MSL Landing Site Selection:
Status of Engineering Capabilities and Constraints and Plan for Site Selection

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with thanks to and contributions from Chris Salvo, Ashwin Vasavada, Adam Steltzner, Miguel San Martin, Leila Lorenzoni, Louis D'Amario, Angela Bowes, Dan Burkhart, Allen Chen, John Gilbert, Beth Dewell, Jaime Waydo, and many others…

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Agenda

- **General Discussion**
- Mission Design/Navigation/EDL Comm
- EDL (Steltzner)
- Surface Mobility
- Mission Performance as function of latitude

MSL Engineering Status for LSW#2

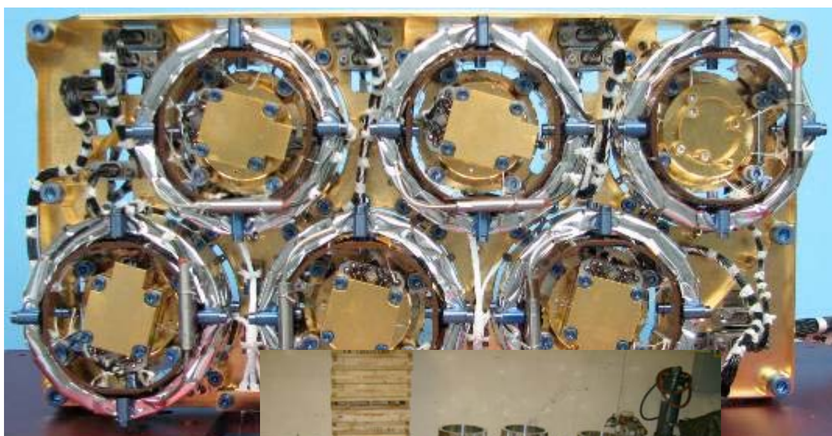
- **MSL Landing site selection is a balance of science value and risk**
  - Primary goal of *this* workshop is evaluation of the science potential of candidate landing sites
  - But we cannot fully decouple the science and engineering trade (yet)
    - Constraints are not "hard" in all directions and dimensions
      - There is some trade between constraints - detailed analysis needed for final risk
      - Risk trade requires understanding and modelling of system performance as function of constraint variables
    - More margin (against any constraint) will always be a good thing
    - Several constraints (altitude, terrain relief, latitude) have very high impact
    - Understanding of some of the constraints is still evolving
  - We have utilized our performance analysis of the MSL system to provide a first order assessment of the engineering safety of the sites for consideration in the science ranking
    - We are willing to retain high science value sites which have yellow* safety evaluations in some engineering categories as of now (Oct 2007) in order to allow this trade to play out to the benefit of science

    ******Yellow due to uncertainty about final MSL engineering capability*
  - We will briefly walk through the current status and rationale for the engineering constraints and talk about the trade space

MSL Status - Where are we?

Mars Science Laboratory

- The Good
  - MSL conducted and passed CDR
    - Project, Flight System, Mission System
  - Cruise stage, descent stage, rover, and payload being manufactured and delivery starting
  - Integration and test starting early in 2008



