

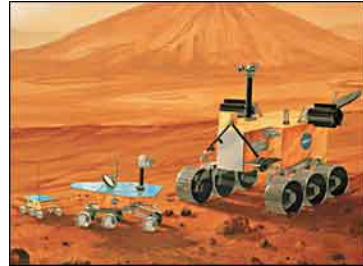
MIT OpenCourseWare
<http://ocw.mit.edu>

16.89J / ESD.352J Space Systems Engineering
Spring 2007

For information about citing these materials or our Terms of Use, visit: <http://ocw.mit.edu/terms>.

Rapid Modeling of Mars Robotic Explorers

Critical Design Review
May 5, 2003
16.89



1

16.89 CDR

The Mars Exploration Program, managed by the Jet Propulsion Laboratory (JPL), is a science-driven program that seeks to understand whether Mars ever was or could be a habitable world. To answer this question, scientists are trying to understand how geologic, climatic, and other processes are interacting to shape the Martian environment over time. Engineers are working on designing and validating advanced technologies that would enable us to explore Mars in ways we never have before, with the goals of higher-resolution images, precision landings, longer-ranging surface mobility and even the return to Earth of Martian soil and rock samples for studies in terrestrial laboratories.

Aside from consideration of these innovative technologies, a wide variety of existing technologies are available for the design of near-term surface exploration vehicles. We believe that a software tool capable of comparing the costs and benefits of a wide variety of rover architectures and designs would immensely facilitate the conceptual design and architecture selection of future rover missions.

Outline of CDR

- Design Overview
 - Mission Statement
 - System Flow
- Subsystems
 - Instruments
 - Acquisition
 - Environment
 - Rovers
 - Power
 - Communications
 - Autonomy
- System Validation
 - Comparison to MER, MSL
- Results of Trade space
 - Attributes, Cost, & Complexity
- Usability
- Conclusions
 - Demo

Team Members

- Stephanie Chiesi
- Babak Cohanim
- Edward Fong
- Kalina Galabova
- Ian Garrick-Bethell
- Mark Hilstad
- Erisa Hines
- Julien Lamamy
- Jessica Marquez
- Tsoline Mikaelian
- Roshanak Nilchiani
- Chris Roberts
- Julie Wertz
- Barry Willhite

Project Goals

- Mission Statement:
 - Develop and validate trade space tool for rapid analysis of Mars surface robotic explorers for Jet Propulsion Lab, CA.
- Product:
 - System trade-oriented tool that models a Mars rover based on particular design parameters and payload
 - Varying parameters creates different rover designs
 - Analysis of trade space, all possible rovers compared
- Scope:
 - No prior-to-landing considerations
 - No active lander

4

16.89 CDR

TARR, JJM

Our mission statement is to create a tool that JPL could use for the architectural design of near future Mars surface missions. It is hoped that it will be used to generate possible rover ideas for Mars Science Laboratory rover, to be launched in 2009.

Early in the design process, we limited the scope of the project to system-level trades, and to certain architectural parameters. We decided that system level trades strictly for rover designs were more desirable than engineering trades (like rocker-bogey suspension versus another suspension architecture).

To ease modeling, we are not considering active landers, which could be used as a processing center, power source, or a drilling center for example.

Motivation

- Support the development of Mars surface missions, by examining how the rover design trade space is shaped by various science and design parameters.

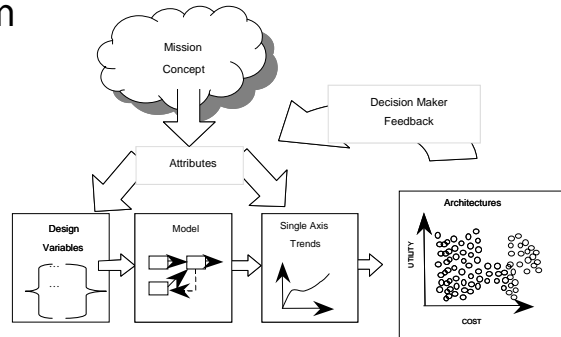
The motivation for this project is the need for an efficient approach to the comparison of Mars rover architectures and high-level designs. In particular, this project is motivated by the desire to produce an effective trade space analysis tool applicable to the design and selection of the 2009 Mars mission – the Mars Science Laboratory (MSL). To our knowledge, there does not exist a rover architecture tool that models all the major factors in rover design.

The trade space analysis tool will create and compare a wide range of rover designs, as determined by combinations of the specified allowable design parameters. Example parameters are different collections of instruments and acquisition tools, landing sites, levels of autonomy, types of communication system, and type of power source. The results of the design comparison will lead to insight into the benefits and disadvantages of different architectures, which should be useful to the engineering and science community.

It will also be useful to see how changes in one or more of the design factors influences the cost and capability of the design. For example, what are the direct benefits of investing in the development of algorithms to enable a higher level of autonomy, or of switching from a solar array to an RTG power source?

System Flow

- Customer need identified
- Design and Science Vectors determined
- Software modules of subsystems developed, validated, and integrated
- Integrated system validated
- Analysis of trade space



6

16.89 CDR

TARR, JJM, BC

By the Trade Analysis and Requirements Review (TARR), we identified the customer's needs and preliminary design and science vectors. Since then, we solidified the design and science vectors based on feedback from Charles Whetsel (JPL), David W. Miller (MIT), John Keesee (MIT), Joe Parrish (PSI), and through group discussions in class. Software modules implementing the model for each subsystem were created and integrated into a rover design tool. A trade space is created by running the rover design tool once for each of many combinations of values for the parameters in the design vector. A graphical user interface is used to analyze the resulting collection of point designs.

Subsystem design modules are written in MATLAB by the members of the individual subsystems, and integrated into a single tool by the systems team. A set of attributes (appropriate for integration testing) was utilized to test the validity of the modules and the tool as a whole.

Science Vector

- Launch scenario
 - Landing date on Mars specified
 - Landing site
 - Range of Rock Coverage
 - Latitude (5 bands)
 - Equatorial ($\pm 5^\circ$), low North or South latitudes ($\pm 5 - \pm 40^\circ$), high North or South latitudes ($\pm 40 - \pm 80^\circ$)
 - Sample acquisition operations
 - Number of samples per site
 - Distance between sites
 - Site size
 - User selectable payload
 - Instrument suite
 - Acquisition tools
- ### MER Science Vector
- Ls = 330° (almost Northern spring)
 - Rock coverage = 5%
 - Latitude = Equatorial
 - Num sample/site = 1
 - Distance = 70.7 m
 - Site size = 4.3 m
 - APXS, Mossbauer Spectrometer, 10x magnifier
 - RAT, Magnets, regular scoop

7

16.89 CDR

JJM

The values of the parameters in the science vector are determined by the user. Unlike the design vector, the science vector is held constant across all designs. Only a few prior-to-landing considerations were assumed. Launch dates and landing time frame are needed for calculation of environment outputs. Terrain rock coverage (analogous to landing site) is needed to determine rock frequency. Landing site ranges are determined by ranges in latitudes, as described by Julie Wertz (JPL/MIT, personal communications).

The instrument and acquisition tool payload is specified by the user in the science vector. Including the instrument payload in the design vector would result in an orders of magnitude increase in the size of the trade space. Designs with different payloads can be determined individually.

Several of the parameters in the science vector were selected in order to constrain the design of the rover, with a particular emphasis on simplifying the autonomy module. Examples of these constraining parameters include the number of samples per site, distance between sites, and site size.

The default values of Science vector are the values for MER rovers.

If trying to create rovers for MSL launch, the appropriate science vector needs to be considered. Ls for 2009 is approximately 160° (end of Northern summer).

Design Vector

- Mission Lifetime
 - 30 to 1000 sols
- Level of Autonomy (8 combinations)
 - Two levels:
 - MER level (low autonomy) [A1]
 - Highly autonomous [A3]
 - Short and long distance navigation considered separately
 - Sample acquisition ability
- Type of Communications (7 choices)
 - Direct-to-Earth (DTE), High Orbiter (HO) UHF or XHF, Low Orbiter, DTE + HO UHF, DTE + HO XHF, DTE + LO
- Power Source
 - Solar powered, radioisotope thermoelectric generator (RTG)
- Wheel Diameter
 - .05 to 1 meters

8

16.89 CDR

JJM

The Design Vector is a set of variables which create a unique rover design. Mission lifetime range was constrained by a) past mission lifetimes (like Pathfinder) and b) realistic Earth operational costs (and time). Also, this wide range allows for rover designs that take advantage of a RTG power source.

There are 8 combinations possible of autonomy. There are three categories in which autonomy has an ‘calculable’ effect on the rover design: short range distance navigation, long range distance navigation, and sample acquisition ability. Each category can operate at either MER level of autonomy (a1) or highly autonomous (a3), terms which JPL and Mars Program uses (Personal communications with J. Parrish and J. Garvin).

The 7 levels of Communications specifically were selected because of their effect on total information exchanged with Earth. Notice the two different bands possible with the high orbiter (UHF and XHF or X-band). We wished to consider two power sources – solar and RTG. MSL is seriously considering RTG in their design, thus our inclusion in the design vector will be relevant to JPL.

A last variable in the design vector (wheel diameter) was added because it constrains the mass and size of the rover, as well as determines the size rocks that can be roved over.

N-Squared Diagram

Design Vector				X	X	X	X	X	X	X	X	X	X	X
	Science Vector	X	X	X		X	X	X		X	X			
		Instr.	X		X	X			X	X				X
			Acquistion		X	X		X	X	X				X
				Environ.	X	X		X	X	X				
					Rover Init.			X						
						Auto. Init.								
							X	X	X	X				
							Comm. 2	X	X					
								Rover	X	X				X
								X	Power	X				X
										Auto.	X			
											Comm. 3			X
												Complexity		
														Cost

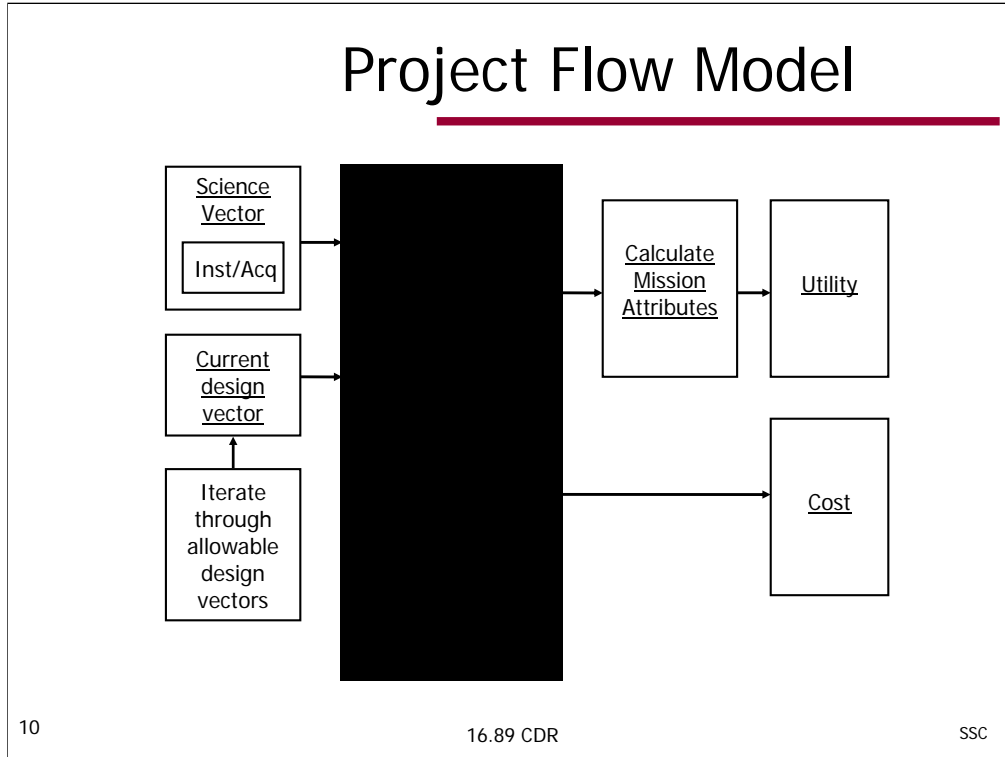
9

16.89 CDR

SSC

The N-squared diagram shows the order the modules are called based on the inputs and outputs of each module. This is done to eliminate all unnecessary loops to create a simpler and more efficient program.

There is one major loop found to be necessary, between Rover and Power. This loop is due to Power needing to know the drive power of the rover to determine the power system size while the rover needs to know the size of the power system to determine the power required to drive the rover. Communications has been split into 3 separate module calls. Communications 2 is used first to determine the sizing of the communications system, communications 1 is used within the autonomy module to determine the communications delay for the sequence of actions, and communications 3 is used last to determine communications system cost.

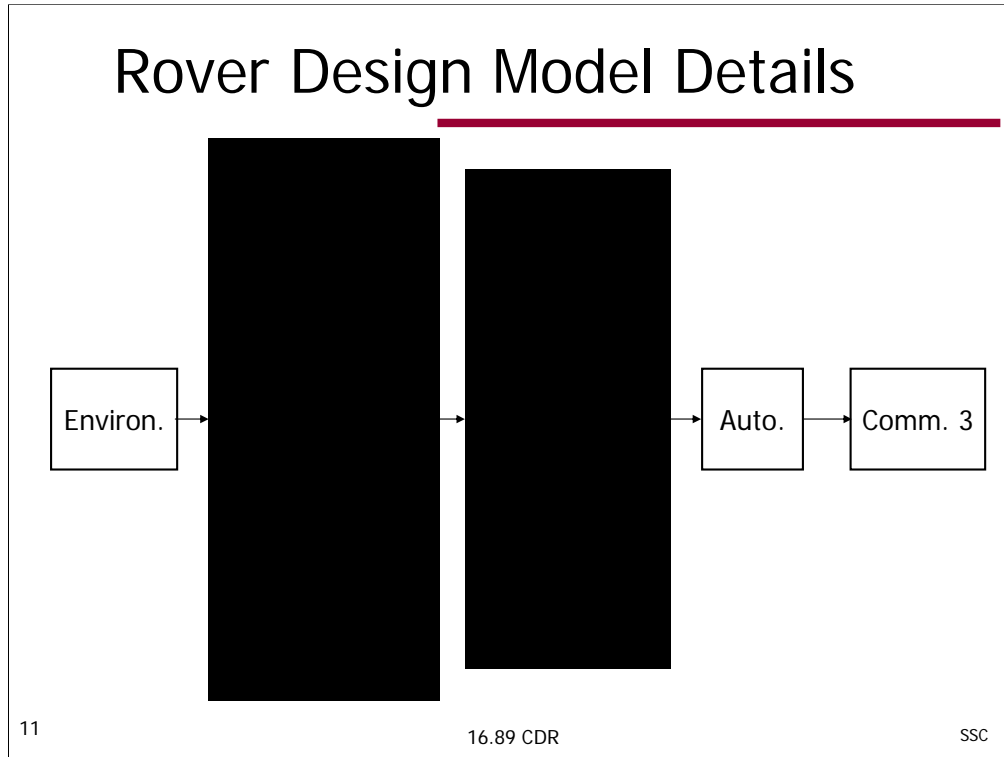


The trade space contains a collection of rover point designs, developed by iterating over combinations of the allowable values of the parameters in the design vector. For a particular iteration step, the parameter values in the design vector are held constant, and these values and those in the fixed science vector are passed as inputs to the rover design tool. For a properly chosen set of parameters in the design vector, there should be a one to one mapping between the design vector and a particular point design.

Concurrent engineering sessions have been conducted to explore the trade space based on various user inputs. These sessions have been used to verify the responses of tool to variation in the design vector, to verify the ability of the tool to capture the design of an existing rover system by using that system's design parameters, and to capture important architectural and design trends. Based on these trends and the cost and utility models, the trade space can be analyzed to identify candidate optimal architectures.

The flow within the Rover Design Model will be described on the following slide.

Rover Design Model Details



This diagram demonstrates the behavior of the rover design model. The rover design model is the sequence of function calls made to the separate subsystems.

The master code contains a series of loops where each loop represents a different variable in the design vector. In this way, all variables and possible values for the variables in the design vector are used to evaluate all possible configurations of rovers. The outermost loop is for the variable representing the wheel diameter of the rover. Before continuing to the other loops for the other variables in the design vector, the environment module is called. This is done since the only design vector variable environment is dependent on is wheel diameter (all other calculations in the environment module are based on the science vector) and this saves computation time if it is called here instead of inside the innermost loop.

The rest of the subsystem calls are made within the innermost loop since they will differ for every different set of values in the design vector. First, there are calls made to initialize the values for some of the subsystem functions. This is achieved by calling an initial rover module, then an initial autonomy module, and finally calling the communications 2 module to get values for variables that will be used in the rover/power loop. After this there is a major iterative loop between the Rover and Power subsystems due to that facts that the power subsystem size changes with drive power requirements, and the drive power requirements are based on rover mass. In turn, the rover mass is also dependent on the size of the power subsystem. After this loop, Autonomy is called to determine its actual values based on the rover and power designs, this includes a call within the module to communications 1 which models the communications delay for sequences of actions. After autonomy is determined communications 3 is called to calculate the cost of communications, including DSN operation costs and equipment costs.



Subsystems

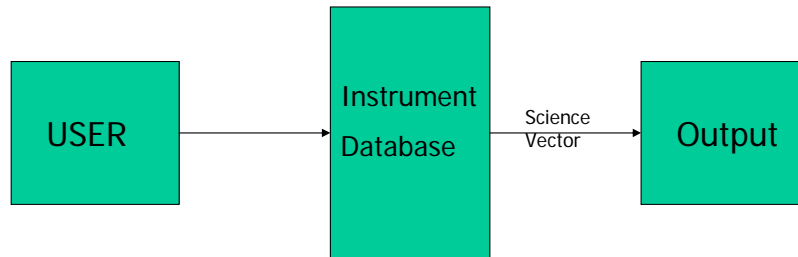


Instruments

Chris Roberts
Julie Wertz

Instruments

- Science Instruments are selected by the User and placed in the science vector



- Instrument data gathered from MSL Database, MER, and developers

14

16.89 CDR

JW,CR

This chart shows the high-level flow diagram depicting the Instruments' role in the overall surface system design code. The Tool User specifies the instruments from a database that currently has 15 instruments included. Then, these instruments and their properties (mass, power, size, as well as other relevant data) are output to the rest of the tool. The rover is designed around the payload. The sources for the instrument information are the following: JPL MSL Instrument database, other JPL sources (such as Al Chen and Charles Whetsel), MSL and MER design documents and notes, and from websites of some of these instruments' developers.

Instruments

- The following instruments may be selected:

CONTACT SUITE	REMOTE SENSING	ANALYTICAL LAB	
Alpha Particle X-ray Spectrometer	Point IR Spectrometer with scene-rastering capability	Microscopic Imager VIS, high magnification - 1 um pixel, 6-color	XRF
Mössbauer Spectrometer	Stereo Panorama Camera, 4 color + Calibration target	Moessbauer Spectrometer [6]	Mass Spectrometers : GCMS + LD-TOF Integrated Instrument Pkg
Raman Spectrometer - In-situ Remote Sensing	LIBS	Oxidation Effects Instrument [7]	Mass Spectrometer: GCMS
Microscopic Color Imager, 30um resolution		Pyrolysis oven integrated w/ GC/MS, amino acid detector	Raman - Analytical Lab

15

16.89 CDR

JW,CR

This chart shows a summary of the 15 instruments currently available to the user. It is important to note that the code has been developed in such a way so as to be modular, and hence expandable, so that more instruments could be added in the future.

Instruments

- Instruments mass values were doubled to account for support structures, cabling, and optimistic estimations from the developers
- Sample Instrument database entry:

Instrument Name	mass	power day	power night	Dimension X	Dimension Y	Dimension Z	cost
Alpha Particle X-ray Spectrometer	1.02	0.34	0	2.6042	1.352	0.597	10
	location	data_per_sample	time_per_sample	temperature_min	temp_min_operable	temperature_max	stability_req"
	Arm	256000	43200.00	173.15	173.15	318.15	0

- Information in database are similar to values proposed by Charles Whetsel

16

16.89 CDR

JW,CR

This chart gives an example of the information that is included in the Instruments module for each instrument.

When the mass of the instruments included in the MSL Instrument Database were compared with the numbers provided in Charles Whetsel's document we found that the detailed Mars Science Lab Instrument Database were consistently below Charles's estimates. However, if the masses of the Mars Science Lab instrument database numbers are rounded up to the nearest 5 kg we find that the database and Charles's estimates are in agreement. The instrument team contacted Charles regarding this discrepancy and he recommended that the numbers in the MSL database were probably a bit low for two primary reasons. The first is that the numbers in the MSL database do not include the supporting structures (mounts, cables, etc.). Second, many of the numbers in the MSL database were provided by developers. There was a consensus that developers tend to give optimistic estimates and that some measure of margin on the mass was in order to help rectify these two factors that were tending to under-represent the mass of the instrument payload. In consultation with Profs. Miller & Keese, we applied a factor of 2 to the payload mass. There are no other margins build into the Instruments module.

