategy**
  - What is needed where it is need as it is needed
- **Navigation strategy**
  - Hybrid: gyroscope + odometer, map, beacon network
- **Hard communication requirements:**
  - Must transport data from mobile to Earth at some point
  - Must have continuous communications between the base and mobile regardless of line-of-sight
- **Soft communication requirements:**
  - Should transport data from mobile to Earth continuously
  - Should be extensible across all missions
  - Should be cost-effective for required level of performance
    - Amount of use system sees per dollar spent on the system

Communications Evolvable Architecture



Ground Network Analysis

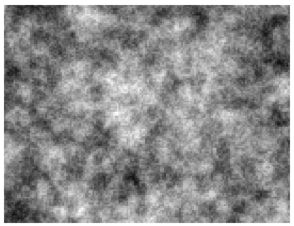
- **Goal of analysis**
  - Determine if a ground network could replace a satellite
  - Provides comparable performance at a fraction of the price



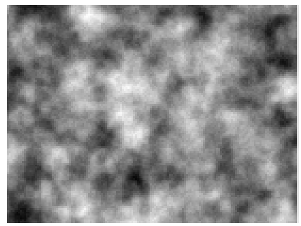
(items in red studied in detail)

Ground Network Analysis Methodology

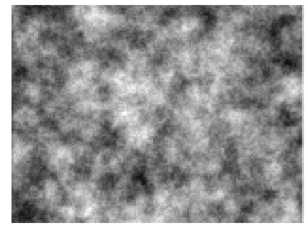
- **Terrain models**
  - Use simulated terrain data to evaluate terrain effects on relays
    - Based on power spectral density of lunar terrain



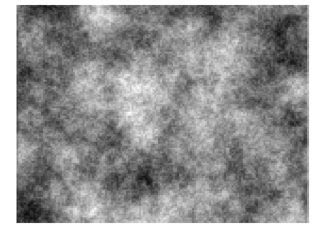
Smooth Mare



Hummocky Upland



Rough Mare

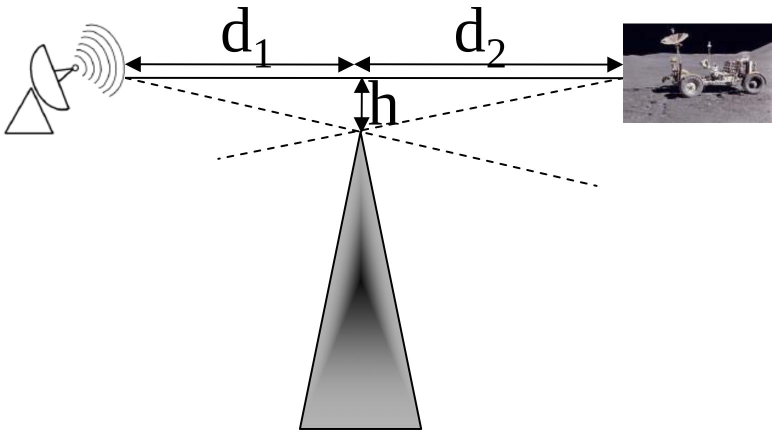


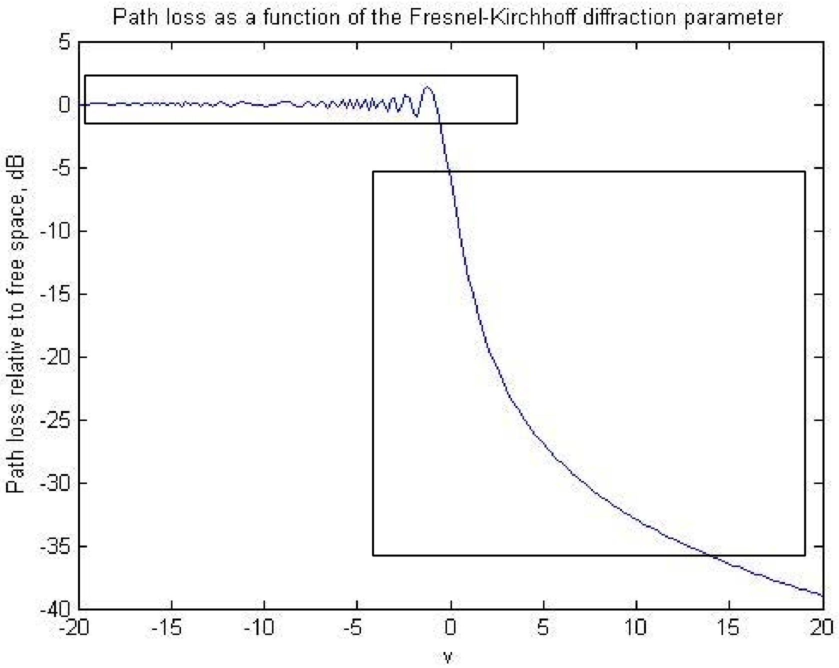
Rough Upland

- **Analysis**
  - Start at point on map and move in straight direction
  - Place relays when needed to maintain connectivity
  - Determine how many relays required
- **Metric: average distance between relays**
  - A measure of number of relays needed

Trade between Range and Energy

- **Limitation: uses line-of-sight (LoS) for connectivity**
- **LoS implies:**
  - All obstacles below LoS path
  - Received energy approximately the same as transmitted energy less space loss due to distance
- **Relaxing LoS assumption:**
  - Range will increase but received energy subject to knife-edge diffraction losses
  - Can compensate for energy by using appropriate link margin





Ground Network Analysis Methodology

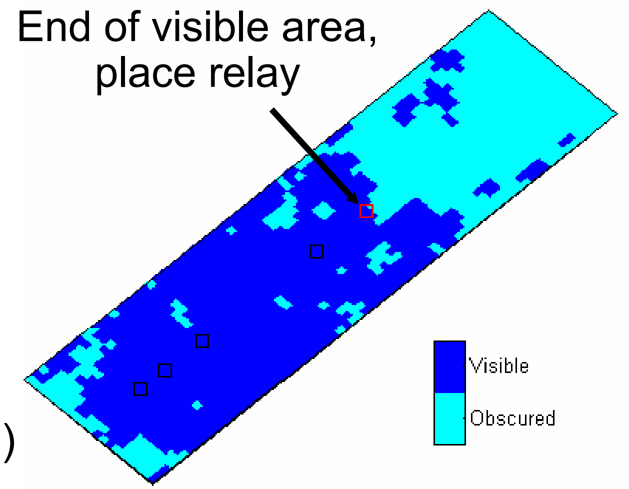
- **Design variables in the analysis**

Property	Parameterization
Terrain type	Four map data sets
Deployment strategy	Two relay placement algorithms
Start location	Set of starting site map locations
Relay height	Various heights (0 to 5 m)