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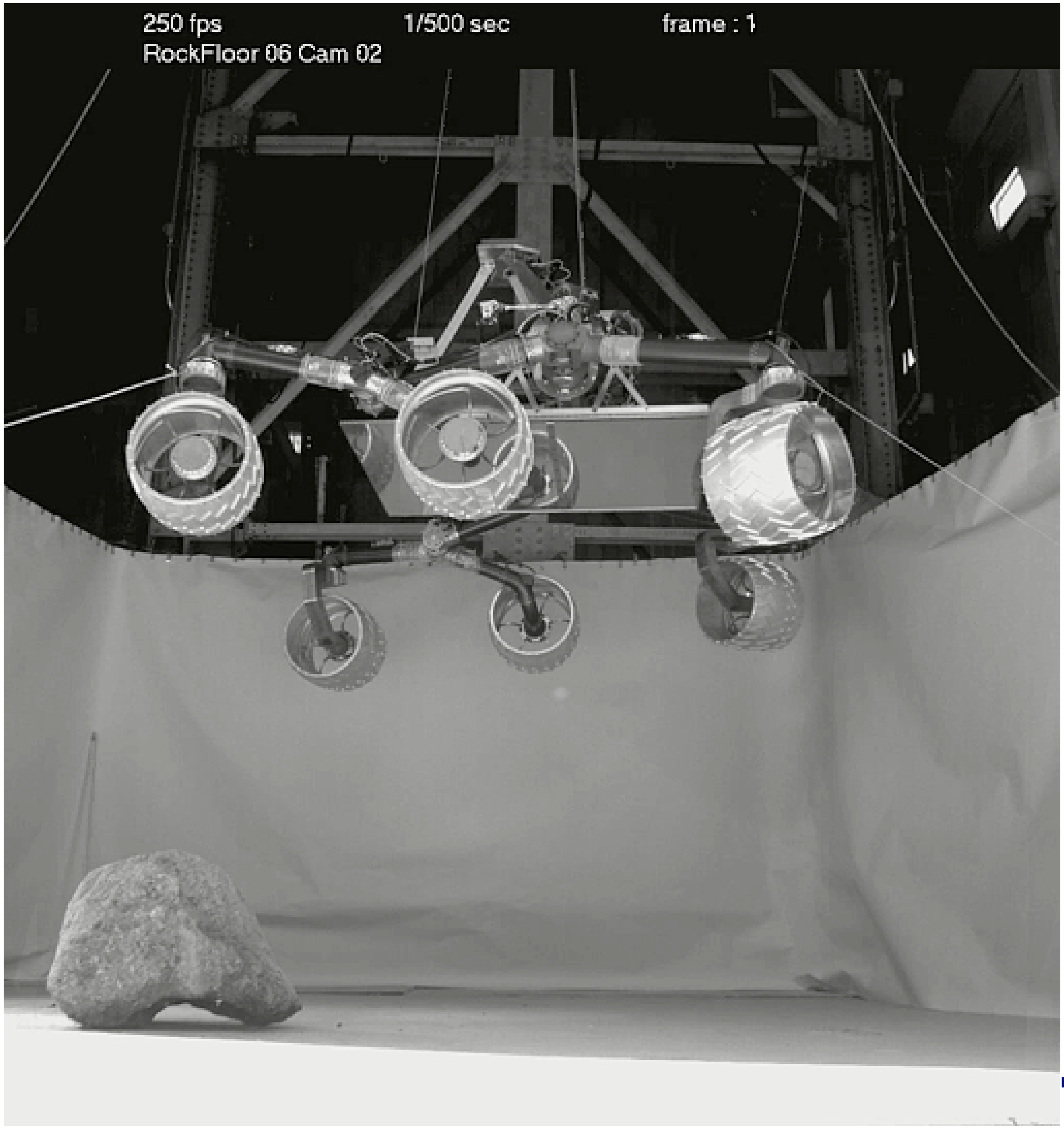
Rover Drop test video



MSL Status

- The Bad
  - Cost constraints are real and significant
  - Motor actuator lubrication failure
    - Requires higher operating temps - more detail later
  - Thermal protection system (heatshield) material failure/change from SLA-561V to PICA
    - Actually working out to benefit of landing site accessibility

Focused Site Selection

- Increased recognition of complexity of landing site evaluation from both science and engineering perspectives
  - MRO coverage required
  - Highly detailed engineering performance simulations
    - Personnel (and cost) impacts of assessing large number of sites

$\Rightarrow$ focused set of 5 landing site candidates (including backups) selected in very near future for final evaluation is a necessity

Agenda

- General Discussion
- **Mission Design/Navigation/EDL Comm**
- EDL
- Mobility/Go-To
- Mission Performance as function of latitude

Launch/Arrival Strategy Considerations

- Launch/arrival strategy requires complex launch/arrival space to cover full latitude range with MRO in view during EDL
  - Generally cannot get simultaneous MRO and Direct-to-Earth during EDL
  - Requires multiple launch vehicle target sets (i.e., multiple launch periods) for Launch Vehicle Target Specification
    - Each target set covers latitude range (longitude range is a function of available propellant, but generally ±100-180 degrees)
  - Final selection of Target Specification required by launch vehicle 1 year before launch
    - Launch is ~Sept 15, 2009