Acquisition

Ian Garrick-Bethell
Eisa Hines

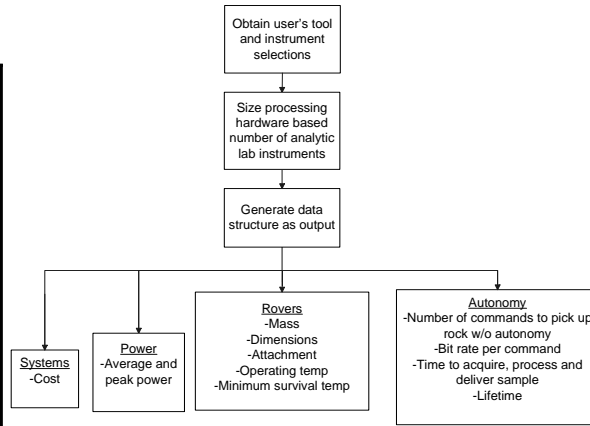
Acquisition

- Use industry, journal articles, JPL, and DLR-Germany resources to create a database of acquisition tools and their properties

Module Flow Diagram

Tools Modeled

Rock Abrasion Tool (RAT)
Rock Drill/Corer
Sample Scoop
Beagle-2 Mole (Pluto)
NASA Ames Mole (MUM)
1-m Drill
10-m Drill
Magnets
Processing Hardware



18

16.89 CDR

IGB/EKH

Several sources were used to find information on the acquisition tools. All tools modeled can be found in the file “create_acquisition_look_up.m”, and all data contain comments that indicate their source or any assumptions and calculations that were made. There are some values that were not obtained, such as cost, that were estimated based on similar tools and are commented as a ‘guess’ or ‘unknown’.

In deciding what values to use for each given instrument, priority was generally given to information attained through direct contact with industry professionals. Two examples of this are a document sent upon request from HoneyBee Robotics and e-mail correspondence with Lutz Richter, DLR-Germany regarding the Beagle2 Pluto mole. Other sources included journal articles, company or project web pages, the JPL PSIG (Project Science Integration Group) document, and JPL presentations. If there was no easy choice between different values reported by different sources, such as power and processing time, the more conservative values were generally chosen. Any values that were unknown or not documented could be generalized from the document provided by Charles Whetsel, JPL.

All tools have been flown or are being flown this year, with the exception of the NASA Ames Mars Undersurface Mole, the two drills, and the processing hardware designed by the Sample Processing and Distribution (SPAD) study. There is a larger version of the scoop and a 1000m drill also in the acquisition structure file but neither are made available to the trade space due to lack of information or need at this point.

As the flow diagram shows, the acquisition.m file reads the user’s tool and instrument selections from the science vector user interface. Using the instrument selections, the module determines the size of the sample processing and handling hardware. The relevant sample processing hardware values and acquisition tool values are then delivered in a structure that is accessible to all other modules, although most modules will use only some of the data (e.g. the Rovers module uses the mass of the tool).

Acquisition

- Example tool: Honey Bee Robotics' RAT for MER

RAT	Whetzel	Honeybee	MER Websites	JPL PSIG Document	Final Value
Mass (kg)	-	0.750	0.72	0.770	0.770
Avg Power (W)	-	30	-	7-10 (peak 17)	10
Time (hrs)	-	-	2	2-2.5	2.5
Size (cm)	-	10.0(L) x 4.0(D)	-	13.7 x 7.5 x 8.0	13.7 x 7.5 x 8.0
Cost	\$1M	-	-	-	\$1M
Max number samples	-	-	10	-	10

- Sample processing hardware based on JPL's Sample Processing and Handling (SPaH) hardware

4 Instr. SPaH	JPL
Mass (kg)	10
Avg Power (W)	25
Time (hrs)	.6
Size (cm)	.3 x .3 x .15
Cost	\$22M

SPaH is designed to support sample processing for four or more instruments

The code scales the mass, power, dimensions, and cost of SPaH if the number of analytic instruments is less than four

Example: User selects a mass spectrometer, a pyrolysis oven, and a APXS → equals 2 lab and 1 contact-arm instrument → processing hardware is sized for 2 lab instruments = one half SPaH values

19

16.89 CDR

IGB/EKH

The Rock Abrasion Tool (RAT) is shown here as an example of a tool that has several data sources reporting differing values. The top chart shows selected RAT values and their sources to demonstrate how values were chosen.

A documented cost for the RAT was not found so the cost value defaulted to \$1 M, which is the Whetzel document(JPL) estimate for instruments. All other critical values were documented by sources referring specifically to the RAT. Three similar mass values were found, so the largest value was taken knowing that the reference in PSIG was someone with Honeybee. For the average power, 10W was used because the Honeybee source is a website and considered less reliable than the PSIG document, which used Honeybee as a reference. The same reasoning holds true for the size values, and the processing time was taken conservatively at 2.5 hours.

The sample processing hardware is a special case because its associated values can vary depending on the number of analytic laboratory instruments that are chosen. If no analytic instruments are chosen (only mast and/or contact instruments) then there is no processing hardware output. If the number of instruments chosen is more than three, the full size processing hardware is assigned as the sample processing hardware output. If between one and three are instruments selected, the acquisition code calculates values from the the SPaH, scaled appropriately to the full size SPaH, and outputs them with the other selected acquisition tool values. All of the values for the SPaH are based on the JPL SPAD study, supplied by Allen Chen, JPL.

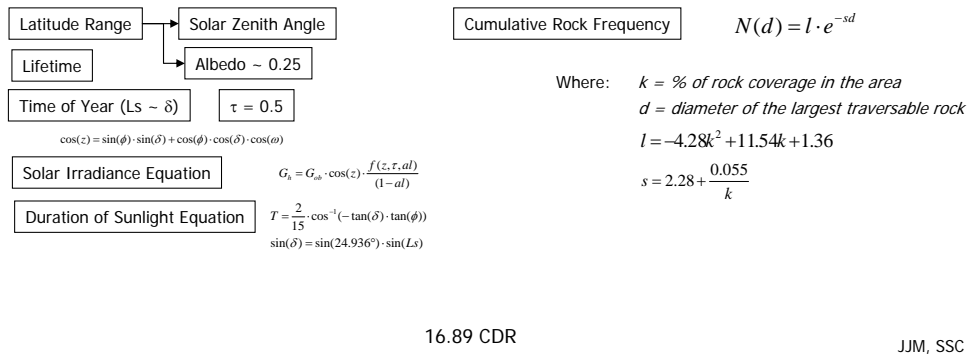


Environment

Stephanie Chiesi
Jessica Marquez

Environment

- Module consists of four major components
 - Solar Irradiance at horizontal surface (Watts/m²)
 - Duration of sunlight (Length of Sol)
 - Rock Frequency by rock size
 - Temperature ranges



There are four major components of the Environment module, listed above. The module outputs a few other things like soil bearing strength and probability of finding subsurface water, for example. The solar irradiance, length of sol, and temperature ranges are outputted as maximum, minimum and average. Rock frequency outputted are for rocks that are greater than the given wheel size.

Solar Irradiance at the surface of Mars was calculated using the journal article “Solar Radiation on Mars – Update 1991” by Appelbaum, Landis and Sherman, published in Solar Energy Vol. 50, No. 1, 1993. The calculations are strictly for horizontal surfaces. Solar irradiance at the surface is a function of the amount of solar energy reaching Mars, the solar zenith angle, the optical depth of the atmosphere, and the surface albedo. G_{ob} , solar energy reaching Mars, is a function of areocentric longitude (Ls) which is a measurement of where Mars is in its orbit. Ls equal to 0 is vernal equinox, Ls = 90 is summer solstice, etc. Solar zenith is a function of latitude, the time of day (usually referred to as hour angle (ω)) and again, Ls. G_{net} is normalized net solar flux function which is tabulated in the mentioned article. In order to figure out which net solar flux needs to be used, optical depth was set to 0.5, which is a good estimate for clear days. An average albedo was calculated also based on tabular information provided in article.

Length of sol was calculated using a second journal article “Solar Radiation on Mars: Stationary Photovoltaic Array” by Appelbaum, Sherman, and Landis, published in Journal of Propulsion and Power, Vol. 11, No. 3, May – June 1995. The equation is plainly stated and no assumptions had to be made.

Notation: ϕ = latitude, δ = declination, Ls = areocentric longitude, z = solar zenith angle, τ = optical depth, al = surface albedo, ω = hour angle from high noon

Rock frequency was calculated based on equations and relations published in the two papers: Golombek, Haldemann, et al. “Rock size-frequency distributions on Mars: at the the Pathfinder landing site, and in boulder fields, thermal inertia of rock populations, and rock shape and burial and implications for Mars exploration rover landing safety and operations.” MER Special Issue of Journal of Geophysical Research, Planets. Dec. 19, 2002 and Golombek and Rapp. “Size-frequency distributions of rocks on Mars and Earth Analog sites: Implications for future landed missions.” Journal of Geophysical Research. Vol. 102, NO. E2, pg. 4117 – 4129. Feb 25, 1997. These papers describe rock modeling techniques derived from observed rock distributions from Pathfinder and Viking. The frequency is a function of rock coverage in the area and size of the rocks. This is then used to create a rock frequency distribution by taking the values of the cumulative function and dividing it into small bins representing small average rock diameters and determining how many rocks of that average diameter there are.

Temperature ranges were developed based on existing actual data from Mars that has been made into a Martian general circulation model. These models have been tuned to match existing data from observatory missions and has been validated against those available observations. While there are some discrepancies in some parts of the overall climate model, these are not in areas that should affect our data needs.

Environment Validation

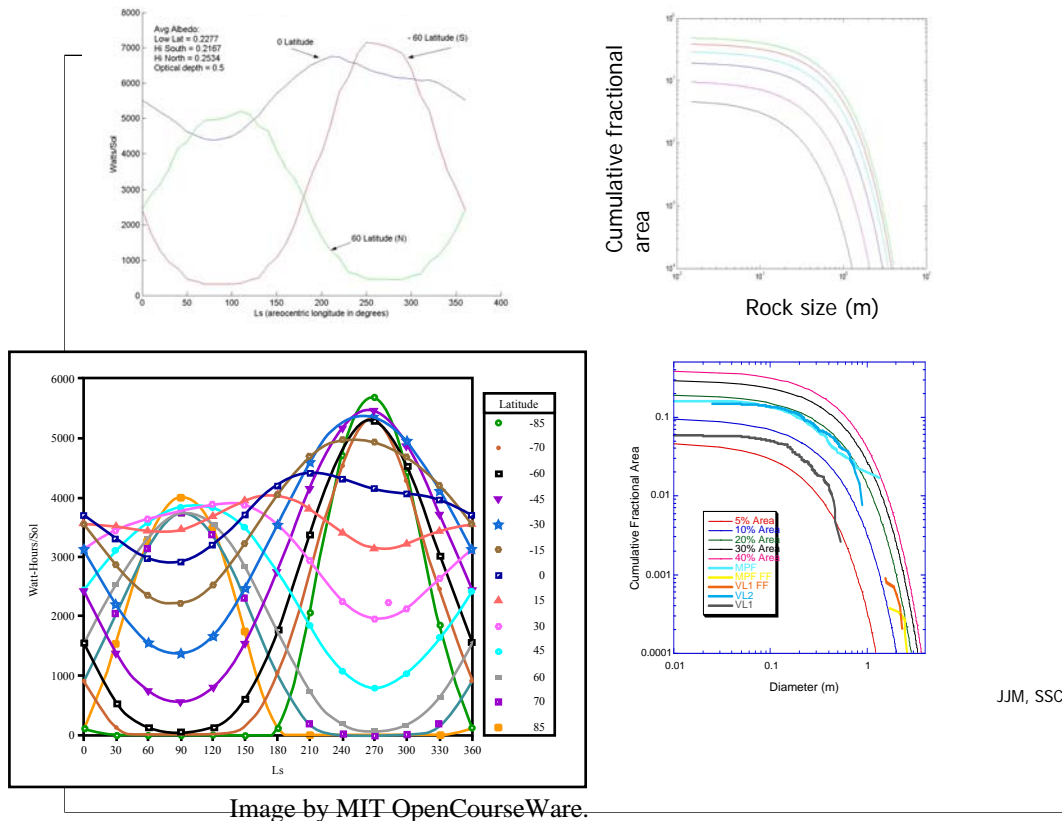


Image by MIT OpenCourseWare.

16.89 CDR

In an effort to duplicate Charles Whetsel’s graph he sent us, I used the equations from the two journal articles and replicated (to a certain extent) the variables. I limited the number of curves because our model only captures three latitude regions – equatorial, hi north and south latitudes. The graph shows how much solar energy is potentially available at a horizontal surface per sol over the course of a Martian year. Note that areocentric longitude is representative of time of year, starting from vernal equinox (beginning of spring).

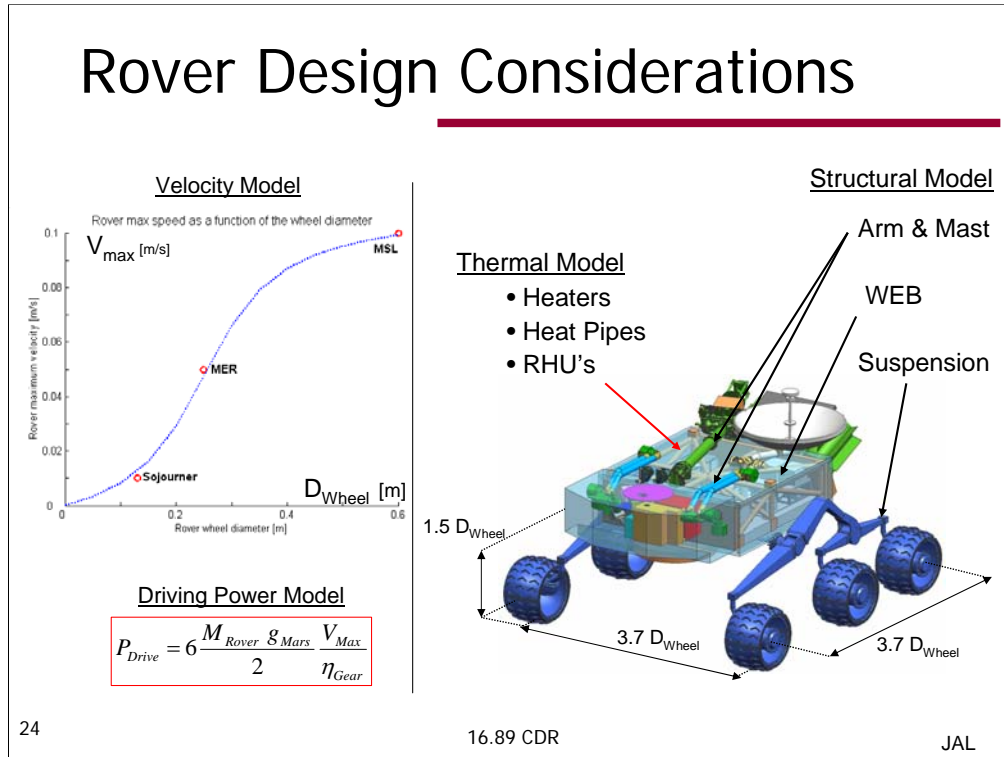
The model calculates similar trends as seen in Whetsel’s document, but the energies are off-set roughly 1000 Watts/sol higher. Possible explanations for this discrepancy are 1) the graph that is presented in Whetsel’s document is for other albedos, and 2) there are improved general circulation model of Mars. The second explanation is more likely because the normalized net solar flux function is dependant on the GCM and the articles I used are roughly 10 years old.

The graphs on the right show the validation of the data used for cumulative fractional area rock modeling by the environment module. Data and equations used are directly from published JPL rock modeling techniques. The environment module is able to replicate the cumulative fractional area data for models of different amounts of rock coverage that also correspond to observed rock distributions from actual missions (Pathfinder and Viking). The top graph shows what is produced by the environment module while the bottom graph is taken from a JPL presentation on modeling the Martian surface. The curves created by the module replicate those shown in the presentation and used in rock hazard modeling.

Rover

Mark Hilstad
Julien Lamamy

Rover Design Considerations



The ROVER module main contributions to the global model are the calculations of the rover size, maximum speed, mass, power and thermal requirements. These properties are modeled based first on Charles Whetsel's notes (size and power), second on a rover database (maximum speed) and finally on a bottom up approach (mass and thermal). The whole rover modeling is driven by one key variable: the wheel diameter. It dictates the size, mass, maximum speed and consequently driving power requirement.

Rover's Dimensions

So far the suspension design is limited to the rocker-bogie technology (used on Sojourner and MER). The rocker-bogie architecture implies relationships between the rover's dimensions and the wheel diameter. These relationships are taken from Charles Whetsel's notes. The wheelbase is proportional to the wheel diameter and set equal to the track. We used the same characterization by the wheel diameter for the arm length and mast and suspension height. They are all some number of times the wheel diameter.

Wheel dimensions

The wheel diameter is a design variable. The wheel width must be scaled accordingly. The width must be big enough that the wheels do not sink. However the width must be less than 0.6 times the wheel diameter not to compromise the rover turning ability. Because the Martian soil bearing strength is not well known and can change locally on Mars surface, the wheel width is set to its highest possible value (0.6^*D).

Obstacle management

With a rocker-bogie suspension the highest climbable obstacle is 1.5 the wheel diameter.

Driving Power

From C. Whetsel's notes the driving power is set equal to half rover weight on Mars time its maximum speed.

The gear transmission efficiency is set to 0.97 (average efficiency for mechanical transmission).

REFERENCES:

MER driving power: from 'MER final, approved for external release' document

Sojourner driving power from 'Mars Pathfinder Microrover – implementing a low cost planetary mission experiment', J.Matišević Marsokhod 75 driving power per wheel from 'Soviets Developments Planet Rovers in Period of 1964 – 1990' A.L. Kemurdjian, edited in 'Missions, technologies and design planetary mobile vehicles' CNES, Toulouse, September 1992

Maximum Speed Model:

The driving power is an output from the ROVER module therefore it is not convenient to use it to size speed. We decided to keep the wheel diameter as the key design variable. Hence we fit a curve Max speed vs Wheel Diameter based on 3 data points for Sojourner (0.13m; 0.01m/s), MER (0.25m, 0.05m/s) and MSL (0.6m ; 0.1m/s) - the curve is also required to pass by the origin.

The important feature with this choice of modeling is that it gives a saturating velocity when the wheel diameter is larger than 0.6-0.7m. Above that speed the rover should not be considered 'quasi-static' but 'dynamic'. Structural integrity then becomes the limiting factor. R. Volpe, JPL: structural integrity 'may limit future speed is structural integrity in the event of accidental collision with the environment (e.g. a large rock). I believe that Don [Bickler] has set that limit around 50cm/s. FYI, 50cm is about one wheel diameter for 2009 rover designs now being considered'.

Hence we assume that such a conservative velocity model captures the vibrations/ packaging/ and frequencies limitations that impact velocity through the structural aspect of the rover.

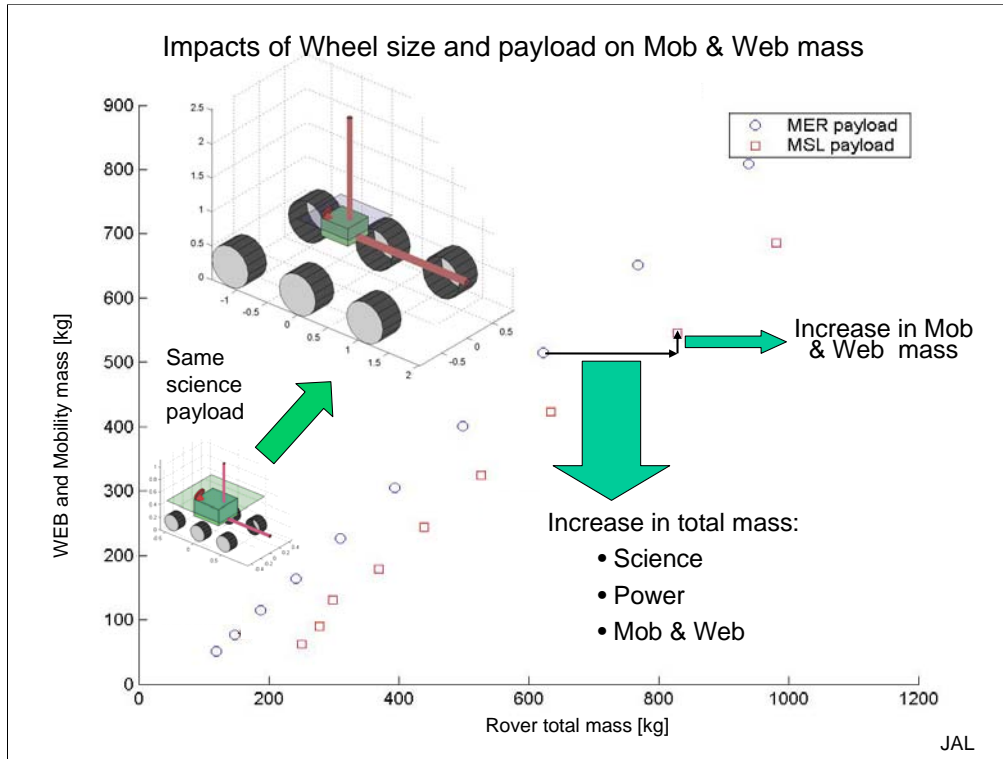
The WEB, suspension, arm and mast are all design with structural (bending and buckling) considerations.

STRUCTURE – WEB

DEFINITION: The WEB (Warm Electronics Box) is the main body of the rover

WEB DESIGN

No data (besides for Pathfinder) was found on WEB mass vs. total rover mass or another variable or over variable. Hence we had to make our own model.