- **Parameter study**
  - Different maps
  - Same map, different deployment strategies
  - Same map, different start locations
  - Same map, different relay heights

Relay Deployment Strategies

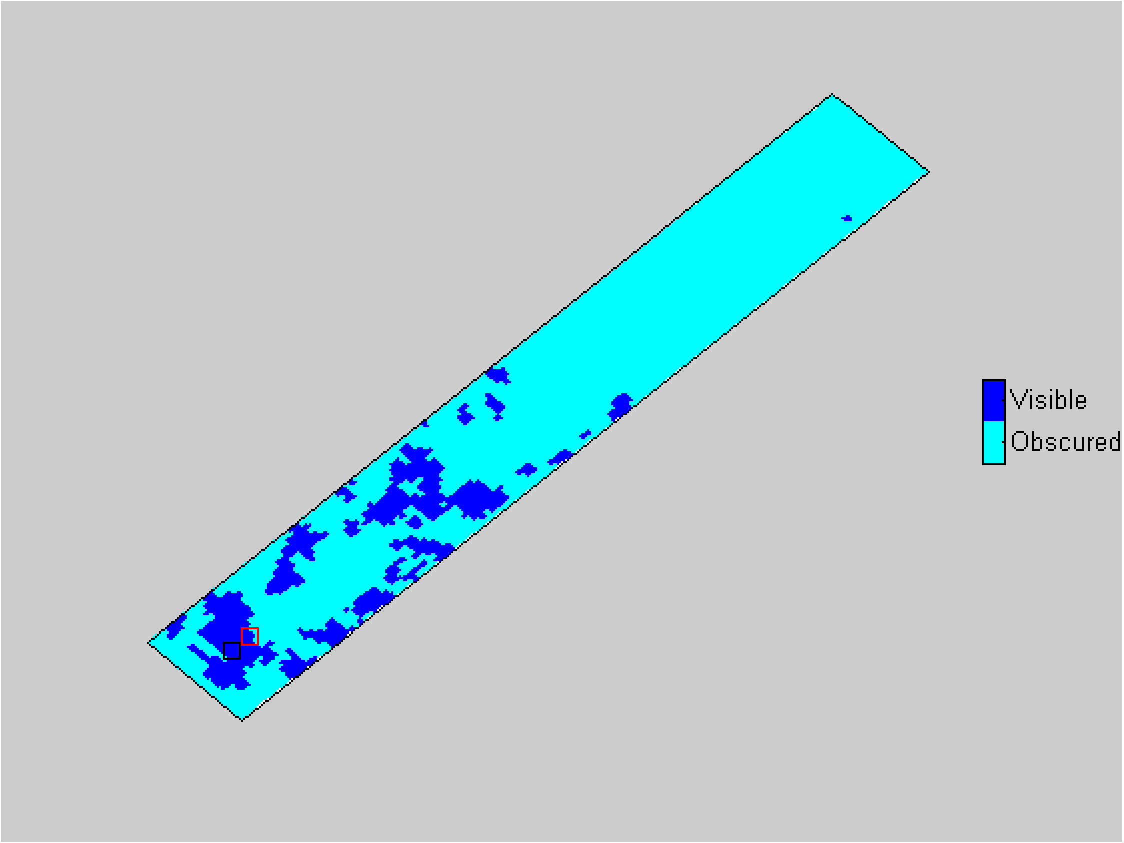
- **Straight-line deployment**
  - Drive in a straight line
  - When connectivity lost, place relay behind
  - Simplest deployment method
    - Operationally easy, lower workload
  - Upper bound on relay requirements
    - Doesn't take advantage of local terrain (tops of hills)



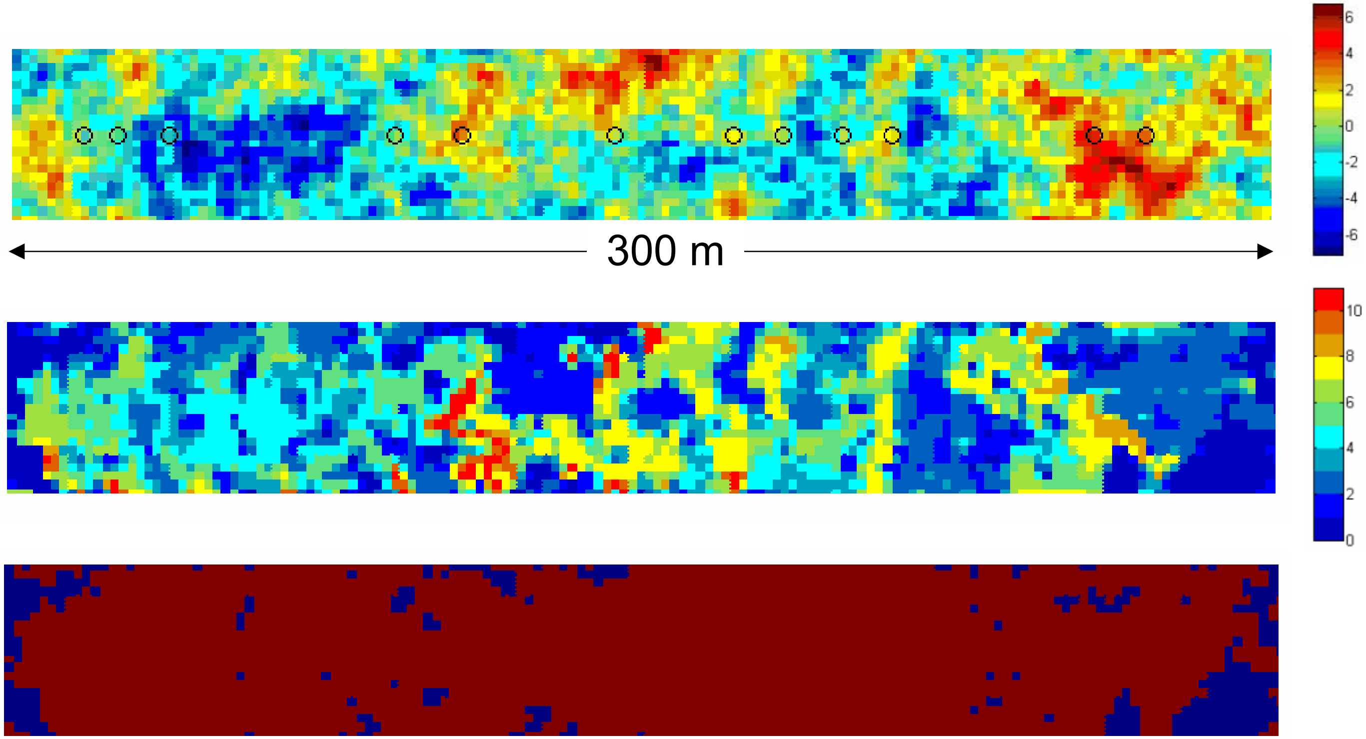
- **Adaptive deployment ("cannon method")**
  - Drive in a straight line
  - When connectivity lost, place relay at nearby point of highest elevation that has connectivity
  - Search within a specified radius (5-10 m away from vehicle)