Launch/Arrival Latitude Ranges

	September 2009																								October 2009																					
	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
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TS4	16-Jul-2010 Arrival
TS5	12-Jul-2010 Arrival
TS6	10-Jul-2010 / 16-Jul-2010 Arrival
TS3	22-Jul-2010 Arrival
TS2	5-Aug-2010 Arrival
> 6	Exceeds Atmosphere-Relative Entry Speed Constraint
	Current MSL 24-day Launch Period

= MRO antenna angle at entry = 109 deg; DTE coverage from entry to landing minus 30-60 seconds

= MRO antenna angle at entry = 108-110 deg; DTE coverage from entry to landing plus 1 minute

= MRO antenna angle at entry = 106-108 deg; DTE coverage from entry to landing plus 1 minute

= MRO elevation angle at landing plus 1 minute = 7-9 deg

= C_3 exceeds launch vehicle capability

"Safe Haven Sites"

- **For a variety of reasons (changes in understanding of EDL system performance, late breaking landing hazard analysis, etc), we may need to retarget after L-1yr (up through early cruise) to a safer site**
  - These "safe haven" sites must meet a higher bar for safety (mainly altitude of -1 km or even lower) ***and*** be in the same latitude band as the primary site to allow MRO coverage
  - It is possible that a primary science site can also be a safe haven, in which case our life is easy
  - Final target spec will be for the [prime + backup + "safe haven"] set (defined by a single latitude band)

Agenda

- General Discussion
- **Mission Design/Navigation/EDL Comm**
- EDL
- Surface Mobility
- Mission Performance as function of latitude

EDL Engineering Constraints

Adam Steltzner
Mike Watkins

Overview

- Landing site safety assessment involves evaluation of broad spectrum of risks
  - Uncertainty exists in data set used to evaluate
  - Mars is frequently unkind
  - Risk evaluation involves judgment
  - “Less” risk is always better than “more”
- EDL engineering safety constraints is a discretized set of thresholds
  - Environmental parameters above (beyond?) which additional risk/work exists
  - Discretization process injects error
    - Discretizing a continuum of environmental characteristic into a finite set
    - We only know to be afraid of that which we can conceive of
  - The engineering safety constraints are complex
    - Some of the constraints are very firm and more brittle than others when exceeded
    - Some of the constraints are not as firm
    - Constraints are interconnected
- We offer a brief primer on a subset of the constraints
  - Supports the search for other things to be afraid of
  - Informs science community of environmental characteristic to be considered in the site evaulation
  - General understanding
  - Time constrains discussion

Landing Site Elevation

Constraint

- Requirement: ≤ +1 km MOLA
- Safe haven:
  - ≤ -1 km MOLA
  - ≤ -2 km MOLA most desirable

Possible Trades

- Terrain tolerance
  - Lower elevation sites yield timeline and propellant margin that can be spent on terrain relief tolerance
- Precision
  - Lower elevation sites can sometimes be used to increase precision performance
- Robustness
  - Lower elevation sites yield timeline and propellant margin allowing increased system/environment uncertainty

Why We Care

- High elevation sites require the vehicle to be decelerated faster
  - Need enough time to complete EDL events required for safe landing
- More fuel is required to land at high elevation sites
  - Parachute under-utilized (not enough time)
  - Atmospheric density is lower
- Low elevation sites allow the radar to better "see" the eventual landing site

Criticality/Firmness of Constraint

- Cannot exceed +1 km elevation
  - System has extremely limited timeline and propellant margin at +1 km sites
  - Elevation capability increase unlikely
- Elevation directly affects critical resources
  - Altitude/timeline margin
  - Propellant margin
- Timeline/fuel risks are greatly reduced at or below -0.5 km MOLA

Landing Site Terrain

Constraint

- Requirement:
  - ≤ 20° slope for 2 – 10 km length scales
    - Also applies to warning track
  - ≤ 43 m relief at 0.2 – 1.0 km length scales; increasing linearly to 720 m at 2 km length scales
  - ≤ 15° slope for 2 – 5 m length scales