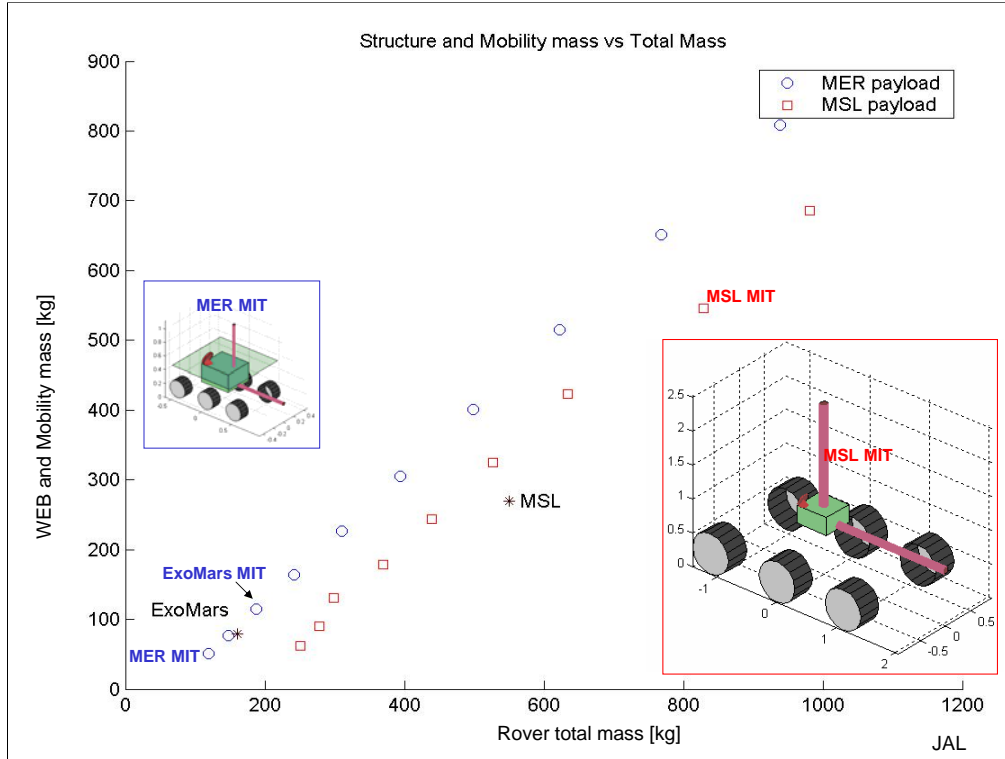
The chart is Rover total mass vs Web Mobility mass.

First consider the plot with circles, it corresponds to a MER-like scenario. The circles represents designs with all the same science payload corresponding to MER mission. Only the wheel diameter is changing from one design to the other. The total mass increases as the wheel diameter increases from 0.25 m (MER) with increments of 0.05m. As the science payload remains the same on this line only the mobility really changes through the wheel size variations. And as is shown the suspension is first for small wheels of the same scale as the payload (WEB) and then becomes relatively much larger with designs that look like trucks with tiny payloads. This allows the global rover model to assess then the benefits of sizing the mobility larger than it would be required to. There is a trade between heavier mass and ability to run over rocks and as a consequence be more time effective.

Now the squares correspond to MSL-like scenarios. Again all the designs with squares have the same science payload (MSL one) and only the wheel diameter changes between them. What is striking is that the difference of mass between MER and MSL science payloads is of 67kg roughly (from 8 to 75kg of science on top of that the power goes from solar to rtg) and the mass of Mob & Web is almost insensitive to such an increase. For the same wheel diameter but two different payloads the increase in mass of Mob and struc is just on tenth of the total mass increase.

The mass of the WEB is small compared to mobility and not very sensitive to increases in payload.

The wheel diameter has a much bigger impact on the mass of the mobility than the payload mass.



The two star points are actual design estimates by JPL and ESA. ExoMars is a Mars rover scheduled for 2009 by ESA and its total mass and WEB & mobility mass were found in 'CDF Study Report ExoMars 09 CDF-14A August 2002. The values for MSL are from AI Chen assuming a payload mass of 75kg (this assumption is explained further below).

We do not have the WEB and Mobility mass data for MER.

Each of the two set of plots (one marked with circles the other one with squares) represents a locus of constant science payload for different wheel sizes. For the circle points the science payload (ie instruments and acquisition tools) is the one of MER, for the square points it is an approximated one of MSL. MSL science payload is assumed to be 75 kg from Emily Eelkema April 1, 2003 'MSL Overview' presentation. Then we pick a set of acquisition tool and instruments which total mass equals 75kg to represent MSL payload in our model.

Design Vectors:

MER	MSL
Lifetime = 90 sols	Lifetime = 500 sols
solar power	rtg
dte	dte
Low levels of autonomy	High levels of autonomy
0.25 m Wheel	0.6m Wheel
science payload = 8kg	science payload = 75kg

Hence on top of a heavier science payload the MSL scenario has also heavier power system and avionics.

MER

For both plots the wheel diameter starts at 0.25m with increments of 0.05m. As the wheel diameter increases both total mass and Mob+Web mass increase. Hence the circle at the lower left of the chart is the MER-MIT design (MER modeled by the MIT team). It is on the locus of the MER payload and has a wheel diameter of 0.25m like MER. Unfortunately we don't have sufficient data on MER to support this point. However we can already affirm that the total mass of the MER-MIT design (around 130kg) is too low compared to MER 185kg. Still the MER-MIT design satisfies the C. Whetsel's guideline for which the mass of mobility and structure is 40% of the total payload mass.

ExoMars

As regard the ExoMars mission the ExoMars-MIT point is fairly close to the real ExoMars data point. This is surprising by the fact that the ExoMars does not use a real rocker-bogie suspension (even if the RCL suspension is not really different from rocker-bogie). This would tend to prove that the mobility mass is not strongly sensitive to the suspension used in so far as it is still a six wheel system.

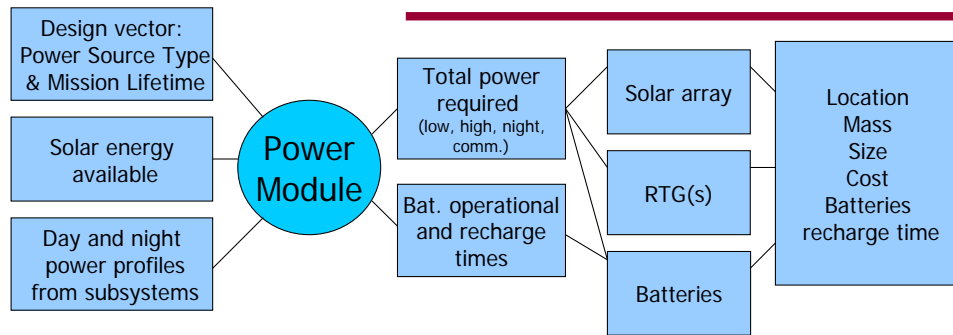
MSL

At first sight the MSL-MIT (MSL payload for a 0.6m wheel) seems to be far from the actual MSL design. However the MSL data point being a mix of AI Chen numbers with a payload mass from Emily Eelkema April 1, 2003 'MSL Overview' presentation, it is not sure that it is a valid data point. Moreover in the same presentation the mass of MSL is estimated between 600 and 900kg which the range of mass to which MSL-MIT belongs to.

Power

Kalina Galabova
Roshanak Nilchiani

Power Module Flow



Main assumptions:

- Silicon solar cells (NASA Glenn research).
- Nickel-Hydrogen batteries.
- Area ratio constraint (set by rover web).
- Depth-of-discharge
- Cost models.
- MMRTG is the RTG of choice.
- MMRTG will be technologically validated by 2009.

28

16.89 CDR

KKG

Our code consists of two parts: Solar and RTG. Nuclear fusion has been discarded as an option not only because of the enormous mass and size of the power system, but mostly because of its technology readiness level (hence reliability) and policy issues.

Module inputs:

- all subsystems' average and peak power requirements for day and night as a function of time
- solar energy (from Environment)
- mission lifetime and power source type (from Design Vector)

Intermediate Calculations:

Four types of total power required: low, high, night, and communications. Solar arrays are designed (or # RTGs chosen) based on average power requirements. Batteries are sized to meet peak requirements during the day and to power the rover at night (if solar option is chosen). The maximum solar or RTG power is estimated and then the difference between that and the peak power required is supposed to be provided by batteries. Their operational and recharge times were calculated to make sure designs are valid.

Module outputs:

- type of each individual piece of hardware (solar panel, battery, MMRTG, power interfaces)
- location for each type (web, deck, external)
- mass and size for each hardware piece
- cost of the entire power system

Assumptions:

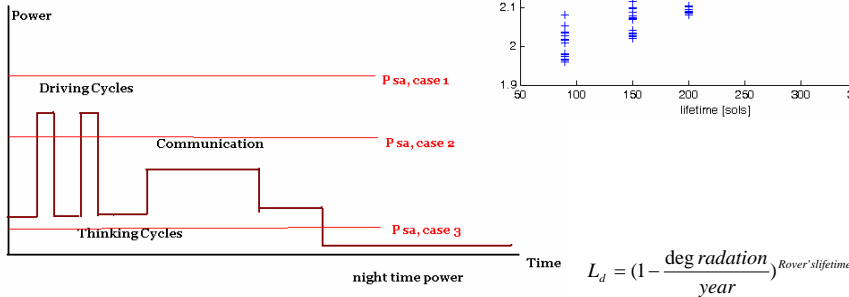
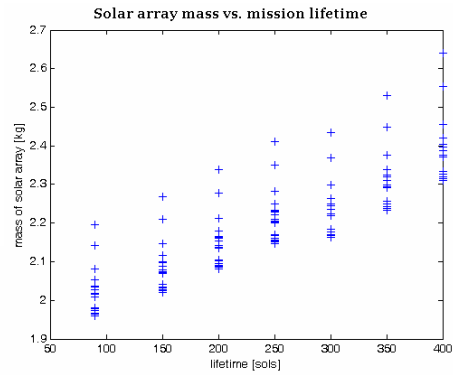
- Based on a research done by Photovoltaic & Space Environments Branch in NASA Glenn Research Center, the Silicon solar cell technology has been chosen. GaAs or Multijunction solar cell can also be tested for by the module.
- The battery chosen to accompany the solar cell is Nickel-Hydrogen. This choice is for decreasing the total possible number of architectures. Switching to Nickel cadmium, lithium ion or sodium sulfure is allowed by the code. Some features of the Ni-H battery that were found to be advantageous for energy storage systems in aerospace applications are as follows: Long life cycle, exceeds all other maintenance free batteries; High specific energy (gravimetric energy density); High power density; Tolerant to overcharge and reversal; No memory effects
- A restriction applied to solar cell module that the solar cell area can not be bigger than web footprint size multiplied by a constant which is area_ratio.
- The battery depth-of-discharge for the solar option is assumed to be 75%, while that for the RTG option was 50%. The decision was based on the fact that the selection of an RTG architecture will most probably be accompanied by longer mission life, which means more cycles are expected then.
- For solar array cost calculation, AIAA 994066 paper (Solar Cell Array System Trades -Present and Future, E. Ralph and T. Woike) and AIAA paper 99-1066 are used. RTG cost was provided by Joe Parrish. Battery cost model was taken from SMAD, FY2000.
- Only US RTGs were considered and the Multi-Mission RTG was the RTG of choice. (will be explained in a later slide)
- MMRTG will be technologically validated by 2009.

Solar array and battery module

- Solar array:
 - Silicon
 - GaAs
 - Multi junction

- Batteries:

Secondary Battery	Specific energy density (W hr/kg)
Nickel Cadmium	25-35
Nickel hydrogen	30



29

16.89 CDR

RN

Solar array and battery Design:

The following types of solar array has been used in the module:

- silicon
- GaAs
- Multijunction

Each of them can be activated in the module. There are some parameters that are important for the design of solar arrays which are functioning mars including: Suspended atmospheric dust, Low operating temperatures, Deposition of dust on the arrays, Wind loading, Peroxide components of the soil, Radiation and Low atmospheric pressure. Many arrays presently in space produce between 20 and 40 W/kg. The best state-of-the-art arrays that fly on some commercial communication spacecraft produce about 70 W/kg. A set of

and

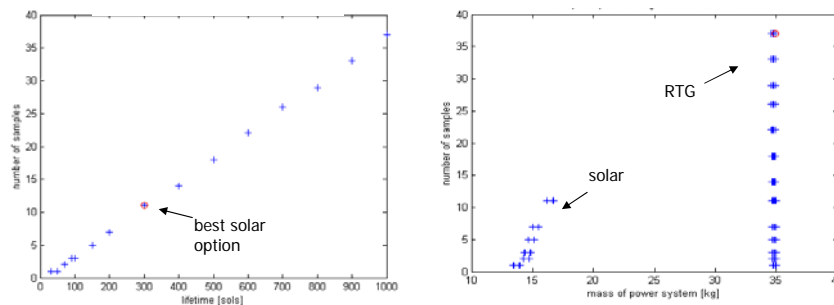
In order to design the solar array-battery combination, a power profiling has been done for calculating the optimal surface area of the panel and mass of the secondary batteries. N1 number of driving cycles with P-driving power, thinking cycles which rover is practically not moving and processing the information, N2 number of communication cycles, P-communication, recharging cycles for charging the communication batteries, and P-night and duration of the Martian night is being considered. On the basis of power profiling, a minimization on the mass and area of the solar panel and battery is being done in the power module. There are some restrictions on the area of the solar panel which are based on the geometry of the rover. The area of the solar panel is being designed in a way not to exceed much further then the footprint of the rover.

Solar array, dust and degradation:

Besides the inherent degradation of the solar cells which is being done with radiation environment, the dust settlement of solar arrays is a big issue in shortening the lifetime of the solar array. In order to avoid this problem, several ways of removing dust has been studied in NASA. In the code, we considered a mechanical dust removal system which extends the life of the solar array.

RTG Module

- RTG selection: **MMRTG**
- Battery choice and sizing: **Ni-H2**
- Validation of model:
 - Confirmation of data by multiple sources.
 - Tested ranges of variables:
 - Power supplied (139 W to 1.12 kW)
 - Mission lifetime (0 to 1000+ sols)



30

16.89 CDR

KKG

RTG selection:

Prior to PDR, the code was designed to select the optimal RTG option considering three types of RTGs: Cassini type RTG, Multi-Mission RGT, and Stirling Radioisotope Generator. We decided to change the strategy, since in reality the choice of an RTG would be determined by the technology readiness of MMRTG and SRG, not by the specific mission scenario. We assumed that the most probable choice should be MMRTG for the following reasons:

- 1) Cassini type RTGs use too much Pu-238 and will probably be out of use after 2005+.
- 2) SRGs are much more efficient than MMRTGs but their current Technology Readiness Level (TRL) is only 4, while MMRTGs have a TRL of 7. If desired, Cassini or SRG specifications can be tried by the code, too.

(The purpose of the picture is to show where an RTG is located—at the tip of a boom, far from the spacecraft electronics)

Battery choice and sizing:

As already mention, the battery of choice is Ni-H. Using a battery in combination with RTGs is not a common situation. In our case, however, it was desirable to design for this option because we expected to have very short periods of peak power demand. Without considering batteries, we would end up with too much excess power, since the number of RTG would be selected based on the peak power requirements.

The sizing formulas used were the same as for the solar option, except that night power requirement were excluded.

Validation of Model:

- Confirmation of RTG data by a number of sources (Joe Parrish, textbooks, www). Battery mass, power, cost were more difficult to validate.

Ranges of variables/parameters used for validation (outside this ranges the code gives an invalid design):

- Power required: [0 to 1.12 kW]—for numbers greater than that, the code advises to have a lander with a small reactor in it, which will supply power to the rover. The amount of Pu doesn't change much every year because of its large half-life, so we expect to have pretty much constant amount of power throughout the entire mission lifetime.
- Mission lifetime: [0 to >3.5548e4 sols]—10 years is the design life of an MM RTG. This is mire than we expect the rover mission to last.
- Battery cost estimation is a concern. An equation used in SMAD is used, but we weren't able to validate the results. Our guess is that the SMAD equation is a little too conservative (I.e. we did not expect battery costs of the order of millions of dollars).

Plots

The two plots show the results of a run testing a rover having all possible instruments. The first plot shows that the solar power option is limited to 300 sols and 11 samples (this is the best solar case). All points above that correspond to RTGs (RTGs are of course possible for <300 sols too). The second plot shows the same result for the number samples but from the point of view of the mass of the selected power system. The mass of the solar option is much less than its nuclear counterpart, but we see clearly that RTGs can allow for more samples to be collected.

Communications

Babak Cohanim
Tsoline Mikaelian

31

16.89 CDR

References:

- Surface System Design Process and Sizing Relationships document, Charles Whetsel, JPL
- Space Mission Analysis and Design, 3rd Ed., Wertz and Larson
- Frequency Assignment Guidelines for Communications in the Mars Region, Recommendation 22-1, Space Frequency Coordination Group
- DSMS Telecommunications Link Design Handbook, 810-005, Rev. E, 34-m HEF Subnet Telecommunications Interfaces
- Mars Odyssey Fact Sheet
- NASA's Mission Operations and Communications Services, AO 02-OSS-xx
- MER Mission Plan document

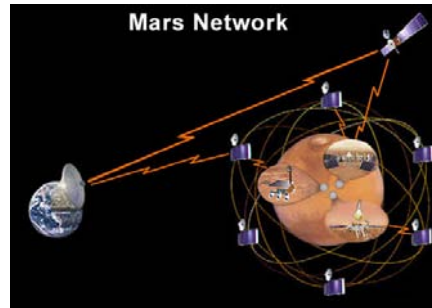
TM

Communications

- Function: Telecommunication subsystem sizing, scheduling, power usage and cost estimates

- Communications architectures supported:

- DTE, LMO, HMO (UHF), HMO(X-band and UHF), DTE & LMO, DTE & HMO (UHF), DTE & HMO (X-band and UHF)
- Can be expanded to incorporate future architectures



- Major limitations: Accuracy of parameters, uncertainties associated with communication windows, resource availability assumptions, no hybrid scheduling

32

16.89 CDR

TM

Function of the Communications module:

The function of the communications module is to size the rover telecommunications system, including antennas and transponders, schedule communications activities based on communication window opportunities, as well as estimate power usage and subsystem cost which includes DSN usage cost in addition to equipment cost.

Based on this functionality, the two major components of the communications module are:

1. Communication schedule calculations which involve calculating the duration of communication, the total delay associated with communicating given data volumes, as well as average communication durations per day and night.
2. Link budget calculations which involve the sizing of the telecommunication subsystem (antennas and transponders) for a Mars rover, as well as power usage calculations and cost estimates.

Modeling of major components:

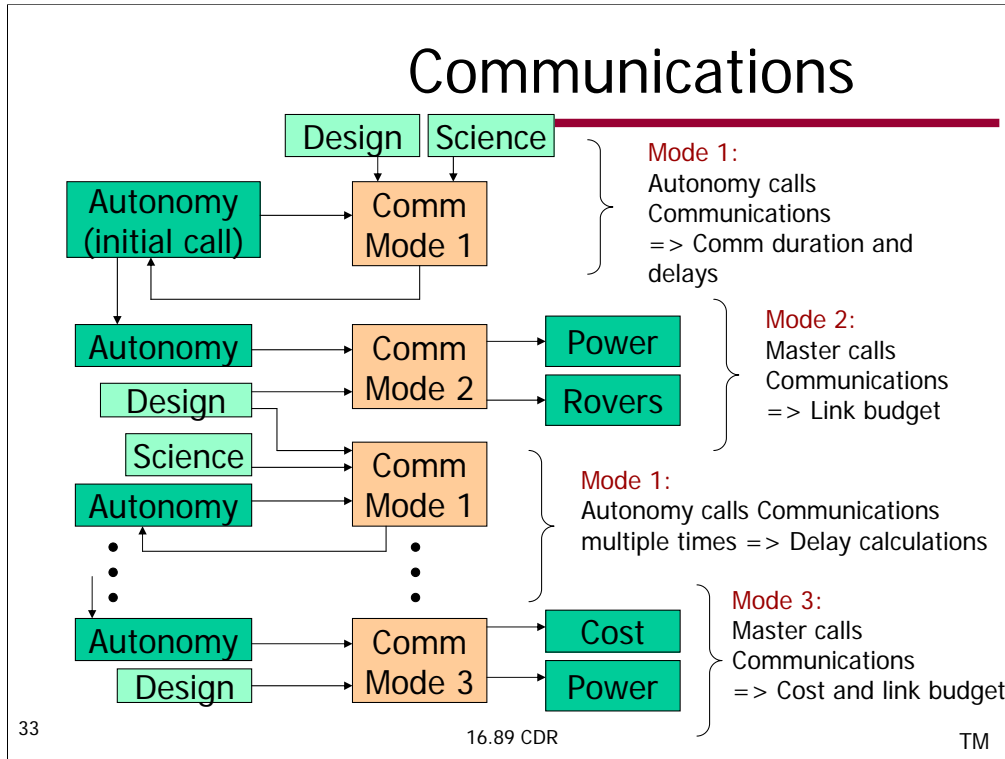
- The algorithm for delay calculation is based on the type of communication architecture which specifies communication window distribution and data rate, as well as on nighttime operation capability. If a response is expected from Earth, in addition to the uplink duration from Mars, the delay incorporates round-time propagation delay, downlink duration, human response time on Earth and the time taken by the rover to execute the received command (assuming that the next command cycle will begin after the execution of the current). Note that the communication window duration varies with latitude of the rover, and this factor has been incorporated into the model.
- The antenna diameter and transmitter power are determined using the link budget equations (Reference: SMAD). Power usage is determined on the basis of average communication duration per day and night.
- Cost model includes equipment costing based on costing relationship in SMAD, as well as DSN usage cost estimates as outlined in 'NASA's Mission Operations and Communications Services' document.

Communication Architectures:

The communications architecture is either DTE (34m HEF Deep Space Network (DSN) antenna use is assumed), via low altitude orbiter, via high altitude satellite operating in UHF, via high altitude dedicated satellite operating in both X-band and UHF, as well as hybrid combinations of DTE with low orbit and high orbit relays. The code can be expanded to incorporate future architecture concepts.