- **Straight-line better: problems with adaptive algorithm**

Straight-Line Deployment Simulation



Analysis Outputs



Relays on Elevation Map

Number of Connections Map

Connectivity Map

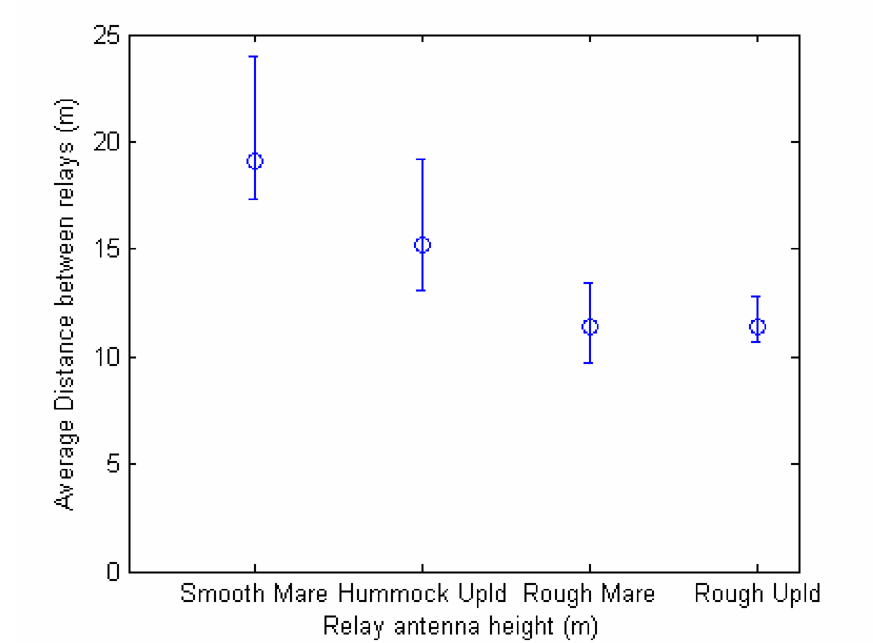
Simulation Properties	
Terrain type	Hummocky Upland
Deployment strategy	Straight-Line
Relay height	1 m

Simulation Results	
Number of relays	12
Average Connections	3.43
Distance / relay	22.5 m

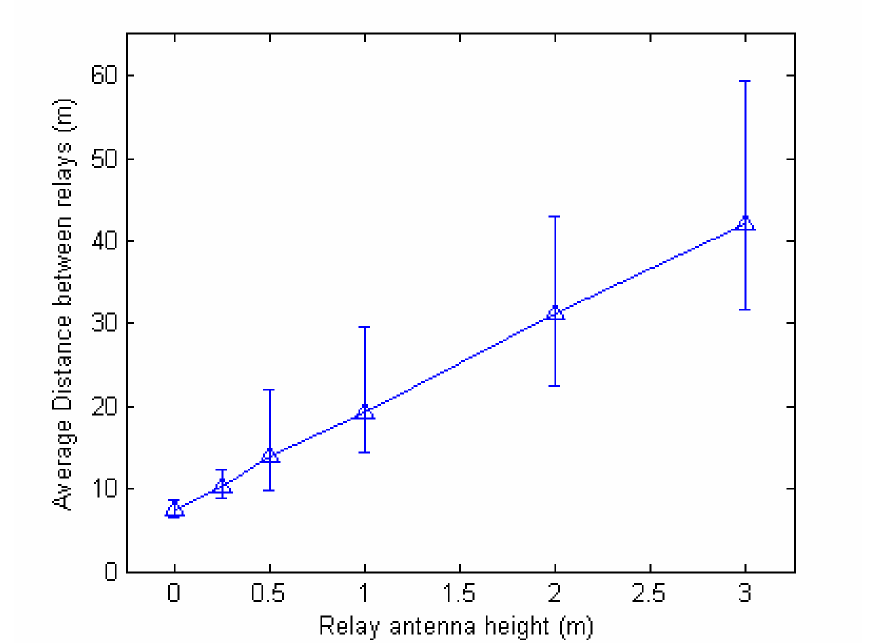
Parameter Study Results

Parameter Study 1: Start Locations
Hummocky Upland terrain, 1m relays

	Min	Max	Avg	Stdev
Number of relays	8	13	9.9	1.5
Avg connections	2.3	4.3	3.1	0.6
Distance / relay	14.6	22.2	18.6	2.5



Parameter Study 2: Terrain Types
1m relays, straight-line deployment



Parameter Study 3: Relay heights
Hummocky Upland terrain, straight-line

Communication Conclusions

- **Relay requirements are site specific**
  - Not just dependent on terrain type
- **Rougher terrain requires more relays**
  - But even smooth terrain needs one every 20 m
  - Inevitably large number of relays of reasonable size
- **Significant improvements with higher relays (> 0.5 m)**
- **Alternate deployment schemes & terrain effects could help lower the number of required relays**

Communication Future Work

- **Relax LoS assumption in analysis**
  - Incorporate knife-edge diffraction model
  - Add trade off with power and antenna gain

- **Consider improved deployment strategies**
  - Better adaptive deployment algorithms
  - Introduce *a priori* global knowledge of terrain