Possible Trades

- Site elevation
  - Reduced site elevation generates propellant and altitude margin that could be used for additional 0.2 – 1.0 km length scale terrain relief (reverse also applies)
- Precision
  - Lower elevation sites can sometimes be used to increase precision performance
  - Increased precision performance may shrink the area over which the terrain restrictions apply (smaller warning track, smaller landing area)
- Winds
  - Reduced horizontal wind magnitudes and wind uncertainties may shrink the area over which the terrain restrictions apply (smaller warning track, smaller landing area)
- Robustness
  - Reduced terrain relief yields propellant margin allowing increase system/environment uncertainty

Why We Care

- 2 – 10 km length scales: large slopes may spoof the system into beginning powered flight too high or too low
  - Why a warning track: if we land near the edge of the landing ellipse, the radar will be looking at terrain outside the ellipse
- 43 m relief at 0.2 – 1.0 km length scales: a certain amount of propellant and altitude margin is allocated to terrain relief tolerance in powered descent
- 1 km to 2 km length scales: transition smoothly between two length scale restrictions above
- 2 – 5 m length scales: ensures stability and trafficability of the rover in touchdown conditions

Criticality/Firmness of Constraint

- All terrain relief/slope constraints appear tradable, especially at lower altitude sites
- Some statistical element to terrain constraints
  - Where terrain features are located in ellipse (not all locations in ellipse are equally likely)
- Consequence of terrain relief has different criticality depending on direction
  - Down-slopes cause additional propellant usage
  - Up-slopes cause reduced altitude/timeline margin

Day of Landing Winds

Constraints

- Requirement:
  - ≤ 25 m/s horizontal uncertainty between 6.5 – 20 km altitude MOLA
  - ≤ 20 m/s horizontal uncertainty between 3 – 6.5 km altitude MOLA
  - ≤ 20 m/s downward vertical magnitude between 1 – 5 km altitude above ground level

Possible Trades

- Site elevation
  - Lower site elevation yields altitude/timeline margin that can be spent on horizontal wind uncertainty
- Precision
  - Lower horizontal wind uncertainties increase precision
- Terrain tolerance
  - Lower downward vertical wind magnitudes yield propellant margin that can be spent on terrain relief tolerance

Why We Care

- 6.5 – 20 km MOLA horizontal wind uncertainty affects altitude and precision performance
  - Spreads parachute deploy Mach "error"
- 3 – 6.5 km AGL horizontal wind uncertainty affects altitude performance
  - Spreads heatshield separation Mach "error"
- 1 – 5 km AGL vertical wind magnitude affects propellant margin
  - Increases powered flight starting velocity and altitude

Criticality/Firmness of Constraints

- Wind constraints are not as firm as other constraints (e.g. site elevation)
- Wind constraints may be exceeded if traded for reduction in other constraints
- Site elevation is most valuable trading chip
  - Impacts altitude/timeline and propellant critical resources

Landing Precision (Miss Distance)

Constraint

- Requirement: ≤ 12.5 km in downtrack direction; ≤ ~10 km in crosstrack direction
- Safe haven: ≤ 16 km in downtrack direction

Possible Trades

- Not really tradable
- Atmosphere
  - Quiescent atmosphere conditions (wind, density structures, etc.) will improve precision performance

Why We Care

- Constraint defines expected landing precision capability of vehicle across range of landing sites
- Terrain safety constraints apply within the potential landing ellipses
  - Exceptions: “warning track” constraint, some atmosphere constraints

Criticality/Firmness of Constraint

- Unlikely to be able to significantly improve performance across landing sites
- Some capability variability with latitude
  - Orientation of ellipse
  - Precision performance
- Some statistical element to precision capability
  - Not all portions of the landing ellipse are equally likely
  - Ellipse more circular than past missions
- Ellipse performance will “never” be known
  - Largely driven by day-of-landing Mars atmospheric conditions

Landing Site Rocks Distribution

Constraint

- Requirement: probability that a rock higher than 0.55 m occurs in a random sampled area of 4 m^2 should be less than 0.5%

Possible Trades

- Not really tradable
- Robustness
  - Reductions in likelihoods of other failure mechanisms may enable a larger failure likelihood allocation for rocks

Why We Care

- Rover mobility system can accommodate rocks up to 0.55 m before the rover lower structure is damaged
- 0.5% of the project allocation for possible failure has been assigned