Major limitations:

- Parameter value assumptions: A number of parameters are unknown, and reasonable value assumptions have been made for these parameters. Examples include the altitude of high orbit relay satellites or the diameter of the receiving antenna on high orbit relay satellites. For communication via a relay, the Odyssey antenna parameters are used. Other parameter assumptions include link budget parameters such as Bit Error Rate (BER).
- Uncertainties associated with communication window durations and overflights. These depend on the orbits of the communication satellites, as well as on the exact landing latitude of the rover, which are not accurately known.
- Availability of Deep Space Network (DSN) resources and the relay satellite resources is assumed.
- Ignored redundancy considerations
- No hybrid scheduling is performed. For the hybrid architectures, it is assumed that DTE is the primary means of communication, while the relays are used as backup.



This diagram represents the program flow and execution sequence of the communications module. The inputs to the Communications module are provided by Autonomy, the Design vector and the Science vector. There are 3 modes of calling the communications module:

- Mode 1: Autonomy calls the communications module. This mode involves communication duration and delay calculations (passed to Autonomy).
- Mode 2: Master program calls the module. This involves link budget calculations to estimate power usage (passed to Power), size and mass of the communication subsystem (passed to Rovers module).
- Mode 3: Master program calls the module. This involves link budget calculations to estimate the cost of the communications subsystem (passed to Cost) and power usage (passed to Power). The cost calculation can't be performed in Mode 2 because of additional information required from Autonomy.

The execution sequence of the communications module is as follows:

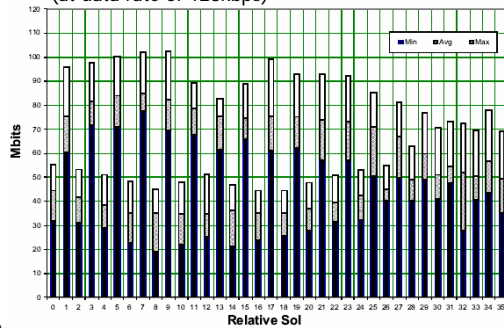
- Initially, Autonomy calls the Communications module (Mode 1), providing a typical data volume to be communicated, and informs whether there is nighttime operation. The Design vector provides the communications architecture, while the Science vector specifies the landing site which is used to estimate the window duration for the purpose of scheduling communication periods. The Communications module calculates the delay and communication duration for the given data volume, which is passed to Autonomy. The purpose of this initial call is to initialize the Communications and Autonomy modules in order to provide an initial estimate of communication power usage (used by Power).
- Following the initialization, the Communications module is called in Mode 2 by the master program. In this phase, the Communications module uses the communication duration and delay information (from initialization), in order to determine the communication duration per day and per night (this is provided to Power module). It also performs link budget calculations to estimate the power requirement (passed to Power) and size and mass of the communication subsystem (passed to Rovers module).
- In the third phase, Autonomy module calls the Communications module multiple times (Mode 1), passing a different set of data volumes to be communicated for each of the operations-intensive phases such as traverse or sample acquisition. The Communications module then calculates the total delay associated with communicating the data volumes, as well as associated values such as the total duration of communication of the data volumes. Following this sequence of calls, Autonomy determines the total number of communication cycles required during the lifetime of the mission.
- In the last phase, the Communications module is called by the master program in Mode 3. Now, information regarding the total number of communication cycles is available, which can be used for estimating the cost (as well as power usage). In this mode, link budget calculations are performed to estimate the equipment cost and DSN usage cost (passed to Cost), as well as power usage and the average duration of communication per day (and night) (passed to the Power module).

Communications

Link Budget Results:

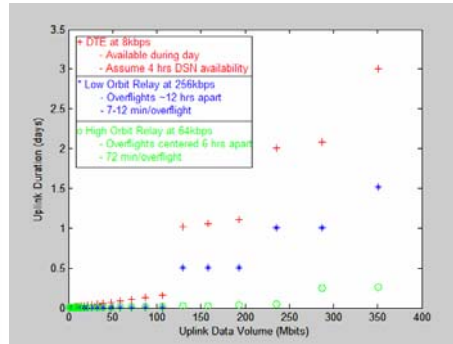
	Item	Symbol	Units	DTE	LMO	HMO (UHF)	HMO (X)
Inputs	Data Rate	R	bps	8000	2.56E+05	6.40E+04	6.40E+04
	Frequency	f	GHz	7.145	0.4597	0.4597	7.145
	Transmit Antenna Beamwidth	a_t	deg	8.5	180	180	60
	Transmit Antenna Pointing Offset	e_t	deg	0.005	5	5	5
	Propagation Path Length	S	km	4.01E+08	1600	20000	20000
	Receive Antenna Diameter	D_r	m	34	1.3	1.3	1.3
	Receive Antenna Pointing Error	e_r	deg	0.005	0.95	0.95	0.95
	System Noise Temperature	T_s	K	30	200	200	200
	Signal to Noise	Eb/No	dB	2.7	2.7	2.7	2.7
	Transmitter Line Loss	L_l	dB	-0.3	-0.3	-0.3	-0.3
	Propagation & Polarization Loss	L_a	dB	-0.3	-0.3	-0.3	-0.3
Outputs	Transmit Antenna Diameter	D_t	m	0.346	0.254	0.254	0.049
	Transmitter Power	P	W	78.3	0.081	3.14	0.94

Odyssey data volume from MER per sol
(at data rate of 128kbps)



34

16.89 CDR



TM

Link budget results:

The table above lists the link budget inputs and outputs for each of the communication architectures (hybrid is simply a combination of the columns shown). The link budget equations are used for calculating antenna size and power, and are validated using the FireSat benchmark in SMAD.

- The data rates are as specified in C. Whetsel's 'Surface System Design Process and Sizing Relationships' document.
- The frequency for DTE is in the X-band, while for low Mars orbit (LMO) the frequency is in the UHF band, and for high Mars orbit (HMO), it is either UHF or a combination of UHF and X-band.
- For DTE, the use of the 34m HEF DSN antenna is assumed (70m may be used as well), which fixes the receiver parameters. For LMO, Odyssey parameters are used (1.3m diameter antenna). HMO telecommunication satellites have not been launched yet, thus the Odyssey parameters are assumed for HMO as well.
- The propagation path length for DTE is assumed to be maximum Earth-Mars distance (400e6 km), to allow design for the worst case. LMO orbiters typically fly at 400km altitude. However, for low orbit, the slant range can be double or more the overhead range, therefore 1600km range is used. HMO telecommunication satellites are planned to be launched at typical altitudes of 10,000km. A slant range of 20,000km is used in this case.
- Eb/No is the ratio of received energy per bit to noise density. Its value is determined by the Bit Error Rate (BER), as well as modulation and coding schemes. Here, it is assumed that $BER = 10^{-5}$, and modulation scheme is BPSK and Plus RS Viterbi Decoding (Reference:SMAD)
- Typical values for line loss and polarization loss are assumed.
- The system noise temperature is found to be a critical parameter in the transmitter power calculation. C. Whetsel's document suggests a power level of 50W. This level of power can't be achieved unless the system noise temperature is as low as 20K. According to C. Whetsel, receivers typically operate at around 30K, which indicates that the power must be around 78W, which is within 2dB of C. Whetsel's 50W power requirement. According to C. Whetsel, the rest may be attributed to "coding gains or some other magic". Another contribution to the larger power level at DTE (78W as opposed to Whetsel's 50W) is the assumption of maximum Earth-Mars range. Not all of the mission occurs at this range, and the minimum range is a factor of 5 less (~80e6 km). The power required at minimum range is calculated to be ~2W. Therefore, Whetsel's 50W seems to be an average power requirement over the mission lifetime.
- For LMO, HMO (UHF) and HMO (X-band and UHF), the power requirements are calculated to be ~0.1W, ~3W, and ~1W respectively. The significantly lower power levels are due to much shorter propagation path lengths (1600km for LMO, 20000km for HMO as opposed to 400e6km for DTE). This is a discrepancy with C. Whetsel's document which suggests power usage of 50W for UHF communications (LMO, HMO). Since DTE communication capability exists on most Mars rover missions, one possible explanation may be that the 50W power requirement incorporates some DTE communications in addition to LMO/HMO (i.e. hybrid).
- Antenna diameter for DTE is calculated to be ~35cm, for LMO and HMO(UHF), it's ~26cm, which for HMO(X-band) it's ~5cm. These are similar to antennas used on MER (around 30cm for DTE, 20cm for LMO/HMO according to Mark).

Communication duration:

The implementation of the communication delay algorithm has been tested and validated by comparing against manual calculations of the delay. It is difficult to compare the results to MER or other Mars missions because of the assumptions underlying the module. Another reason is that data on command cycles and associated delays is generally unavailable.

The only comparison was made with Odyssey data volume received from MER per sol at a rate of 128kbps (left plot; Reference: MER Mission Plan document). Note that Odyssey is a low altitude science orbiter. The right plot shows uplink data duration as a function of data volume. For low orbit, the data rate assumed is double the data rate used to uplink MER data to Odyssey (data rate based on C. Whetsel's document). The left plot shows that a maximum of ~ 100Mbits can be uplinked per sol at 128kbps. The right plot indicates ~ 300Mbits per day at 256kbps, which is the equivalent of ~150Mbits at 128kbps. The discrepancy is attributed to our assumption that all relay satellite resources are available for the Mars rover mission. In reality, Odyssey has a limited memory availability (100 Mbits per sol for MER) which constrains the amount of data that can be uplinked per sol. Additionally, the uplinked data is buffered, and emptying the buffer relies on the availability of the DSN



Autonomy/Avionics

Edward Fong
Barry Willhite

Autonomy - Overview

- Purpose: to determine the amount of samples analyzed using different levels of autonomy
 - Calculate performance times for rover activities:
 - Navigational planning and movement
 - Long-distance traversals
 - Reconnaissance
 - Sample Approach
 - Sample Acquisition
 - Sample Processing
 - Using activity times, determine the amount of samples that can be analyzed given the mission duration

36

16.89 CDR

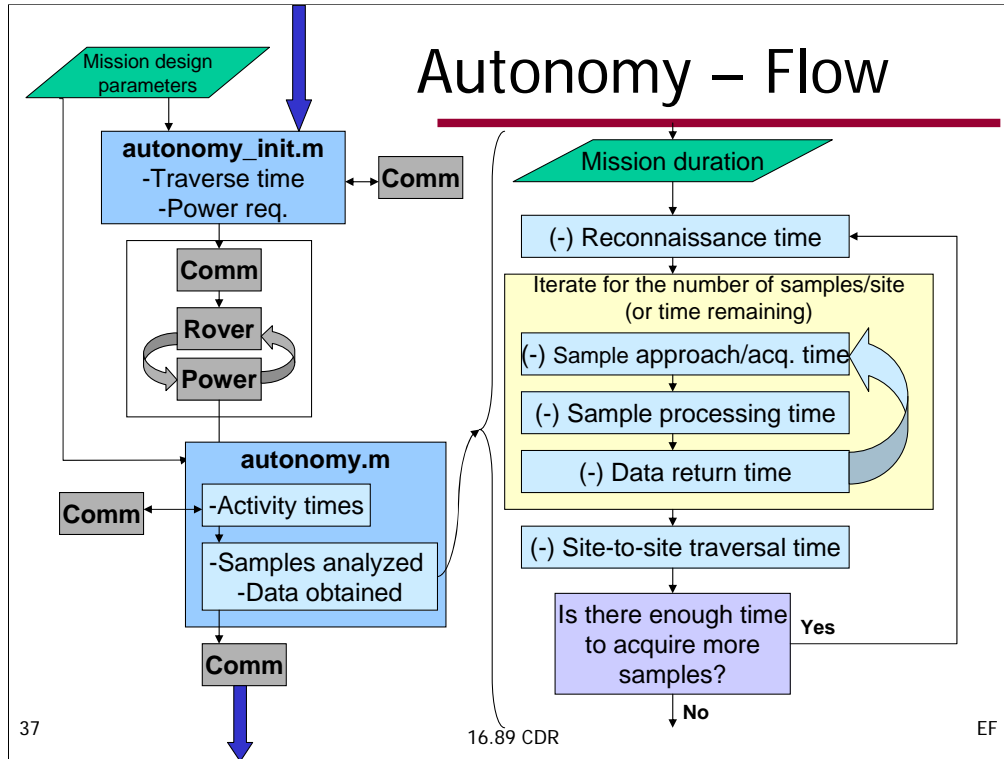
EF

The purpose of the Autonomy module is to ultimately determine the amount of science (directly related to the amount of samples processed) that a Martian rover can obtain given the mission duration and its autonomous capability. The amount of samples processed is based on the amount of time it takes to perform the tasks necessary to obtain and process a sample. Depending on the activity, those times can be influenced by a number of factors such as the processing power onboard, the ability to perform nighttime operations, the level of autonomy, etc. Because the level of autonomy plays the largest role in affecting performance times, that is the focus of this module – though the other aspects were roughly modeled and incorporated as well.

The Autonomy module needs to determine the time it takes to plan its path and move the planned distance (we modeled a 0.5 rover length movement/think cycle – method provided by Charles Whetsel) based on the autonomy levels selected. These times will depend on the size of the rover and processing power of the rover's computer. With the help of the Rover (which provides us with the rover's speed) and Power module (which limits our traverses if there is not enough power), we can determine the actual distance moved in a given sol. In addition, we also receive data from the environment module which helps us determine the amount and size of obstacles we can expect to encounter – allowing us to account for the time it takes to move around those obstacles when calculating our movement times for long-distance traversals and sample approaches.

The reconnaissance, sample acquisition, and sample processing times all depend on the instruments and tools selected by the user for each category and their operational times and communications requirements with Earth (which we get from the Instrument and Acquisition modules) – the acquisition tools' communication requirements with Earth will depend on the level of autonomy. The actual communication times and delay are calculated and provided to us by the Communication module.

After the times for the various rover activities are calculated, we can determine how long it takes the rover to approach and process a sample in a site, how long it will be at a site (based on how many samples we're analyzing per site), and how many sites it can visit given the mission duration. Using this information, we can determine the total number of samples visited.



This diagram provides a general idea of how the autonomy module interacts with other modules and the method by which it calculates the total number of samples analyzed.

The autonomy module is made up of two separate pieces of code. The first set of code (`autonomy_init.m`) determines the rover's theoretical average speed based on its actual driving speed and path planning time. The path planning time is determined by the processing power of the rover (the number of computers it has onboard) and the size of the rover. This section also works with the Communication module to determine the communications time for a driving sol. From those calculations, we can determine our traverse power requirements which we then pass on to power.

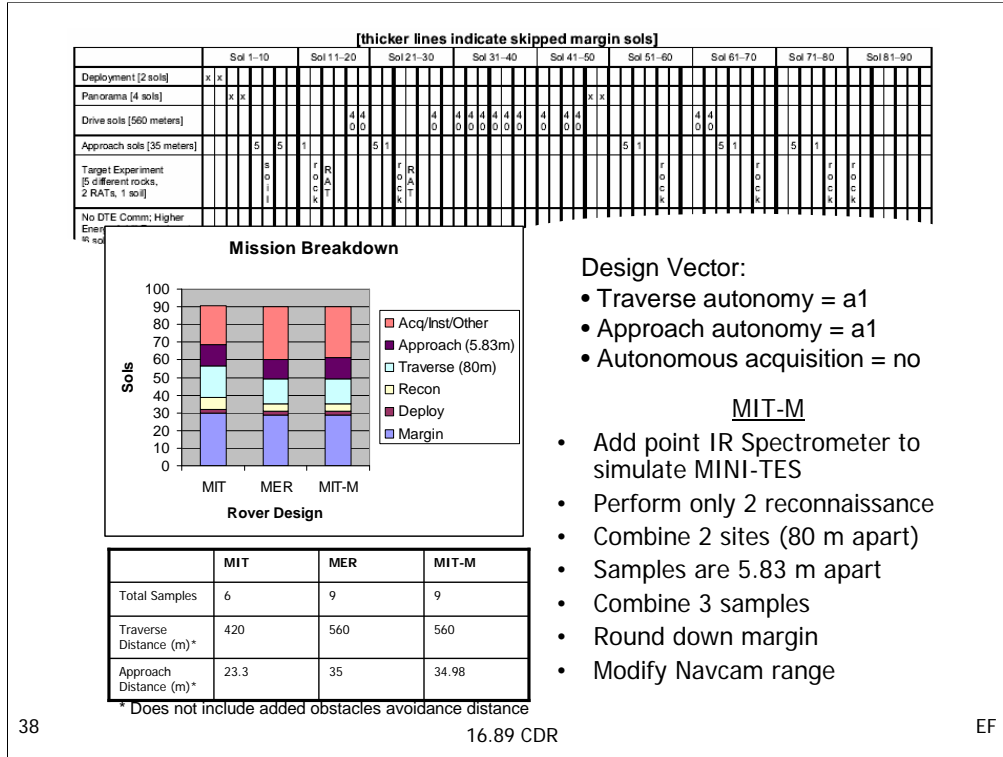
After the Communication, Rover, and Power modules run, the second set of code (`autonomy.m`) receives any limitations placed on our roving capabilities by power. From this value, and the levels of autonomy, the site-to-site traversal and sample approach times are calculated. After we perform the activity time calculations (reconnaissance, sample approach and processing, and data return times), we can determine the samples analyzed and data obtained. The structure for performing this calculation is illustrated on the right-half of this slide.

The basic structure of our mission profile is as follows:

- 1) We perform a reconnaissance of a site, send the information back to the user on Earth, and receive a reply specifying which samples to analyze – this is the reconnaissance time. The rover only performs one reconnaissance per site.
- 2) We approach the sample, acquire it, process it with our instruments, and return the data to Earth.
- 3) Step 2 is repeated until we explored a certain number of samples for the site (as set in the science vector).
- 4) Once we are done with a site, we move on to the next site and start with step 1.

As each action is performed, the amount of sols left in the mission decreases according to the activity. As each sample data is returned to Earth, the tracker for the number of samples analyzed and data sent back is incremented. This cycle is performed until the mission time is exhausted – providing us with the total number of samples analyzed and data obtained.

Note that step 2 is constantly looped through. The main purpose for this is to account for acquisition tools and instruments that have consumables which may become exhausted.



When we try to model MER using our module, we get ballpark values but not matching ones. However, this discrepancy can be explained. The MER Mission Plan document provides us with three sample mission designs. Since these scenarios (an example is provided in the slide) do not fit our model of traversing to a site, sampling a constant number of samples, then moving to the next site, we basically took the average site separation and sample separation distances when running our module. In addition, because of the non-structured way the MER mission plans are laid out, we had to model obtaining only one sample per site. The level of autonomy for traverse, sample approach, and acquisition were set to the lowest levels (representative of MER).

The left bar in the graph represents the activity breakdown over a 90 sol mission using our mission structure and the MER averages. As you can see, we did not go as far or collect as many samples as the MER document described. To fit the MER mission plan into a format similar to the structure we used, we had to perform some modifications (represented by MIT-M), they are as follows:

- 1) Added point IR-Spectrometer to simulate the MINI-TES (which was not modeled). This increased our reconnaissance time from 1 to 2 sols (representative of MER).
- 2) Performed only 2 reconnaissance – MIT would perform a reconnaissance for every sample because of our one sample/site fit to MER.
- 3) Combined 2 sites – this allows us to model the 560 m long-distance traverse.
- 4) Listed samples 5.83 m apart – this allows us to model the 35 m total sample approach distance.
- 5) Combined 3 pairs of samples – MER does this in the displayed mission plan.
- 6) Rounded down margin – this is just a rounding issue.
- 7) Modified Navcam range – our model of low-level autonomy only allows the rover to traverse a maximum of the navcam range in a given sol (which is currently set at 30 m). The actual limit depends on the available power (which we model), the terrain (which we model), and the time-out value. Instead of having the user define the time-out value and then modeling the probability of failure, we decided that it was simpler to just replace that limitation with the range of the navcam. This scenario allows a traversal of 40 m – therefore, increasing the navcam range to match the MER plan will better model this particular mission scenario.

Once we made these changes, our MIT-M results mimic MER almost exactly – including the number of samples obtained and total traverse distances. The only discrepancy was a difference of a single day modeled into the sample approach time. This is explained by nothing that the MER scenario did not bother with the accurate rover placement when performing soil analysis (hence the 1 sol that would place it at a precise location was omitted).

What this shows is that the reason why our module does not model MER exactly is primarily because our mission plan structure does not match the mission plan structure of MER. Though we do get pretty close values, we get “exact” values when the structures are made to be similar. Therefore, our time calculations are able to roughly model MER’s mission scenario and will be able to model a MER-like rover using our structured mission plan fairly accurately.