- **Integrate relay deployment with vehicle design and operations models**

Summary

Conclusions, Accomplishments

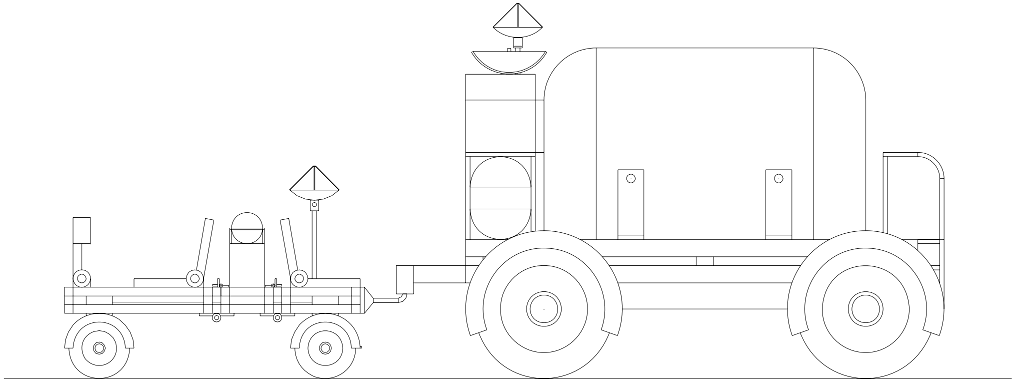
- Value delivering activities on the surface were captured in the four types of design reference missions
  - Representative for major exploration surface activities
- Independently confirmed superiority of camper architecture
  - Elimination of duplicate functionality and flexibility
- Created a set of subsystem models with more resolution compared to PSV
  - Mostly physics-based / engineering-based models
- Created a versatile integrated capability modeling framework for surface operations based on vehicle designs
- Generated design specifications (including CAD) for an extensible planetary surface mobility system
  - Dedicated UPV and camper designs, both with a common core and extensible modules for Earth, Moon, Mars environment customization
- Had fun, learned a lot

Future Work

- Create more detailed subsystem models taking into account COTS, modularity, effects of geometrical design
- Further refine the interface between vehicle model and MUSE for more enhanced capability analysis
- Based on 16.89 results and future modeling:
  - Build virtual and physical mockups (CAD, rapid prototyping, full-scale mockups)
  - Use mock-ups for human factors, operability analysis
- Build a camper prototype and perform field testing
- MUSE
  - Extend the analysis framework to Mars, Earth
  - Incorporate terrain data for the entire planetary surface
  - Extend to include ECLSS consumables
    - Structure already in the code
  - Incorporate more logistics, comm/nav

Thank you

Questions?



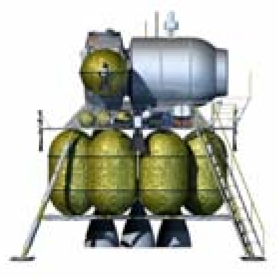
Backup Slides

Ground rules & Assumptions (2)

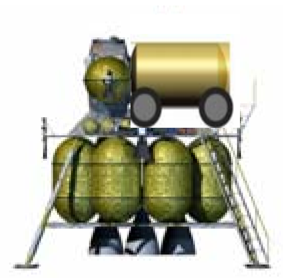
- Pressurized mobility assets provide adequate shielding and life-support to survive and wait out a solar particle event (SPE)
- There exists a capability to forecast major flares with lag times between electromagnetic and particle radiation of less than an hour
  - Capability is currently being developed (SOHO)
- Crew has to be able to return to a sheltered environment in under 3 hours in case of a SPE
  - Limited exposure to SPE ionizing radiation flux is acceptable (see dosage limits for short-term exposure)

Camper Dual Use: Re-Supply and Mobility

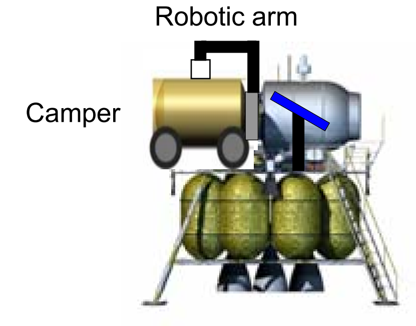
Human lunar lander concept using 2 crew compartments



2nd crew compartment could be common with camper



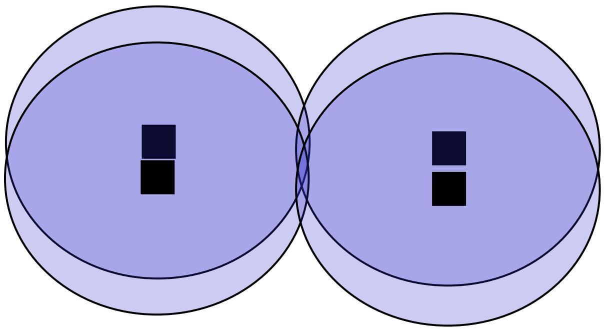
Camper used as "lunar surface MPLM" before mobility use



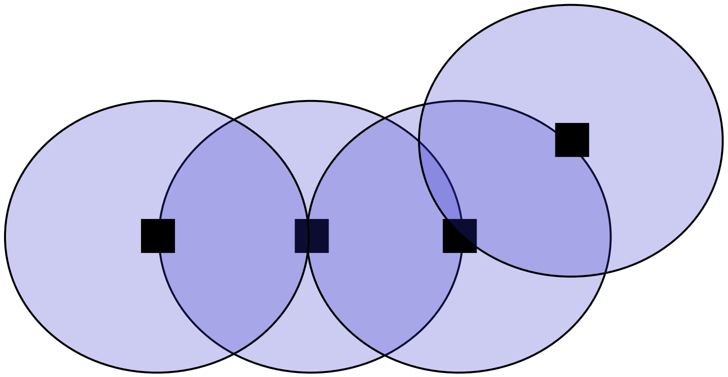
- **Camper crew compartment provides limited pressurized volume**
  - **Same functionality as human lunar lander crew compartment**
  - **Opportunity for commonality**
  - **Opportunity for accretive build-up of a surface outpost**
- **Re-supply of an outpost on the lunar surface is key to long-duration lunar exploration (DRM-3)**
  - **Non-trivial task, because of large amount of pressurized consumables**
  - **Camper could serve as lunar surface MPLM before being used for surface mobility: option for dual use of mobility hardware resulting in cost-reduction**

Possible Strategies to Improve Robustness

- Redundant coverage
  - Drop 2 relays at each relay location
    - Single fault-tolerant
    - Sensitive to location-based disturbance

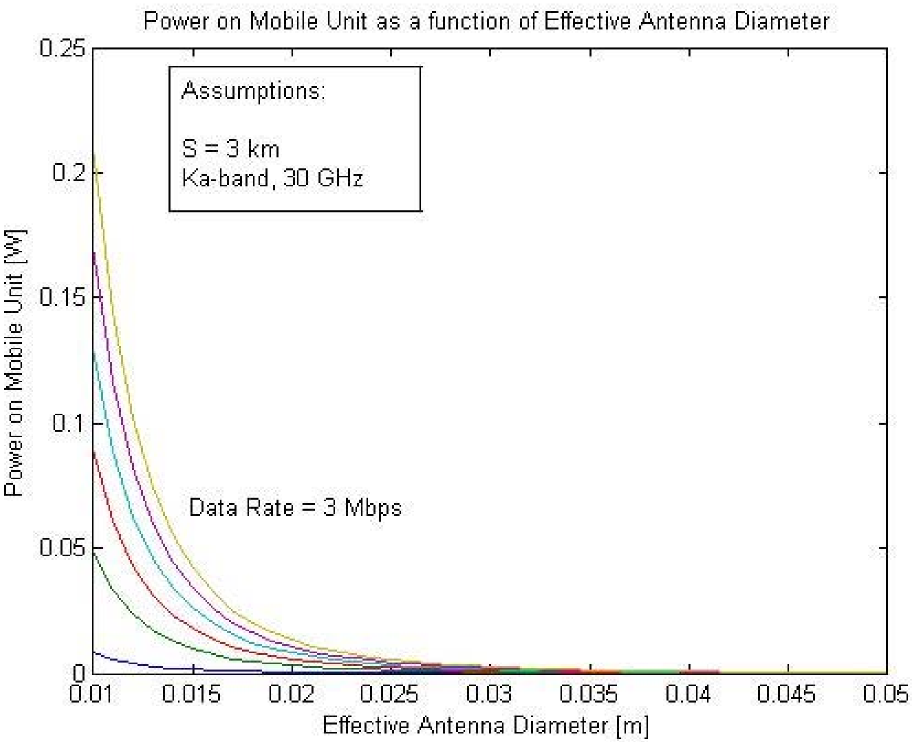


  - Drop relays close enough to provide double coverage
    - Single fault-tolerant
    - Not as sensitive to location-based disturbance
    - May require some power increase to compensate for terrain



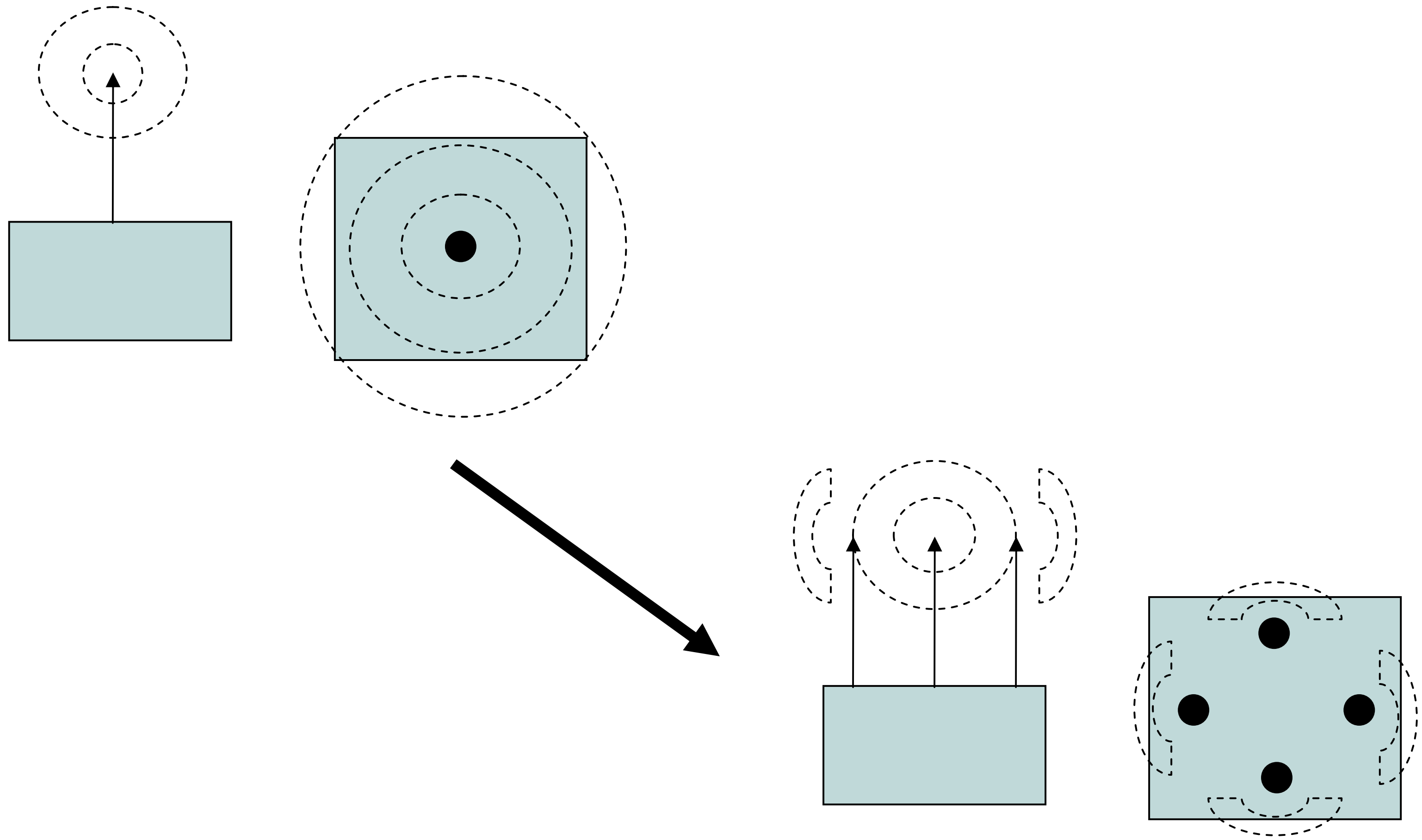
Possible Strategies to Improve Robustness

- Emergency power-ramping
  - In event of a failed relay:
    - Ramp up power to compensate for signal loss from terrain, distance
    - Improve power efficiency by decreasing data rate
  - Single fault-tolerant
  - Time limitations before onboard power drops too far