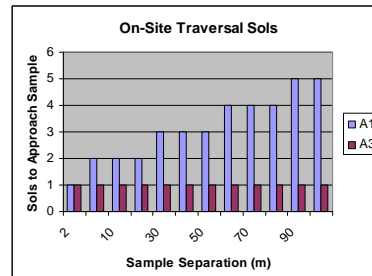
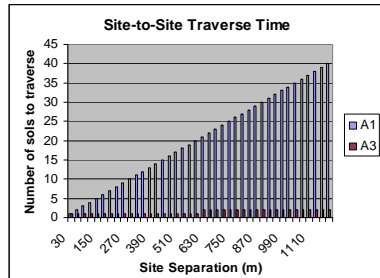
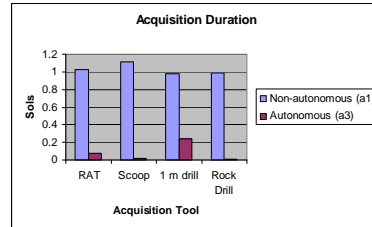
Autonomy

Design Vector:

- Traverse autonomy = a3
- Approach autonomy = a3
- Autonomous acquisition = yes

# sols for:	MSL*	MIT
3000 m traversal	7.86	10
Sample approach (10-20)	< 0.5	0.020 – 0.03
Approach, acquisition, processing (rock analysis)	3	3

*2001 MSL SDT Report (using wheel diameter = 0.5m, Ls = 185, Latitude = -30, Rock Coverage = 20%)



39

16.89 CDR

EF & BW

The table on the top-left corner of this slide compares our time calculations for the high level of autonomy, using a 2001 NASA MSL SDT Report. As can be seen, our numbers closely match those provided by the SDT Report. The three graphs show the general trend when looking at the difference between the different levels of autonomy for long-distance (site-to-site) traversal, sample approach (on-site traversal), and sample acquisition. The basic idea is that the lower level of autonomy will take more time to perform a given task than if it were made more autonomous. A more in-depth look as to the implications of using different levels of autonomy will be discussed later when we explain the value of autonomy.



System Validation

Setup for MER Mission

	MER	MIT		MER	MIT
DESIGN			SCIENCE		
Lifetime [sols]	90	90	<i>Instruments</i>		
Power Type	'sol'	'sol'	Pancam	1	inst(10)
Telecommunication	'dte'	'dte'	Mini-TES	1	
wheel diameter [m]	0.25	0.25	Microscopic Imager	1	inst(3)
autonomy_l_d [-]	'a1'	'a1'	Alpha-Particle-X-ray Spectromet	1	inst(1)
autonomy_s_d [-]	'a1'	'a1'	Mössbauer Spectrometer	1	inst(2)
autonomy_night_navigation [-]	'n'	'n'	<i>Acquisition</i>		
instrument night processing		'n'	Rock Abrasion Tool (RAT)	1	acq(3)
autonomy acquisition		'n'	Magnetic targets	3	acq(10)
lander [-]	'n'	'n'	<i>Navigation</i>		
number_computers [-]	1	1	Navcams	1	nav(1)
			Hazcams - front	1	nav(2)
			Hazcams - rear	1	nav(3)
Site Information					
sample per site [-]	1	1			
separation site [m]	70.7	70.7			
site diameter [m]	4.3	4.3			
terrain [% rock coverage]	0.05	0.05			
ls_landing [deg]	330	330			
obstacle_factor [-]	1	1			

41

16.89 CDR

BC & RN & BW

System level validation to MER specs.

Design vector - assigned by user. No information found on MER instrument night processing or autonomous acquisition so just assumed to be 'no'

Site Information – average values for MER landings

Science – instrument suite. Took out mini-TES due to lack of information.

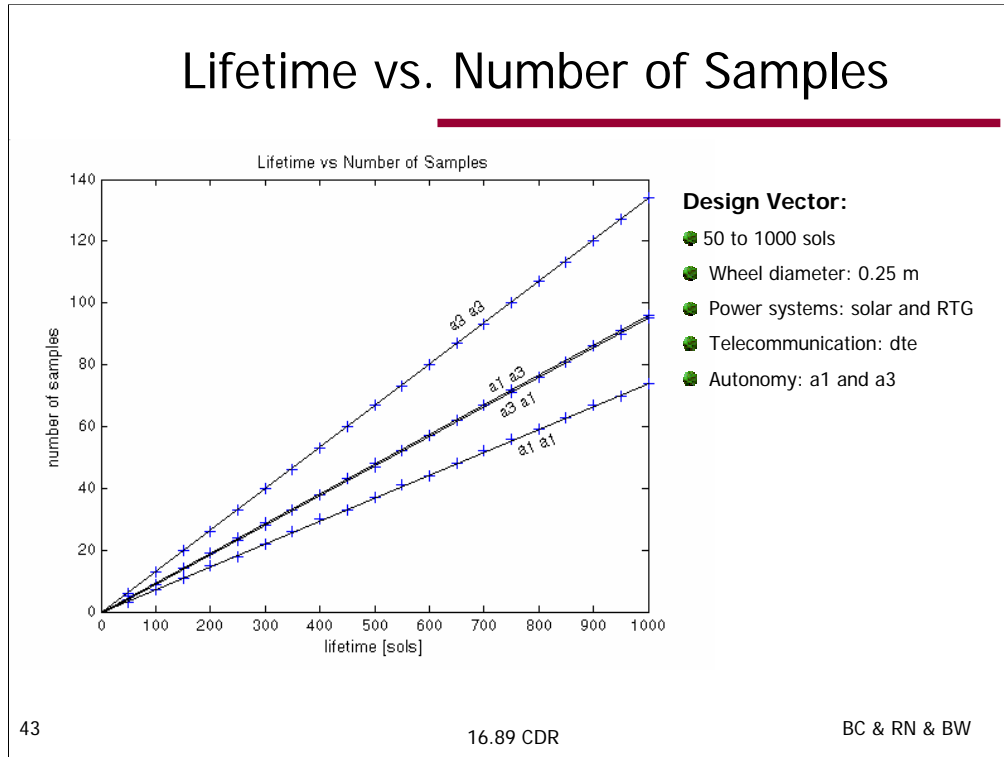
Autonomy, comm, power, rover specs – low on peak power, probably due to low on mass. Roving time to thinking time ratio is still incorrect.

Autonomy

Setup for MER Mission

	MER	MIT
AUTONOMY		
Traverse Distance [m/sol]	25-40	30
COMMUNICATIONS		
Type	dte	dte
POWER		
Peak Power [W]	140	123
Roving Time (t1) [s]	10	12.33
Thinking Time (t2) [s]	20	28.92
ROVER		
Mass [kg]	185	124
Size - [L,W,H] [m]	[1.04, 0.84, 1.6]	[1.18, 1.08, 1.13]
Top Speed [cm/s]	5	4.8
Actual velocity [cm/s]	1-2	1.4

Lifetime vs. Number of Samples



The following design vector has been used:

lifetime = [50:50:1000]

wheel diameter = 0.25 m

number of computers= 1

power system= solar and RTG

Telecommunication= dte

autonomy= a1 and a3

autonomy_s_d= 'a1', 'a3'

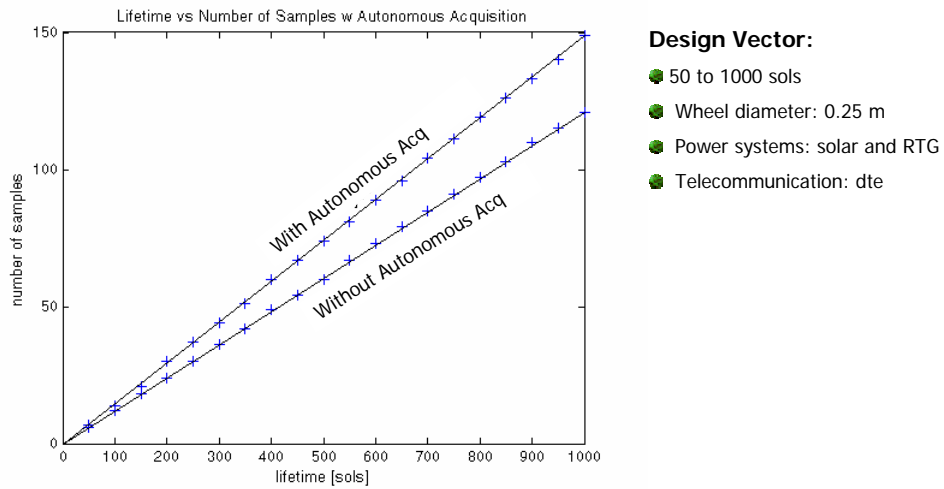
No Autonomy acquisition

No navigation at nighttime

No instrument nighttime processing

The plot shows that as you expand upon MER autonomy in either long distance traversal or short distance traversal (respective in plot) you get an increase in the number of samples. Intuitively then, if both levels were to increase, there would be another jump in number of samples

Lifetime vs. Number of Samples



44

16.89 CDR

BC & RN & BW

The following design vector has been used:

lifetime = [50:50:1000]

wheel diameter = 0.25 m

number of computers= 1

power system= solar and RTG

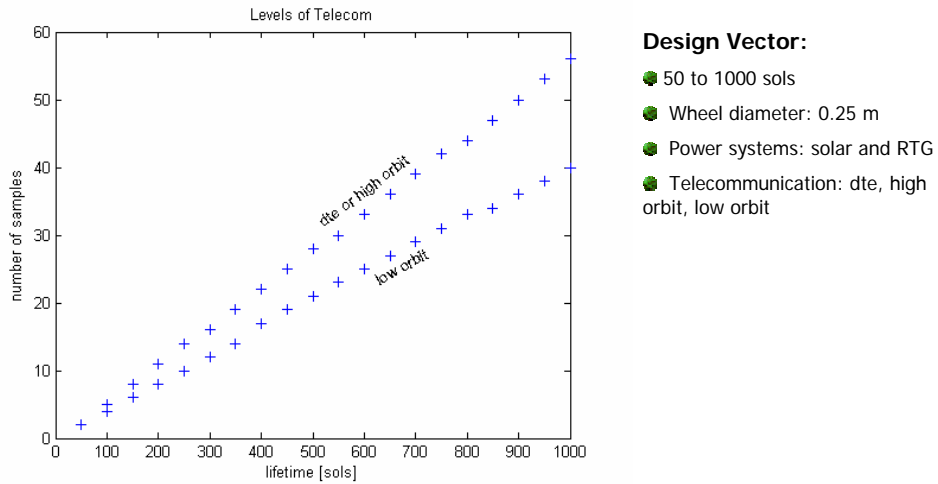
Telecommunication= dte

autonomy= a1

autonomy_s_d= 'a1', 'a3'

Autonomous Acquisition allows for more samples

Lifetime vs. Number of Samples



45

16.89 CDR

BC & RN & BW

The following design vector has been used:

lifetime = [50:50:1000]

wheel diameter = 0.25 m

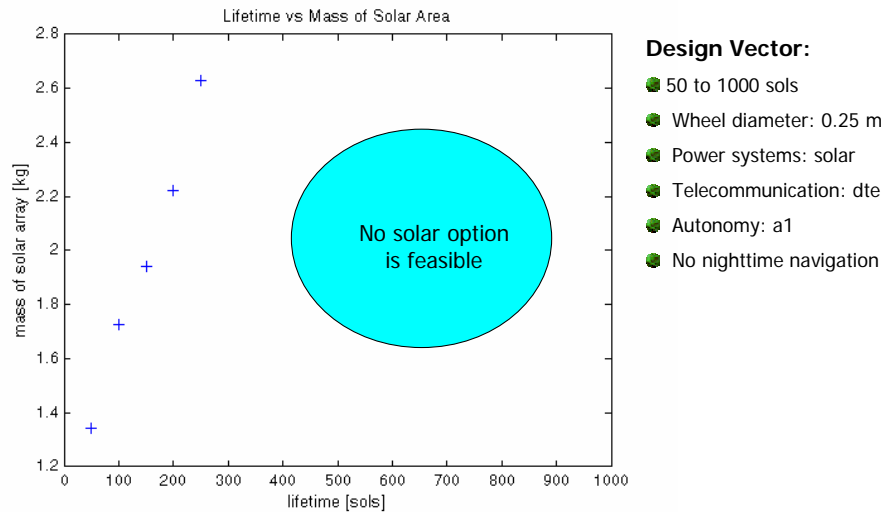
number of computers= 1

power system= solar and RTG

Telecommunication= dte, low orbit, high orbit

This shows the trade off of different comm systems. For our baseline, dte and high orbit gave the same number of samples.

Lifetime vs. Mass of The Solar Panel



46

16.89 CDR

BC & RN & BW

The following design vector has been used:

lifetime = [50:50:1000]

wheel diameter = 0.25 m

number of computers= 1

power system= solar and RTG

Telecommunication= dte

autonomy= a1

autonomy_s_d= a1

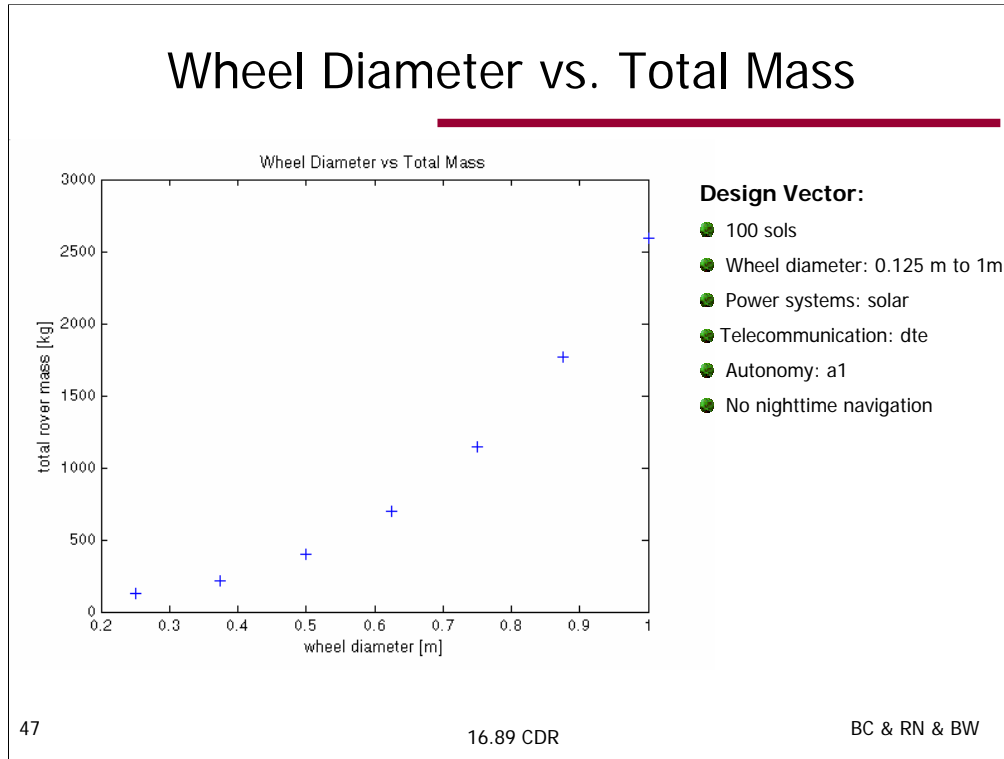
No Autonomy acquisition

No navigation at nighttime

No instrument nighttime processing

Plot shows that as lifetime increases, solar panel size (mass, area) increases. After a specific time, solar panel designs become invalid due to depreciation and dust accumulation.

Wheel Diameter vs. Total Mass



The following design vector has been used:

lifetime = 100 sols

wheel diameter = [.125:.125:1]m

number of computers= 1

power system= solar

Telecommunication= dte

autonomy= a1

autonomy_s_d= a1

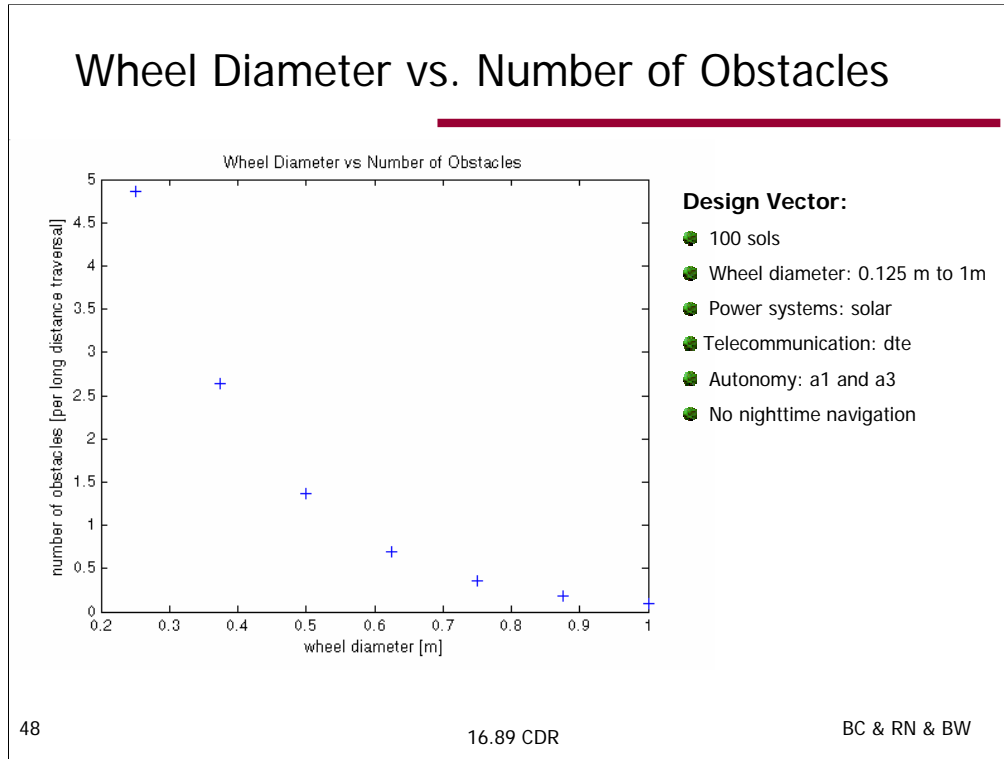
No Autonomy acquisition

No navigation at nighttime

No instrument nighttime processing

Wheel diameter vs total mass – as wheels get bigger, rover gets bigger, mass of wheels and structure increase

Wheel Diameter vs. Number of Obstacles



The following design vector has been used:

lifetime = 100 sols

wheel diameter = [.125:.125:1]m

number of computers= 1

power system= solar

Telecommunication= dte

autonomy= a1 and a3

autonomy_s_d= a1 and a3

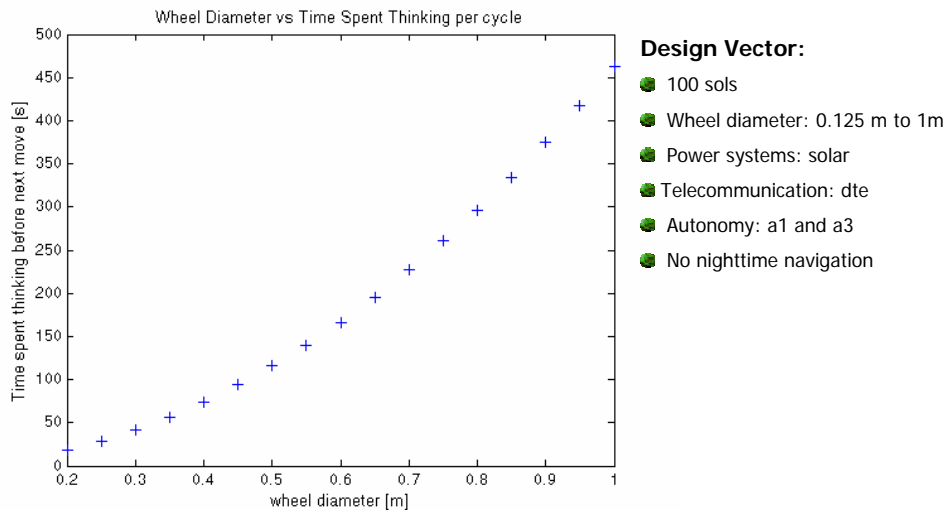
No Autonomy acquisition

No navigation at nighttime

No instrument nighttime processing

Wheel Diameter vs Number of Obstacles – as wheel diameter increases, number of obstacles it can climb over increases, thus the number of obstacles it has to contend with decreases. The power of the curve goes along with the power in the distribution of different rock sizes

Wheel Diameter vs. Thinking Time



49

16.89 CDR

BC & RN & BW

The following design vector has been used:

lifetime = 100 sols

wheel diameter = [.125:.125:1]m

number of computers= 1

power system= solar

Telecommunication= dte

autonomy= a1 and a3

autonomy_s_d= a1 and a3

No Autonomy acquisition

No navigation at nighttime

No instrument nighttime processing

Wheel diameter vs Time Spent Thinking per cycle – as the rover increases in wheel diameter, it increases in size, thus the footprint increases. The bigger the footprint, the more time the NavCam spends looking at its local environment and plotting its course

Trade Space Results

Analysis within Design Vector
Sensitivity to Science Vector
Value of Autonomy
Analysis of Design Complexity

Cost Modeling

- Subsystem-level cost modeling
 - Lack of information on cost of autonomy, production, and development
 - Rover: SMAD relationship based on total mass
 - Communications: SMAD, NASA references
 - Acquisition, Instruments: Industry, JPL, German Airspace Center references
 - Power: SMAD, AIAA, Payload Systems references
- Operations Cost
 - Function of lifetime, scales linearly to Pathfinder operational costs (NASA reference)

51

16.89 CDR

JJM

Subsystems' cost models were calculated if appropriate models were available. This is the case for Communications, Power, Acquisition, and Instruments. Unfortunately, rover cost models were not at our disposal. Five cost data points for rovers were known. From these five points, no relation between cost and mass could be developed. While there is the possibility that a simple cost relationship could be developed as a function of packing density, the data to develop this relationship was not available. Currently, the rover cost is modeled using SMAD cost estimation modeling, which is usually used for low orbit satellites but is a function of mass.