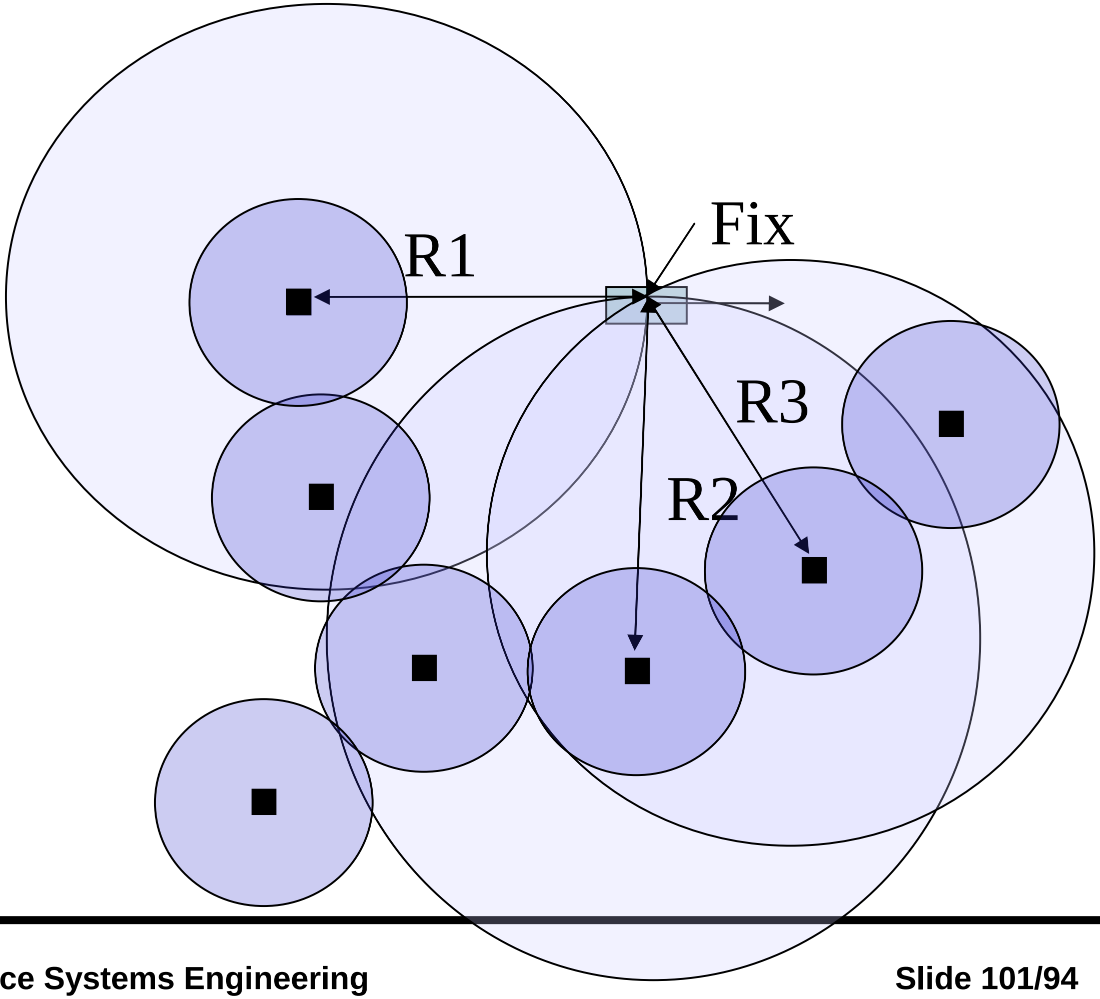
Possible Strategies to Improve Robustness

- **Consider different antenna design concepts:**



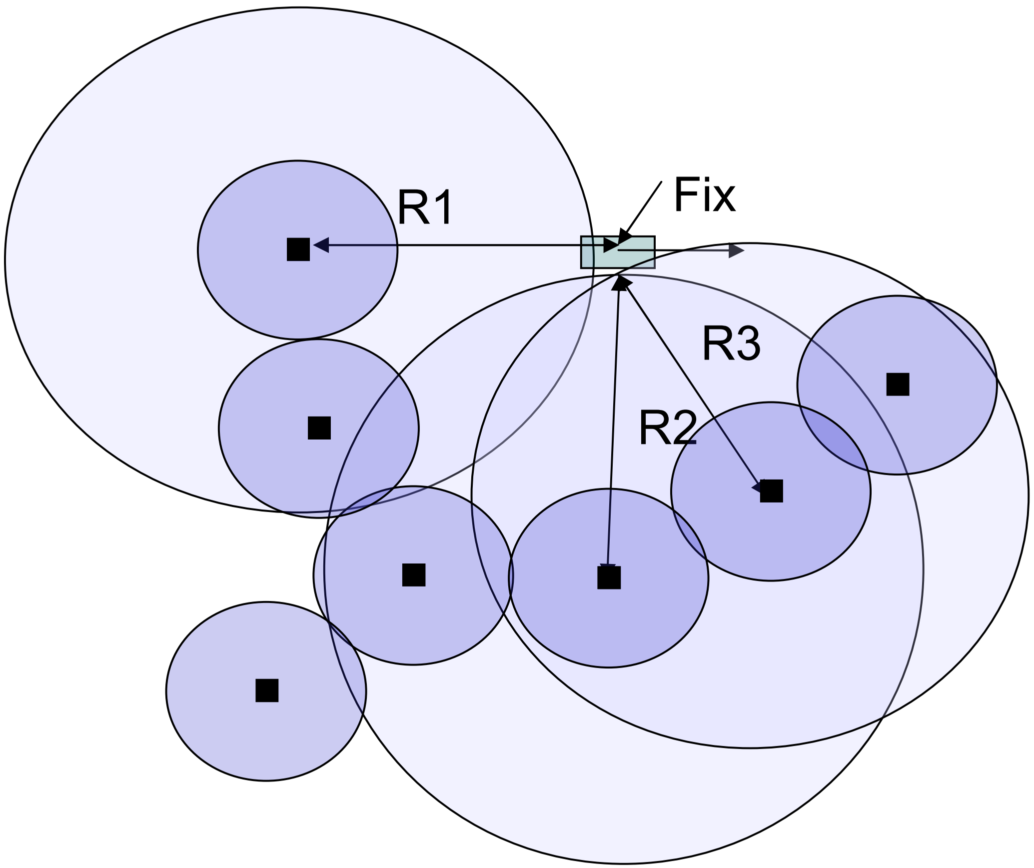
Possible Strategy to Improve Robustness and Coverage

- Trade increased range for lower data rate in emergency
  - Assumes navigation payload <u>can</u> achieve greater range
  - Limitations for this strategy need to be analyzed



Navigation Architecture

- **Trilateration**
  - Navigation payload on communication relay
  - Navigation pings should have greater range than communications
  - Use pinging process and clock synchronization to determine range



Extensibility DRM 3 and DRM 4

- Approximate horizontal force ~ 6x10^6 N
- Approximate digging/lifting force ~2,296 N
- Average regolith density ~ 1,250 kg/m^3
- Moon gravity ~ 1.63 m/s^2

- Bucket Capacity ~ 0.04 m^3
  - Based on SOLAR 010 and 015 Plus
- Lifting capacity ~ 1,408 kg

- Plowing ~6x10^6 N
- Towing ~ ?

Average Bulk Density of Regolith g/cm^3 (kg/m^3)	Depth range (cm)
1.50 (1500)	0-15
1.58 (1580)	0-30
1.74 (1740)	30-60
1.66 (1660)	0-60

Science Payload

UPV Payload

Time Of Flight-Mass Spectrometer	10 *kg*
Mars Organic Analyzer	11 *kg*
Spares and consumables	4 *kg*
Survey equipment	15 *kg*
Shovels, hammers, corers	30 *kg*
Atmospheric samplers	30 *kg*
Still/video cameras	20 *kg*
Hand lenses	2 *kg*
Aeolian sediment trap	5 *kg*
Rock sample holders	30 *kg*
	157 kg

Camper Payload

Drill (20 m)	*250 kg*
GC-MS (2)	*75 kg*
Optical microscope	*15 kg*
APXS	*5 kg*
X-ray fluorescence	*15 kg*
Amino acid, chirality analyzer	*11 kg*
Raman spectrometer	*8 kg*
Infrared spectrometer	*8 kg*
Solubility/wet lab	*20 kg*
Sample packaging/Glv. Box	*150 kg*
Computers	*15 kg*
Cameras	*10 kg*
Rock saw, grinder, sieves	*10 kg*
Metabolic analyzer	*15 kg*
Protein, DNA	*25 kg*
	632 kg

Human Activities Module

Inputs	Outputs	In Modules	Out Modules
Number of Crew	Total Volume	Design Variables	Power
Excursion Duration	Lvng Space Height	Payload	Structure
Sci. Payload Vol	Length		Chassis
Sci. Payload Mass	Radius		Thermal
Num EVAs	Center to Floor		
	Floor Chord		
	Airlock Surf Area		
	Driving Power		
	Peak Power		
	Science Power		
	Night Power		
	Head Generated		
	Total Mass		
	Water Consump.		

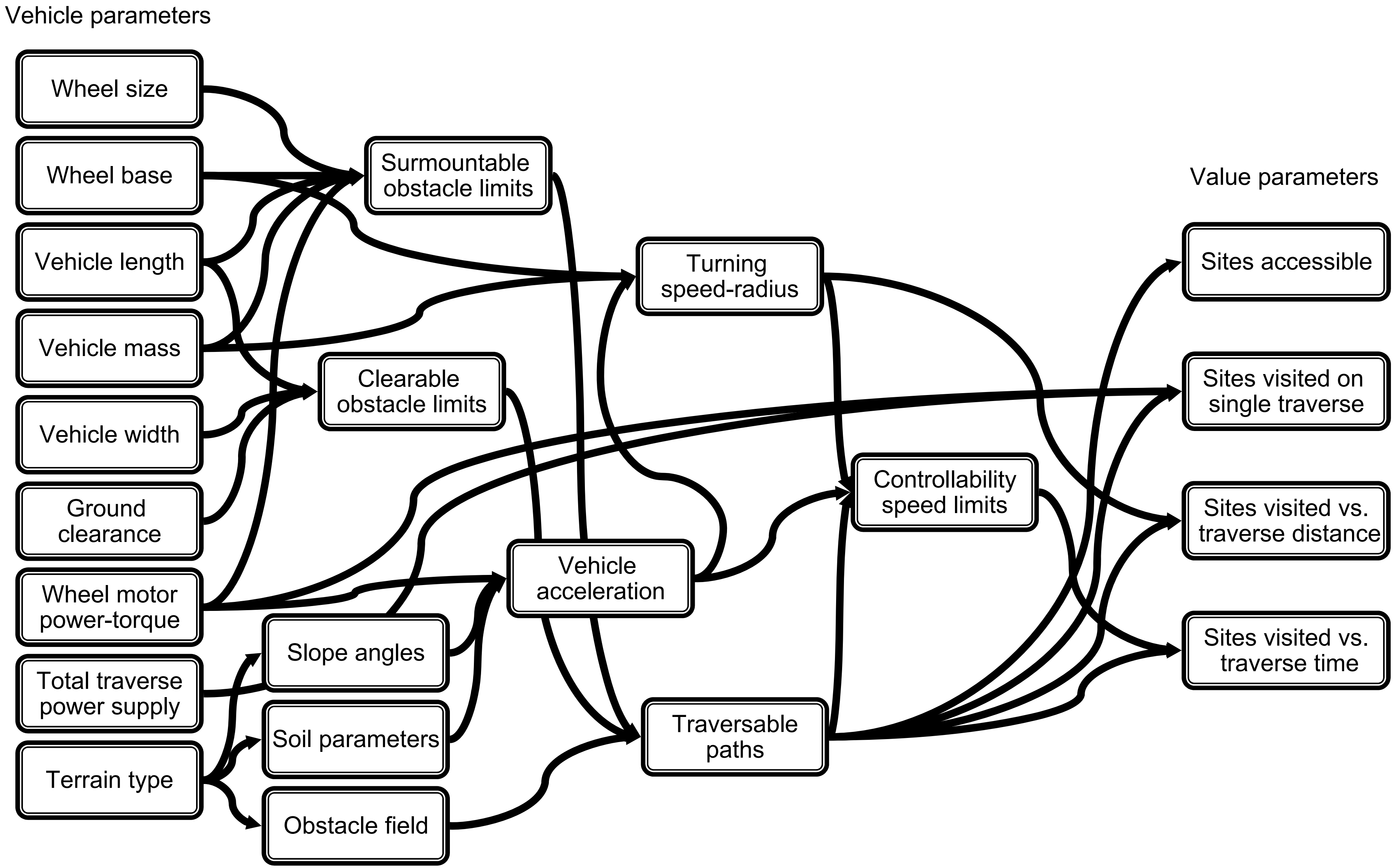
Human Activities Module

- Moon & Mars Modifications
  - Designed for these environments
    - Only variations are input parameters, specifically number of crew and duration of excursion
- Earth Modifications
  - Replace Airlock with kitchen