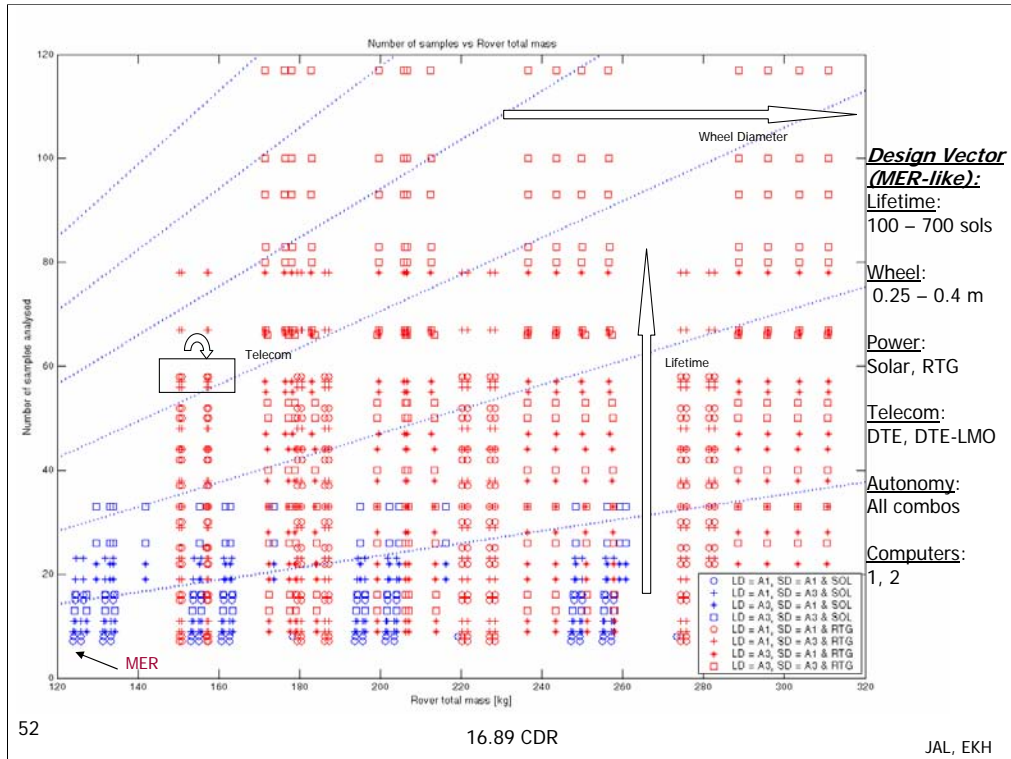
Communications used SMAD and NASA references and their cost modeling is a function of the usage of the deep space network.

Acquisition and Instruments estimated costs when necessary for individual tools and when available, included actual costs suggested by their list of references.

Power subsystem used several references. SMAD was a limiting source because it focuses on low orbiting satellites, thus other references were found, like AIAA papers and discussions with J. Parrish at Payload Systems. The costs include solar and RTG power sources.

Pathfinder operation costs were taken from the Goddard Space Flight Center website. Operational costs for our rovers were scaled based on Pathfinder lifetime operational costs.

<http://meds02.qssmeds.com/~dwilson/spaceops02d/MM/MM.2.n.pdf>



This is our rover trade space, using the ‘surrogate’ for cost – rover mass – versus number of samples, which is the best attribute we have to describe science return or value. The blue lines across the plot are “iso-metric” lines – they represent the ratio of 1 sample per every 7 kg of rover mass. Ratios increases (2:7, 3:7, etc) are represented with greater slopes.

Different symbols represent different levels of autonomy and the red symbols are RTG powered and the blue symbols are solar powered.

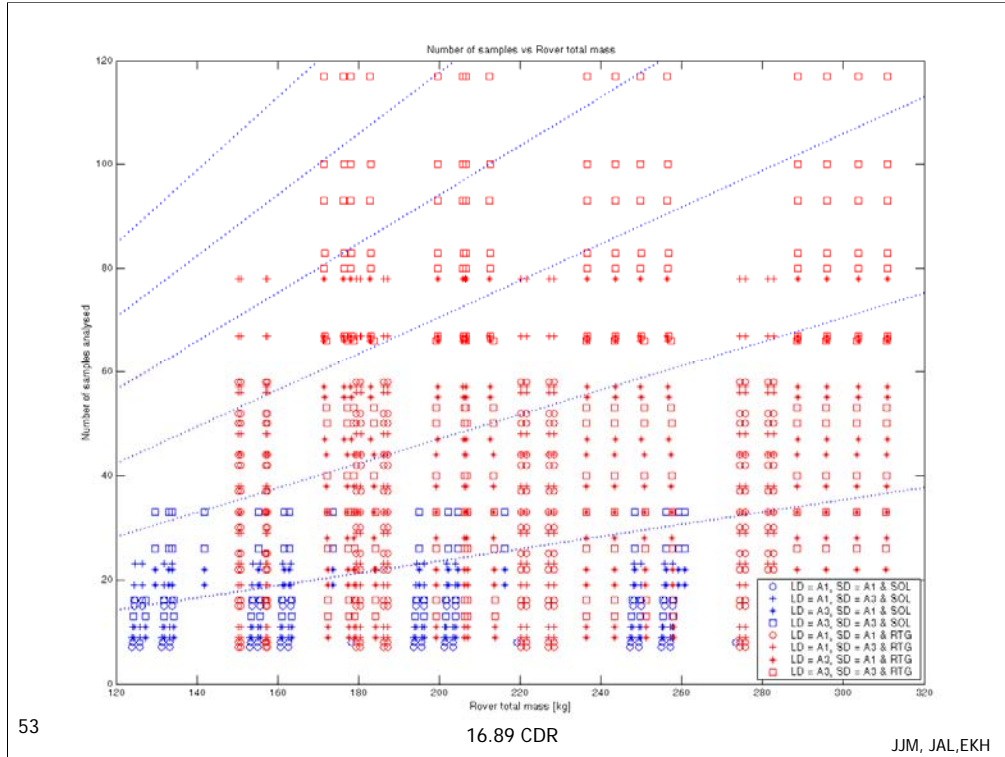
Note that solar powered systems are limited in their lifetime, and hence the number of samples they can acquire.

Note the Pareto front that has developed.

* More refined lifetime outputs solar powered designs to have higher number of samples (about ten more). (BACKUP)

Note that between DTE and DTE-LMO there is an increase in mass but there are no benefits (equal number of samples).

Wheel diameter translates to heavier designs without any benefits in number of samples; lifetime increase numbers of samples without increasing mass.



This the ‘surrogate’ for cost – rover mass – versus number of samples, which is the best attribute we have to describe science return or value. The blue lines across the plot are “iso-metric” lines – they represent the ratio of 1 sample per every 7 kg of rover mass. Ratios increases (2:7, 3:7, etc) are represented with greater slopes.

Line 2:7 145kg== Lifetime 200; 0.25 m wheel diameter; solar; dte-lo telecom; LD a3; SD a3; Acq yes; Night process no; 2 computer

175kg== Lifetime 300; 0.25 m wheel diameter; RTG; dte telecom; LD a3; SD a3; Acq no; Night process yes; 2 computer

245 kg== Lifetime 600; 0.35 m wheel diameter; RTG; dte telecom; LD a3; SD a1; Acq no; Night process yes; 2 computer

Across different power systems with same ‘performance’ levels, we see that we get longer lifetimes for RTG systems.

Line 3:7 220 kg== Lifetime 700; 0.35 m wheel diameter; RTG; dte telecom; LD a1; SD a3; Acq yes; Night process yes; 1 computer

235 kg== Lifetime 700; 0.35 m wheel diameter; RTG; dte telecom; LD a3; SD a3; Acq yes; Night process yes; 1 computer

Same performance metric between designs, however, LD A3 will save you about 200 sols, which would equate to about \$60M in operations.

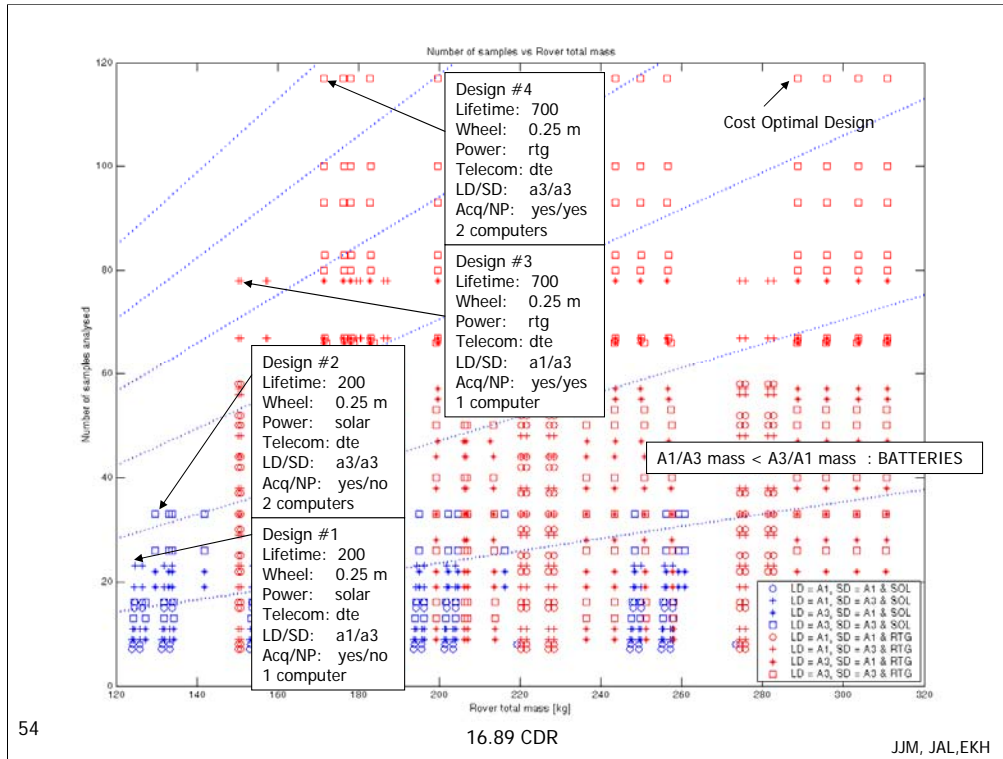
Line 5:7 175 kg== Lifetime 600; 0.25 m wheel diameter; RTG; dte telecom; LD a3; SD a3; Acq yes; Night process yes; 2 computer

200 kg== Lifetime 700; 0.30 m wheel diameter; RTG; dte telecom; LD a3; SD a3; Acq yes; Night process yes; 1 computer

Similar performance metric between designs, shows that an extra computer saves 100 sols in operation lifetime.

Author: Jessica Marquez

Julien Lamamy



Highlighted in this plot are the designs that are on the Pareto front, which are rover designs that are non-dominated. This means that there are no designs that have a lesser mass for that number of samples, the two attributes considered of importance for design comparison. Two interesting trends appear. The first is the fact that autonomy levels for long distance and short distance in the Pareto front are only A3/A3 (expected) or A1/A3. Careful analysis of the trade space reveals that A3/A1 autonomy requires more battery supplies, thus is more massive and not in the Pareto front. This would seem to indicate that A3 level of autonomy for short distance navigation would be more beneficial, if lesser mass is desirable. The other trend to note is the 2 vs 1 computer trade. Two computers always provide more samples but they are coupled with the inclusion of night time processing.

Note that for solar designs, night time processing isn't a desirable attribute (expected – otherwise need batteries) At the RTG level, it doesn't make a difference to have night time processing (in terms of mass) but increases number of samples.

NP = night processing ability

Pareto Front

23 samples, ~124.5 kg; # 392

Lifetime 200; 0.25 m wheel diameter; solar; dte telecom; LD a1; SD a3; Acq yes; Night process no; 1 computer

33 samples, ~129.5 kg; # 401

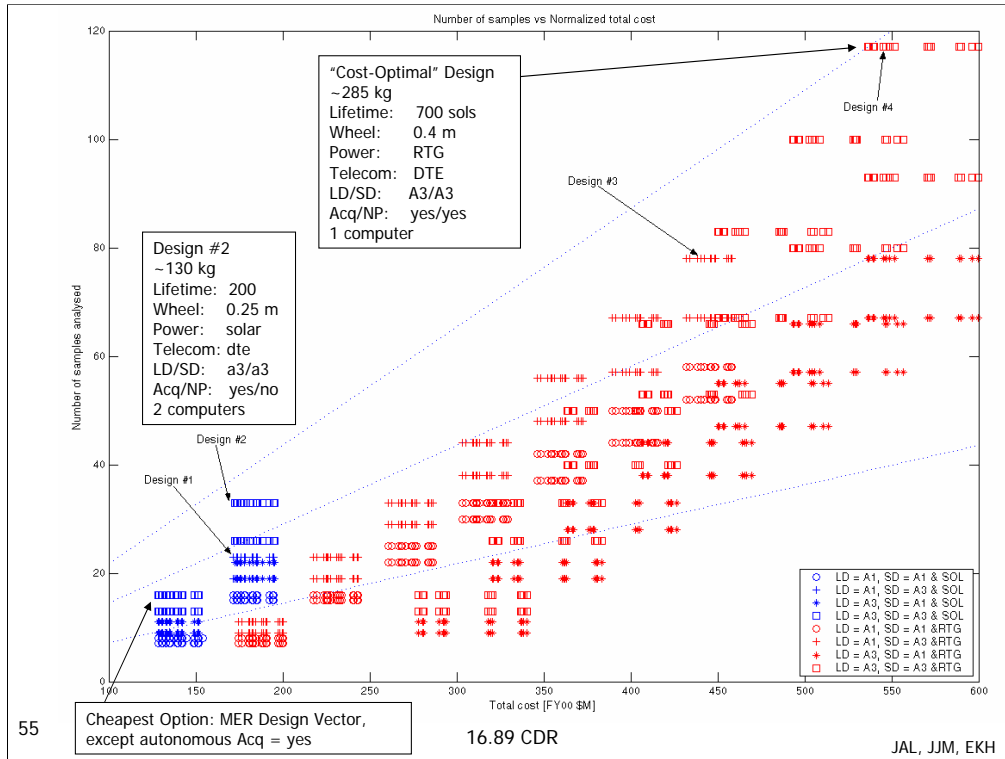
Lifetime 200; 0.25 m wheel diameter; solar; dte telecom; LD a3; SD a3; Acq yes; Night process no; 2 computers

78 samples, ~150.5 kg; # 1804

Lifetime 700; 0.25 m wheel diameter; rtg; dte telecom; LD a1; SD a3; Acq yes; Night process yes; 1 computer

117 samples, ~171.5 kg; # 1821

Lifetime 700; 0.25 m wheel diameter; rtg; dte telecom; LD a3; SD a3; Acq yes; Night process yes; 2 computers

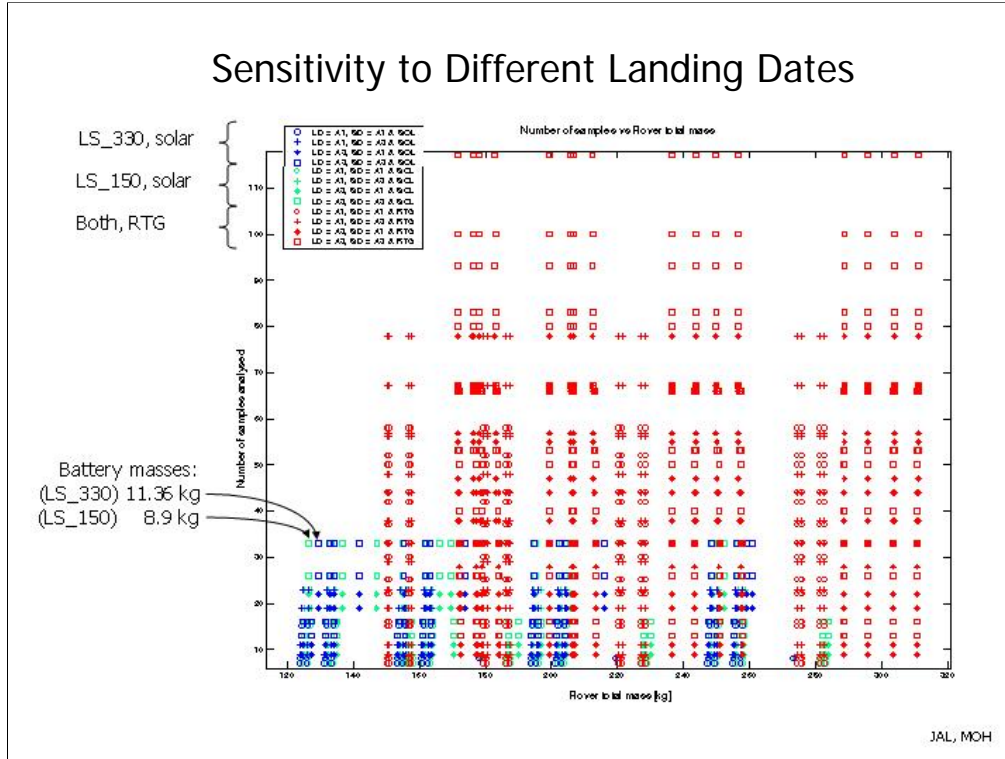


The Isometric lines shown in the cost modeling plot are ratios of 40, 80, and 120 Samples to \$550M. Note how design 2 & 4 are almost on the isometric line 120:550.

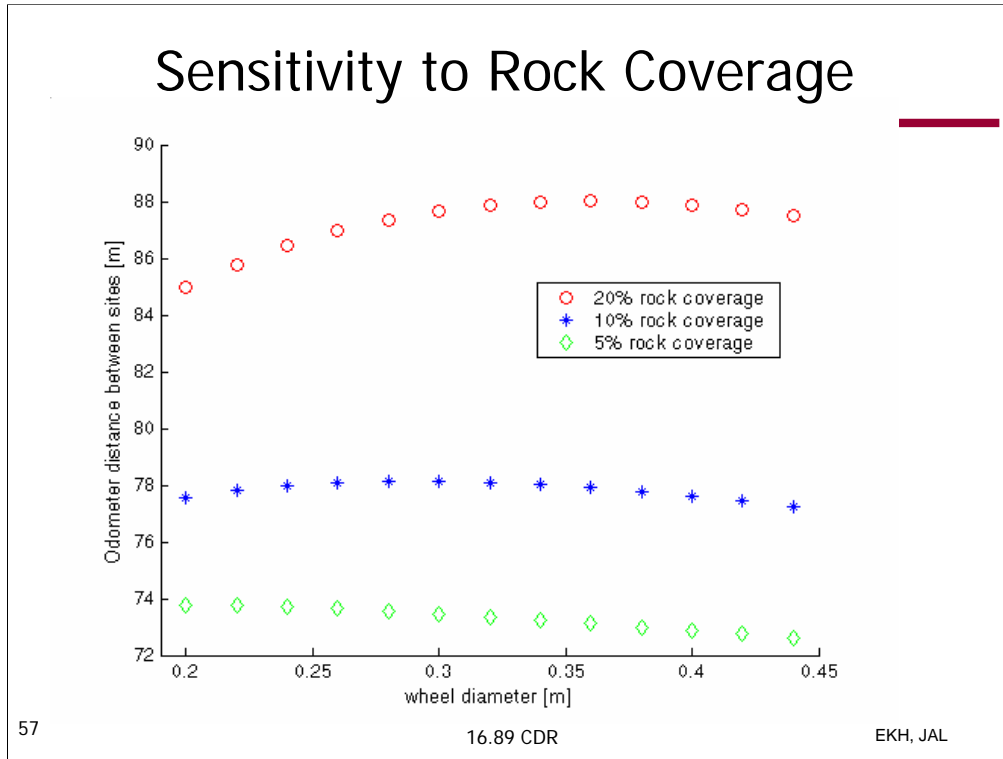
The optimal Design (2012) is shown for comparison purposes. Designs #1 – 4 from the Samples vs. Mass plot are highlighted for comparison.

Note that the total costs are low – MER estimates found on the web had cost values for 2 rovers at \$800M (including launch).

Note the solar power option cost boundary.



This plot demonstrates the effects of moving the landing date from LS_150 (beginning of summer) to LS_330 (beginning of winter). Designs with RTG power sources are not affected by changing the landing date, but designs with solar arrays show increased mass for a given number of samples returned. There are more hours of sunlight each day during the summer than during the winter, so for a given daily energy requirement, larger solar arrays are required during the winter than during the summer. Winter landings also require larger batteries, since colder temperatures lead to requirements for more heater energy, especially during the night hours when the rover is reliant on battery power.



This graph shows how the odometer distance traveled between sites increases or decreases as the wheel diameter increases. Three different terrains are shown based on percentage rock coverage (5%, 10%, and 20%). Each rock coverage required creating a different trade space in which all other values of the science vector were held constant. The design vector was the same for each trade space as well, limited to iterations over wheel diameter and power options only. It is obvious that the less rock coverage corresponds with shorter distances traveled to get from one site to another. More interesting, there seems to be an optimal wheel diameter for each rock coverage that is different than the others. For example, for 5% rock coverage, the optimum wheel diameter is .2 m and for 10% rock coverage, the optimum is .28 m.

Because of the way the mean_free_path is calculated by the ROVERS module, there is some trade off between having a larger rover that can drive over more rocks versus having to drive further around big rocks because of its larger size.

Unfortunately, the change in odometer distance is captured in a 2 meter difference for the 5% and 10% rock coverage which doesn't necessarily justify the increase in mass and cost to obtain a shorter distance traveled. (An increase in productivity was actually driven by the autonomy levels.) For 20% rock coverage, which is uncommon according to current data, there is a little more payoff in increasing from a .2 wheel diameter to an optimum of .34 but the average increase in mass is 80 kg.

Qualitatively, a trend is easily seen. Quantitatively, however, the values shown are not large enough to cause major shifts in determination of optimal architectures.