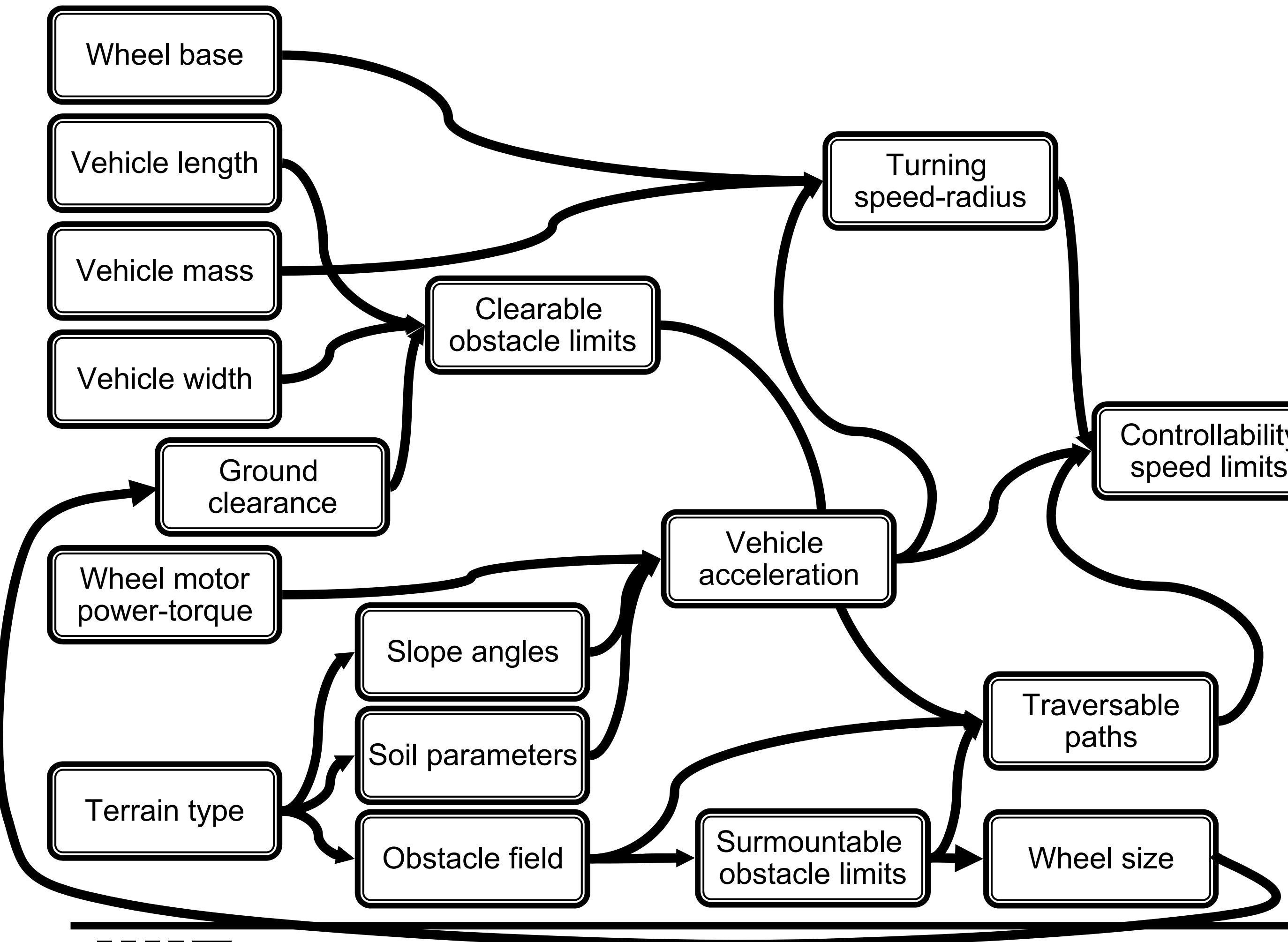
Human Activities Module

- Basis
  - number of crew on excursion
  - duration of excursion in days
  - volume required to conduct science
  - mass of science tools required
  - number of EVAs per excursion
- For Mars mobility, there seems to be a “gap” in performance between architectures using campers, and architectures using pressurized rovers
- Given constant speed and range, and given a certain DRM-1 configuration, there is an optimum number of days on traverse
- Sensitivity analysis will be performed on the influence of range and speed (both driving and walking)

Original Modeling Approach (03/13)



Final Modeling Approach (Today)

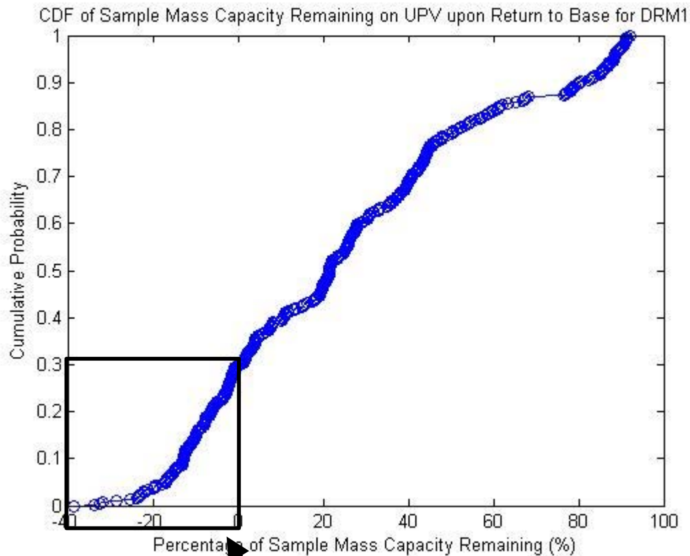


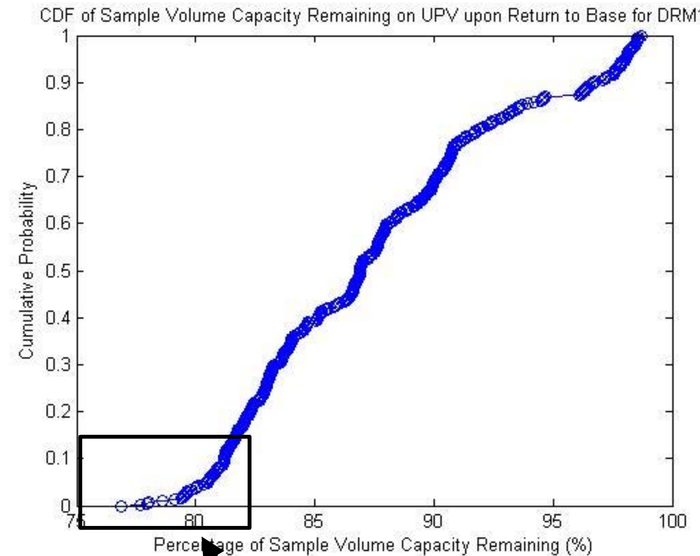
Validation and Extensibility

- Where possible, model elements validated against Apollo LRV parameters and similar PSV models
- Some elements, such as wheel physics and motor characteristics, based directly on Apollo LRV data
- Current integrated design version implemented with aggregated/averaged parameters for speed, simplicity; could be extended via exhaustive lookup tables
- Mars extensibility: expect
  - more benign terrain slopes and obstacles in most areas
  - possibly worse soil interaction
  - power increase due to gravity

Results: Sample Collection on DRM-1

At the end of a DRM-1 excursion…





30% probability of running out of sample mass capacity

Always have at least 77% sample volume capacity available