The design vector for this run was:

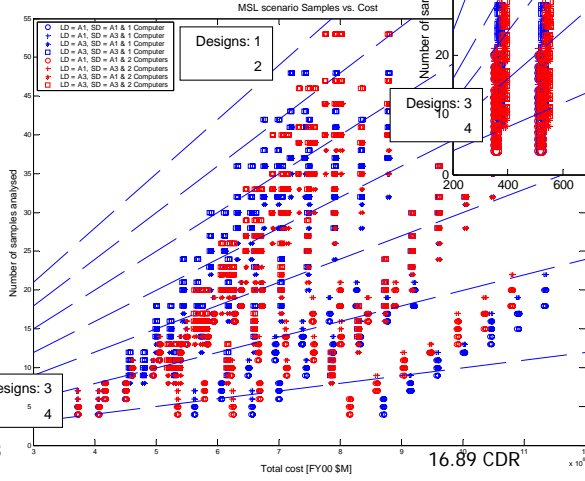
```

100 sol
2 computers
solar, rtg
dte comm
a1, a3 autonomy
y - auto acq
n - night nav
y - night processing

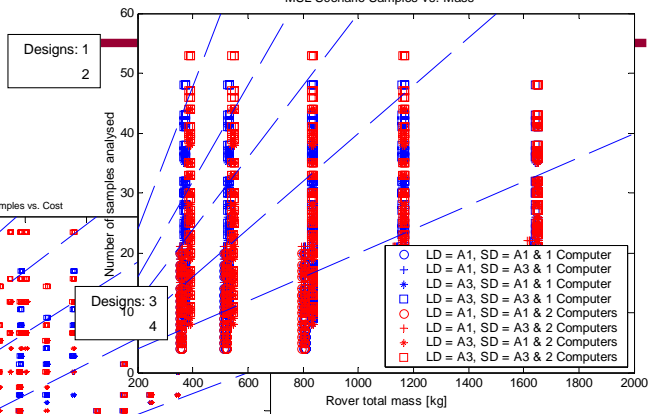
```

MSL Trade Space

Total cost vs. Number of samples



MSL Scenario Samples vs. Mass



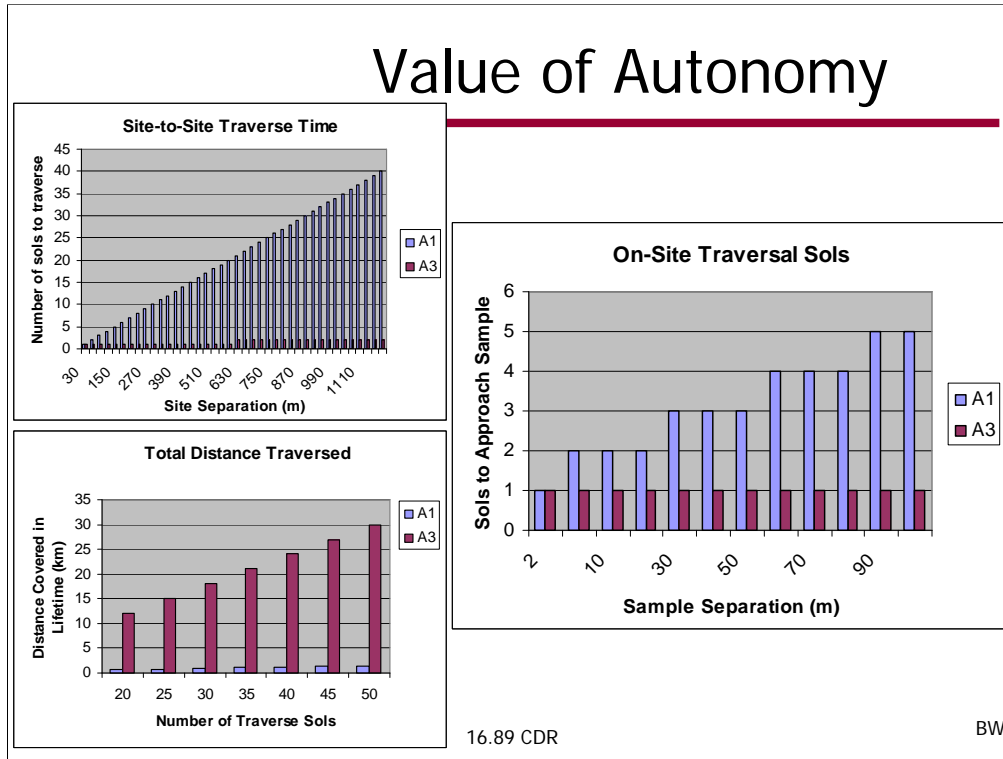
Total mass vs. Number of samples

58

16.89 CDR

JAL, EKH

Value of Autonomy



16.89 CDR

BW

These three graphs demonstrate the value of navigation autonomy in terms of performance. To recap, A1 Autonomy is based on MER capabilities, and is thus limited to the navcam range (30 meters) in a traverse sol. A3 level autonomy, which need not stop and communicate every navcam range traversed, can traverse up to 600 meters in a sol depending on how much power is available. All of these graphs are based on inputting MER specifications into the program and allowing only the level of autonomy to change. In all graphs, A1 level autonomy is blue and A3 is red.

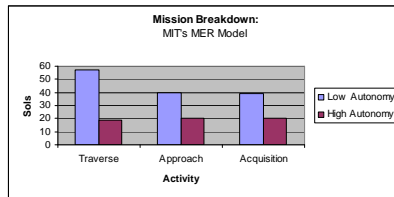
The two graphs on the left depict the value of site-to-site autonomy levels. The top graph shows the time it takes in martian sols to traverse from one site to the next, based upon the distance between sites. Because the distance between sites for MER is less than 100 meters, there is not substantial difference between the performance of the two. However, it is clear from the graph that as site separation increases, the value of A3 autonomy does as well. For instance, if the sites were 1 km apart, a rover with A3 level autonomy would save 32 sols for every site visited. Thus, if one rover is to be able to explore different regions of the surface of Mars, you will either need A3 or a lot of patience!

The graph on the bottom left depicts how far a rover can travel during its entire lifetime based upon the level of autonomy in long distance traversal. One MER rover is supposed to travel about 600 meters during its lifetime. Again, this point is on the left of the graph shown, and can hardly be seen because it is dwarfed by the distance achievable by A3 autonomy. The two columns on the far left of this graph are the distance that could be covered with MER using A1 and A3 autonomy. As can be seen, if MER had A3 autonomy, it would be able to travel more than 10 km during its 90 sol lifetime as opposed to 600 meters.

The graph on the right demonstrates the value of on-site, sample-to-sample autonomy levels. This type of autonomy is based on whether the rover can guide itself to within "grabbing" range if its target rather than require guidance from the ground. Since MER only collects one sample per site, adding extra on-site "sample-to-sample" autonomy would not significantly affect science return. However, from this graph we can see that unless the samples at a site are less than two meters apart, A1 and A3 take a different number of sols for sample approach. Take, for example, a scenario that the samples at a site are approximately 30 meters apart. A3 autonomy would save 2 sols for every sample approached. If several samples were to be collected at each site, this has potential to add up very quickly.

These graphs strictly show the added performance value of different levels of autonomy in short and long term traverse. Because it is extremely difficult to estimate the cost of developing, testing, and implementing A3 autonomy on a Mars rover, it will be up to a future mission designer using our program to determine whether or not the added performance we calculate is worth the price tag that NASA can best estimate.

Value of Autonomy

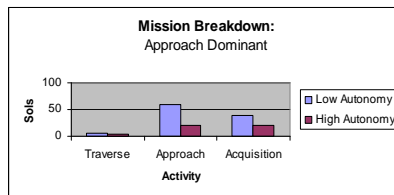
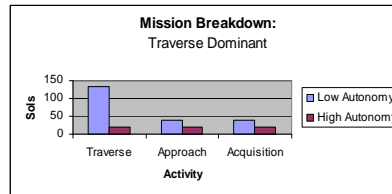


Mission Design:
(MIT's MER Model)

- Site separation: 70.7 m
- Approach distance: 4.3 m
- # Samples/site: 1

Mission Design*:
(Traverse Dominant)

- Site separation: 200 m
- Approach distance: 4.3 m
- # Samples/site: 1



Mission Design*:
(Approach Dominant)

- Site separation: 50 m
- Approach distance: 35.7 m
- # Samples/site: 5

60 *All other design properties follow the MIT MER Model 16.89 CDR

EF

The benefits to be derived from the combinations of different autonomy settings depend on the nature of the mission.

In the first graph, the blue bars presents the breakdown for the total number of sols spent on long distance traverse, sample approach, and acquisition. MER uses the lowest level of autonomy for all three activities. The red bars next to them represents the the number of days that would have been spent performing the same activity. For this scenario, the mission would benefit the most by investing in a high level of autonomy for long distance traverse.

The second graph emphasizes a long-distance traverse dominated mission by dramatically increasing the distance between the site separation. This scenario models the amount of time it would take to obtain 20 samples. As can be seen (similar to the previous scenario), a higher level of autonomy for this activity can dramatically cut down the amount of time spent on this mission – which could lead to a shorter mission duration or the opportunity to collect more samples.

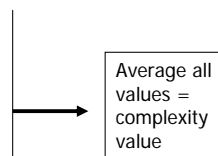
The third graph represents a scenario of obtaining 20 samples where the time is dominated by approaching the sample. Notice that the distance between sites is fairly close to the site separation amount. Such a scenario might be highly unlikely but was modeled to demonstrate that the the desired level of autonomy is dependent on the mission design and that the most beneficial combination of autonomous capabilities also varies accordingly.

Again, the cost to develop and test these higher level of autonomy capabilities would determine if such an investment would be worth it.

Complexity

- The complexity value allows relative comparison of how much technological development is required to complete a set of designs
- Each design element (e.g. power system) is ranked with a development level for planetary landers and/or rovers:
 - Level One: Flight proven on a lander/rover, or will be flown this year
 - Level Two: Validated on a lander/rover in relevant environment
 - Level Three: Analytically demonstrated or lab tested on a lander/rover
 - Level Four: Technology concept formulated
- After ranking each element, the total complexity is found by averaging all elements
 - An average of 1.0 would be as complex as MER
 - An average of 4.0 would be a design that is very technologically immature
- Room for growth and/or intentionally biasing the complexity of certain options

Design Element	Option	Level	Option	Level
Power	Solar	1	RTG	3
Telecom	DTE	1	Other	2
Autonomous Long Distance Nav.	a1	1	a3	3
Autonomous Short Distance Nav.	a1	1	a3	3
Night Navigation (currently not modeled)	No	1	Yes	4
Autonomous Sample Collection	a1	1	a3	4
Night Instrument Processing	No	1	Yes	2
Lifetime	< 90 sols	1	> 90 sols	2



61

16.89 CDR

IGB

The table above shows how each element of the design vector is assigned a development level between 1 and 4. The justifications for the assigning a certain development level to a design element are sometimes subjective, as described below. Some consultations were made with the Autonomy module team.

Power: Solar is well proven, and is thus level one. RTG's have flown on spacecraft, but not on rovers, and are therefore not level two. RTG's would not be level four, since a proven RTG design exists. Thus, they fall closer to level three.

Telecom: Direct to earth as a primary communication system is flying on MER, and is level one. Other methods of communication, such as using orbiting satellites, have been achieved on rovers, although not as primary communication. Thus, anything other than DTE is ranked level two.

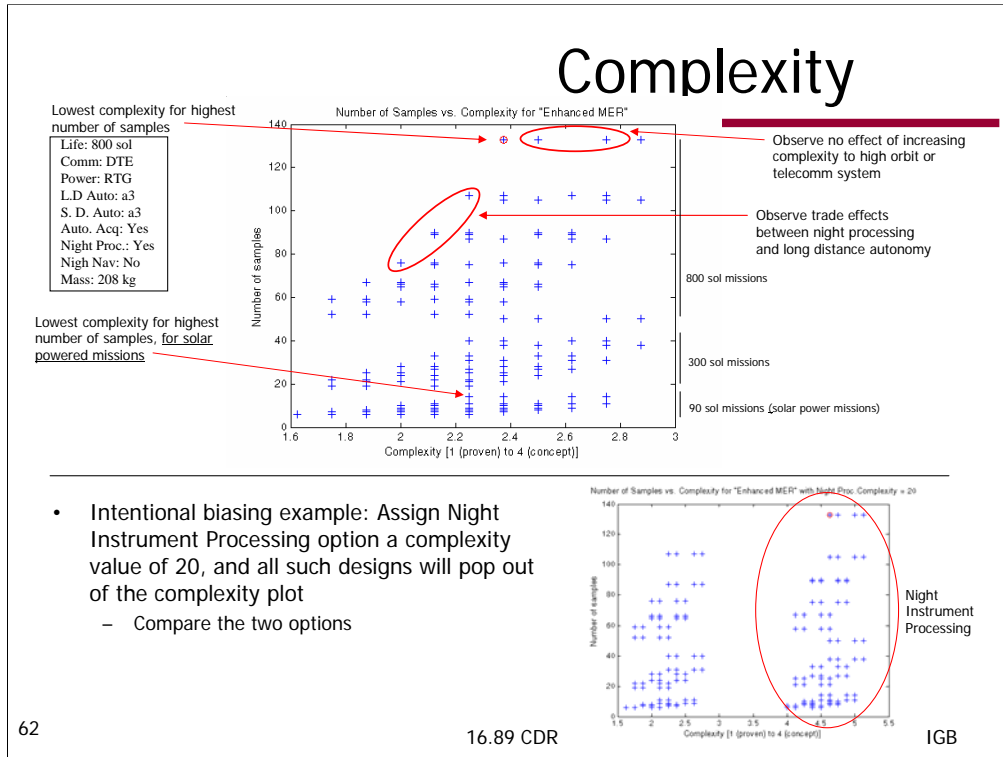
Short and Long Distance Navigation Autonomy: a1 long and short distance navigation is flying on MER, and is thus level one. a3 is an advanced autonomy state that has been partially tested, but not completely validated, and is thus level three.

Night Navigation: technology has not matured beyond level four.

Autonomous Sample Acquisition: problems with rover vision sensors leave autonomous sample acquisition at level four.

Night Instrument Processing: MER processes data for ½ hour at night, but this is not the larger scale nighttime processing that is captured by the code. Thus, this option is closer to level 2.

Lifetime: MER is designed for 90 sols, and thus lifetimes shorter than 90 sols are level one. Most parts on landers/rovers are capable of longer lifetimes though, and thus anything greater than 90 is level two.



Plot of complexity vs. number of samples shows a concave-up Pareto front. Points along the front provide lowest complexity for a given number of samples. By moving up and down the front, the user can see the effects of changing levels of autonomy, and other design elements. In this case, the front is all RTG's, with 800 sol mission lifetimes.

A fractal effect is observed, where the same shaped front appears for lower lifetime missions. The solar powered mission is visible as the lowest front, and the optimum design is the upper corner.

Note that there is a multiplicity of designs for most points on the Pareto front. For example, the wheel diameter might be different for two points.

If the user would like to see the difference between a mission with and without a certain design option, they can intentionally increase the complexity rating for the design, and it will shift right in the plot.

Notes on the science and design vectors chosen:

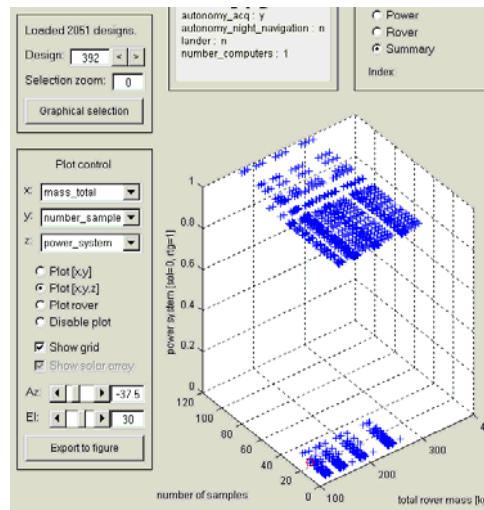
-Enhanced MER is the MER validation mission used elsewhere in this presentation, plus the "MUM" mole and a mass spectrometer.

-Design vector includes all options, but a reduced set of lifetimes: [90, 300, 800] sols.

Usability

Plot types

- Three different plot types are available:
 - 2D (x, y)
 - 3D (x, y, z)
 - Rover
- 3D plots
 - Useful for visualizing the effects of changes in the design vector.
 - For example, the plot at right shows the relationship between rover mass and number of samples, separated by power system type.
- Any on-GUI plot can be easily exported to a MATLAB figure.



65

16.89 CDR

MOH

Three types of plots can be displayed on the GUI, and exported to separate figures.

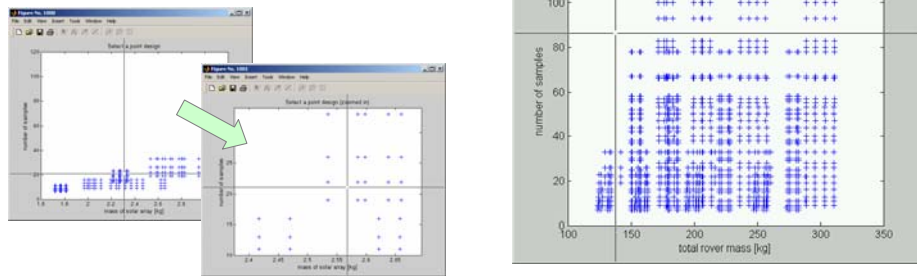
1. 2-D (x,y). Plots the parameters chosen from the x and y popup menus.
2. 3-D (x,y,z). Plots the parameters chosen from the x, y, and z popup menus.
3. Rover. Draws a picture of the rover, showing the chassis, wheels, solar array, mast, and arm. Additional details, such as the rocker/bogie suspension, RTGs, etc., could easily be added to the drawing routine later, if desired. Display of the solar array can be toggled using the [Show solar array] checkbox. When a drawing of a rover with a solar array is exported to a figure, the solar array is made translucent to show underlying detail; however, for some reason MATLAB does not support transparency on axes embedded in GUI windows.
4. Disable. It is possible to disable plotting, in order to reduce display time when working with extremely large data sets.

The Az (azimuth) and El (elevation) sliders and edit boxes can be used to rotate the plot. Clicking on a plot radiobutton resets the view perspective to the default perspective for that view.

The [Graphical selection] button launches a window in which the user can click to choose a particular point design. This process is detailed on the next slide.

Graphical Design Selection

- [Graphical selection] button.
 - Allows user to choose a point design from a plot of any two output or input parameters.
- User-selectable zoom level
 - Enables selection of a particular point in a densely packed group
 - Example: zoom factor of 5:



66

16.89 CDR

MOH

The graphical selection tool allows the user to choose a particular point design from a 2D trade space plot. The user chooses the x and y axes data from the plot control section of the GUI, and then presses the [Graphical selection] button. A figure with the x and y data appears, with a set of crosshairs over the plot. The user directs the crosshairs to an interesting point, and a left-click causes a red circle to appear around the selected point, and the GUI to update with the design data for the selected point. If the number in the selection zoom box is greater than zero, the first click will cause the plot to zoom in by the specified factor, centered about the point design closest to the click point. A second mouse click then selects the desired point from the zoomed-in view.

Feedback From User Testing

- Performed usability tests with Joe Parrish (Payload Systems, Inc.)
- Implemented several changes based on his suggestions
 - Added real-time feedback of progress during design computation.
 - Added 2D, 3D, and disable options to the on-GUI plot (rover model was already there).
 - The 3D plot capability was added to enable simultaneous comparison across multiple variables.
 - Added integrated (automatic) help text at each step of the trade space creation process.
- Identified improvements to be made in the future
 - Additional methods for simultaneously comparing multiple parameters (color, shapes, etc).
 - Improve documentation in design vector creation process.
 - Retain science vector values between presses of the [Science vector] button.

67

16.89 CDR

MOH

Summary of usability test:

Joe Parrish from Payload Systems, Inc. volunteered to test the user interface. The scenario he had in mind was a mass-limited mission (185 kg) suitable for launch on a Delta II. He was interested in seeing what set of science instruments would result in the highest return mission with this constraint; however, this tool is designed to iterate over multiple rover architectures for a given payload. Due to the extremely large number of instrument suites that could be considered by iterating over all combinations of the science payload, the tool was instead designed for analyzing a range of rover designs built around a pre-determined complement of instruments. With this in mind, Joe selected a large collection of science instruments, including a 1-meter drill, with the intention of seeing if any of the designs would fall under the 185 kg mass limit. He then specified the allowable parameters for the design vector, with some suggestions and help from the class. This step appeared to be the most non-intuitive stage of the process. After creating the trade space, he used the 2-D plotting capabilities to compare various designs.

Comments and suggestions:

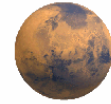
- Instructions display at startup is great.
- Science vector selection is intuitive.
- There should be a check to make sure that instruments are compatible, and that when one instrument requires another to function, that both are selected.
- The values of the landing site characteristics should be boundary checked, and corrected if out of allowable ranges.
- Design vector selection is confusing, but one or two lines of comments in the code would probably make a big difference. Need detailed instructions available too, though not necessarily in the code.
- Need real-time feedback of trade space calculation progress, including number of valid and invalid designs.
 - This has been addressed by adding a real-time status indicator on the GUI.
- Solar panels should not have dust wipers. Having wipers obscures the relative costs and benefits of solar vs RTG.
 - This has been addressed. The power team deleted the dust wipers from the solar designs.
- Want to be able to differentiate between, say, solar and RTG designs in a given plot.
 - This has been partially addressed by adding a third dimension to the plot capabilities.
- Subsystem property window should show units.
- Want to be able to see, for example, how productivity maxes out for a1 autonomy designs, within a larger trade space.
 - This has been partially addressed by adding a third dimension to the plot capabilities.
- Confusion between 'plot' and 'select' buttons regarding use of the trade space plots.
 - This has been addressed by integrating plots into the GUI, and replacing the plot button with an [Export to figure] button.
- Should be easier to browse designs.
 - This has been addressed by integrating plots into the GUI, and linking them to the browsing buttons.

Thank you to Joe Parrish for his time and constructive feedback!



Conclusions

Limitations



- Modeling constraints
 - Current technologies only coded
 - Limited environment and rover design modeling
- Different fidelity across subsystems
- Limitation on configuration of the rover
 - Ex: Rocker-bogie vs. four-wheels
- Polar landing sites not considered

69

16.89 CDR

BC & RN

Single rover design – initially it was the aspiration of the class to begin with a single rover design and expand that to multiple rovers. A lander sizing was also desired, but within the limited time that the class possessed, a single rover design proved to be hard enough to do

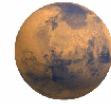
Technology – since it is difficult to know the size, performance, cost, etc... of new technologies, current technologies are used. As new technologies advance, they can be included into the code

Fidelity – there is limitations on fidelity levels between different subsystems, as well as fidelity on a whole. The more fidelity, the more complex the models, and the more computationally expensive the simulations. A certain level of fidelity was achieved so as to display trends between interesting trades.

Topology – rover topologies have been given to us by the way we size our vehicle. New topologies can be introduced with the advent of new code, but the code itself does not create new topologies (e.g. 4 wheels instead of 6)

Polar – a different set of rules apply to polar rover design which we opted to leave out so as to simplify our simulations

Capabilities



- Single rover design with architectures:
 - Solar and RTG power system designs
 - Hybrid communication systems
 - Different levels of autonomy
 - Different instrument suites
 - Different environments and landing sites
- Upgradeable
 - Modular
- User interface for trade space analysis

70

16.89 CDR

BC & RN

Power – trades between solar and radio-isotope power. Interesting trade made (re) newly available

Comm – hybrid communication systems consisting of combinations between DTE, Low Orbiter Relay, and High Orbiter Relay

Autonomy – ‘a1’ (MER) vs ‘a3’ (Higher level) autonomy to show how much more autonomy could give you. Also included in this suite is long distance traversal, short distance traversal, night processing, night navigation, and autonomous acquisition.

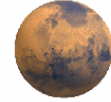
Instruments – science GUI for instrument suite. Available instruments as of current and nearly available technologies

Environment – modeled different latitudes, terrains, and times of Martian year

Upgradeable – highly modular, allowing for updates of the code as new technologies and strategies are developed

GUI – user interface for easier use

Improvements



- Simulation performance
 - Memory usage
 - Speed
- New technologies
- New physical rover configurations and architectures
- Lander
- Multiple rovers
- Costing models
- Utility and complexity models
- Polar landing site option
- Launch/landing models

71

16.89 CDR

BC & RN

Configurations – allowing for new configurations (e.g. 4 wheels instead of 6)

Polar – models for polar missions

Technology – as the world develops new technologies, the code can also take these in and adapt

Lander – models for a lander system

Multiple rovers – higher level topology, allowing for teams of rovers and/or landers

Costing – always a difficult thing to do. As cost models mature, so can the capability of the code to accurately to this trade

Utility -- Function of specific mission science goals (ie. The payload and the science vector).

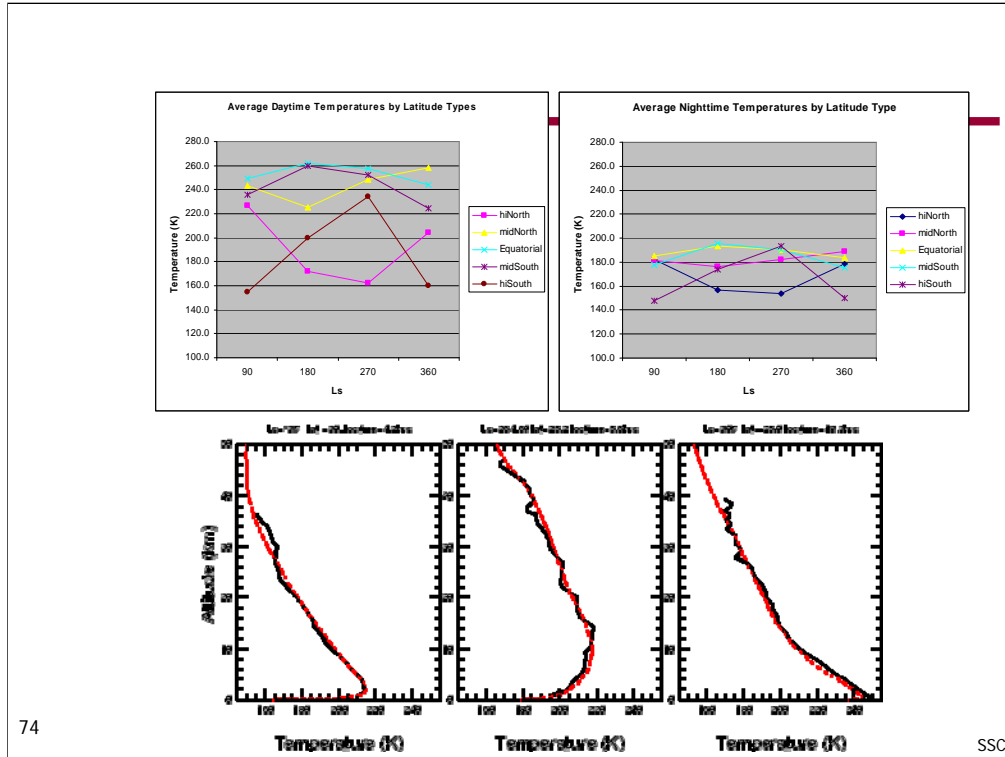
Simulation performance – the code is very complex, and if the class had more time, the code could have been streamlined much better. For large design vectors, the amount of information stored is very high. Eliminating everything but the most crucial information would be desired, but we don't always know what the most crucial information is.



Back-up Slides



Environment



74

SSC

These are temperature data being used by the environment module. You can see the effects of season on the temperatures, with the most marked effect on hiNorth and hiSouth latitude ranges while equatorial temperatures vary very little and mid latitude ranges vary slightly more than equatorial temperatures.

These data were taken from a Martian general circulation model. These models have been tuned to match existing data from observatory missions and has been validated against those available observations. This agreement gives us a confidence in the model's ability to predict the Martian climate in areas where sufficient observational data do not exist. While there are some discrepancies in some parts of the overall climate model, these are not in areas that should affect our data needs.

Example of very good fits to the observations that can be obtained with the database MGS scenario at various seasons. The black solid lines show temperature profiles measured by radio-occultation with Mars Global Surveyor. The red dashed lines are the MCD predictions at the same locations and times. The model is usually able to simulate accurately the variations of the temperature profiles due to change in dust loading and insolation.

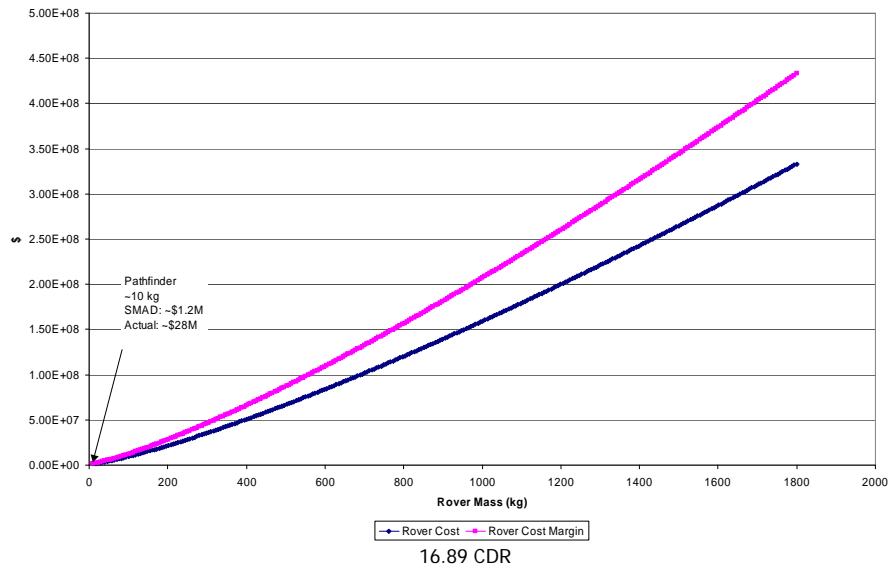
-<http://www-mars.lmd.jussieu.fr/mars/node4.html>



Cost

Rover Cost Modeling

Rover Cost Modeling

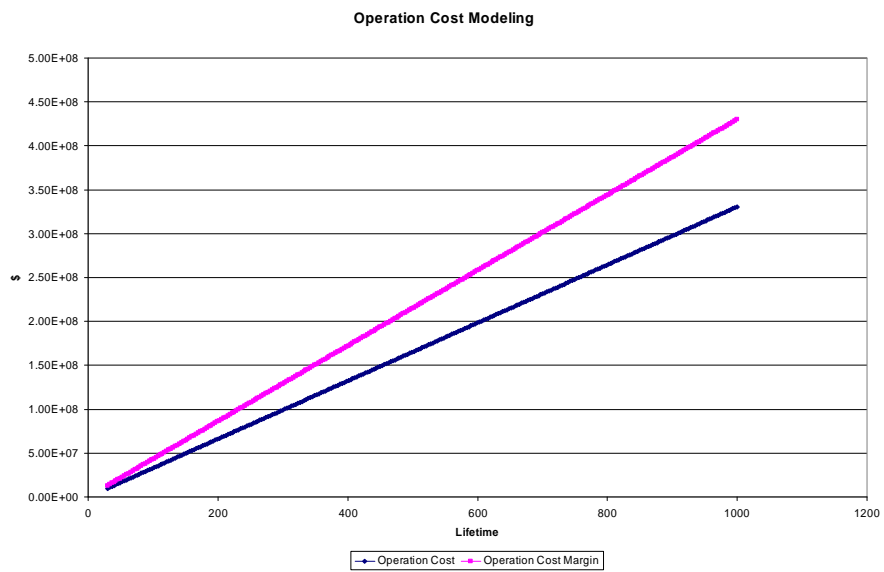


76

JJM

Using SMAD relationship for cost of a satellite – this is the plot of Rover cost modeling. Margin is 30%.

Operation Cost Modeling



77

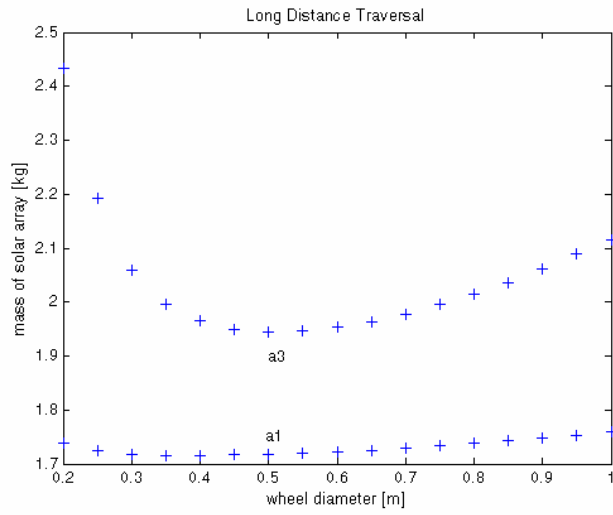
16.89 CDR

JJM

This is the relationship between operation cost, which is linearly proportional to operation costs of Pathfinder. Margin is 30%

Validation

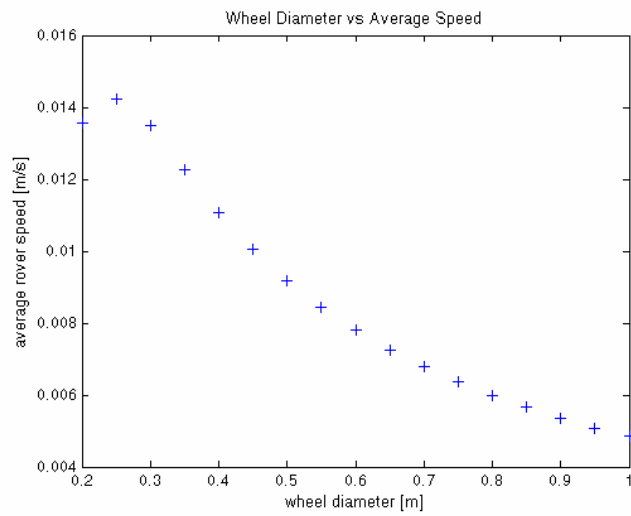
Long Distance Traversal



79

16.89 CDR

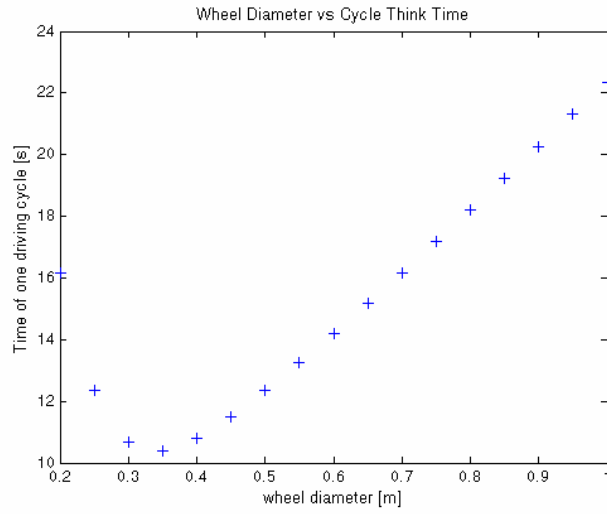
Average Speed



80

16.89 CDR

Think Time



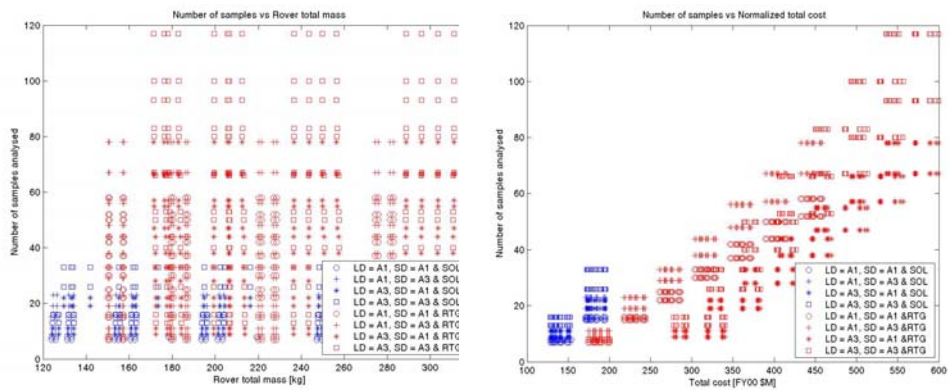
81

16.89 CDR



Tradespace

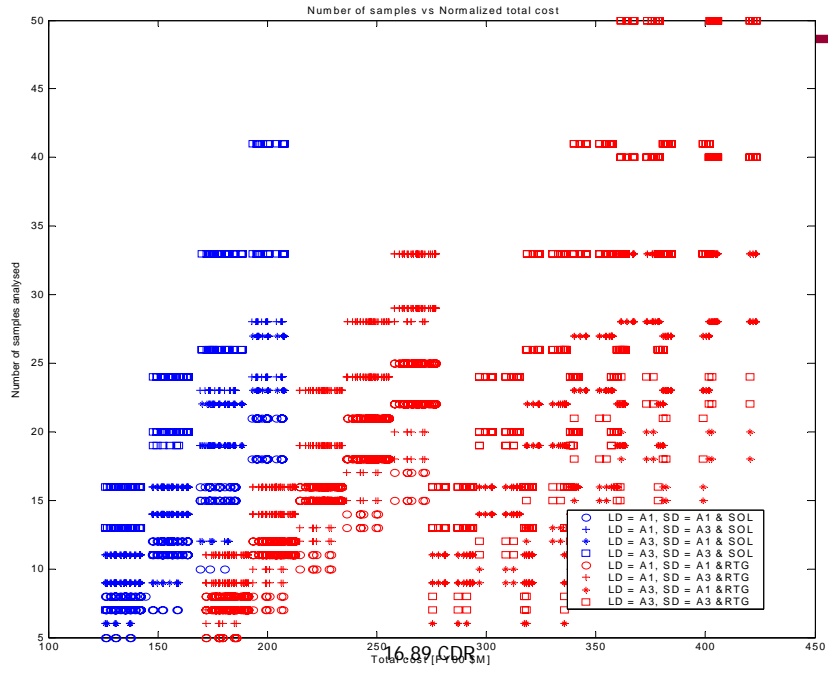
MER-like Scenarios



83

16.89 CDR

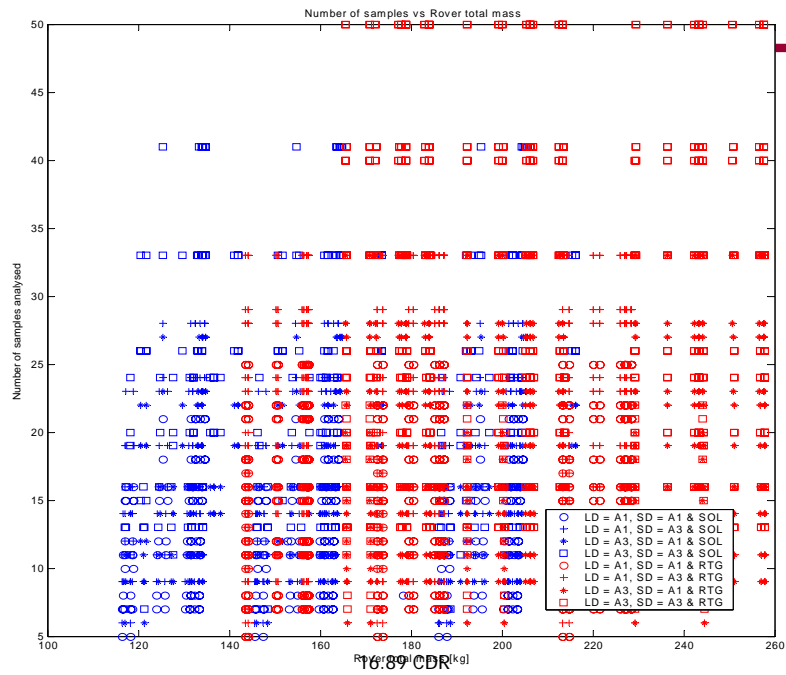
MER trade space for Ls 330 degrees: Total cost vs. Number of samples

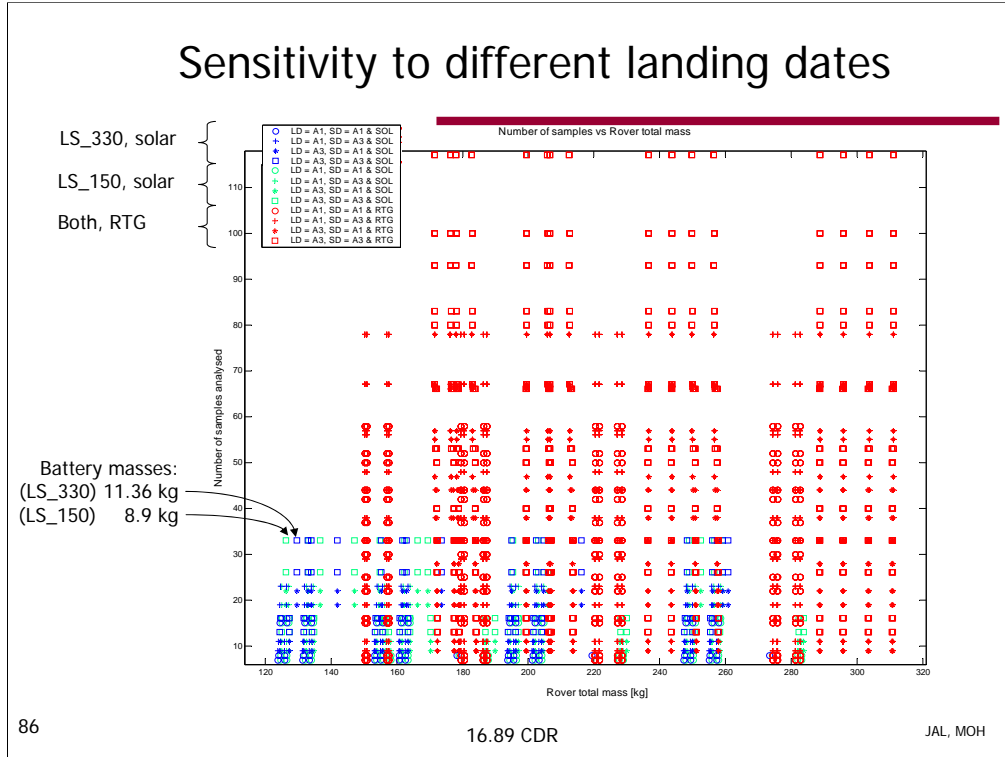


84

16.89 CDR

MER trade space for Ls 330 degrees: Total mass vs. Number of samples





This plot demonstrates the effects of moving the landing date from LS_150 (beginning of summer) to LS_330 (beginning of winter). Designs with RTG power sources are not affected by changing the landing date, but designs with solar arrays show increased mass for a given number of samples returned. There are more hours of sunlight each day during the summer than during the winter, so for a given daily energy requirement, larger solar arrays are required during the winter than during the summer. Winter landings also require larger batteries, since colder temperatures lead to requirements for more heater energy, especially during the night hours when the rover is reliant on battery power.