Criticality/Firmness of Constraint

- Risk of belly pan strike directly impacts probability of safe landing
  - No other constraints can be traded to reduce this impact
  - Vehicle cannot be modified to increase clearance
- Some statistical element to rock constraint
  - Where rocks are located in ellipse (not all locations in ellipse are equally likely)
  - Percentage of chance of failure that can be allocated

Detailed Site Assessment Process

- Site assessment involves detailed environmental characterization and design tuning
  - Monte Carlo performance simulation used as assessment tool

- Environmental characterization process
  - Terrain digital elevation maps required for several purposes
    - Radar/terrain interaction model and assessment of relief/slope tolerance require ~10 m resolution DEMs
    - Touchdown interaction model and rock strike probability assessment likely require high resolution DEMs
    - Data sets: CTX, HiRISE, photoclinometry
  - Computationally intensive detailed atmosphere modeling required to assess altitude and precision capability at each site
    - Mesoscale modeling captures site specific atmosphere features for guided entry
    - LES modeling may be required to capture low altitude features that impact performance

- Design tuning at each site provides most realistic day of landing risk assessment
  - Options exist for modifying the way the vehicle is flown for each site
    - Tuning guided by performance simulation results
    - Exploring design options is time and personnel intensive

- Team has laid groundwork for site assessments for ~5 sites
  - Throughput is largely team constrained
    - Results generation is labor intensive
    - Results synthesis is a small group affair
  - Radar models (utilizing DEMs) in development
  - Atmosphere modeling community engaged
  - Evaluation process has been preliminarily exercised

EDL Constraints Summary

Constraint Summary:

- Landing site elevation is a valuable trading chip
  - System taxed along many dimensions at high altitude sites
  - Margin at and above +1 km elevation sites is very small
  - Winds and terrain tolerance may be purchased with site elevation reductions
- Landing Precision
  - Performance may vary across launch/arrival/latitude/altitude space
  - Sites with uncertain atmospheric conditions (winds and density) degrade performance
- Rocks abundance above 0.55 m directly impacts landing safety
  - Reductions in other constraints do not directly yield additional capability

EDL Safety Assessment Posture:

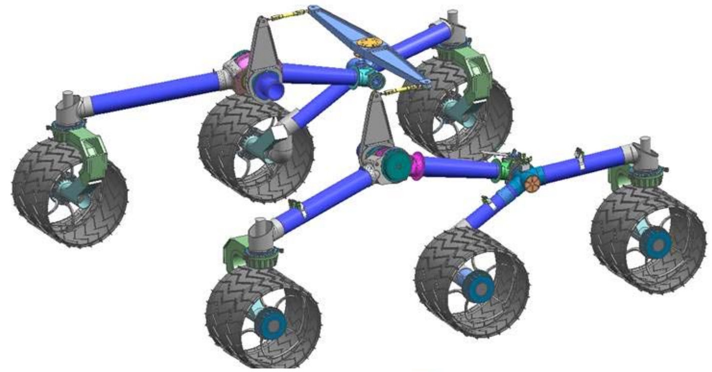
- Detailed site assessment is needed to understand true integrated risk at any one site
  - Data sets for evaluation are still pending
- Meeting the engineering constraints does not make all sites equal
  - Safety assessment values safer sites more
  - Safety assessment requires relative comparisons of detailed site assessments

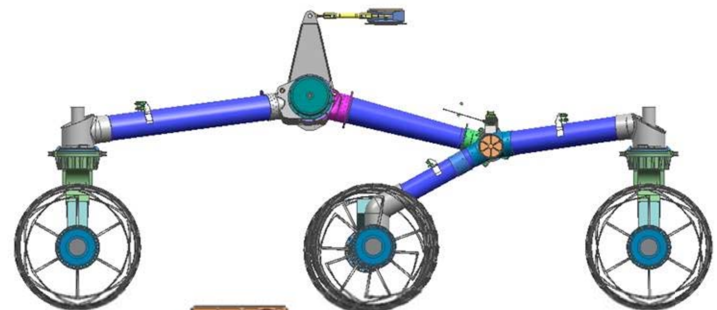
Agenda

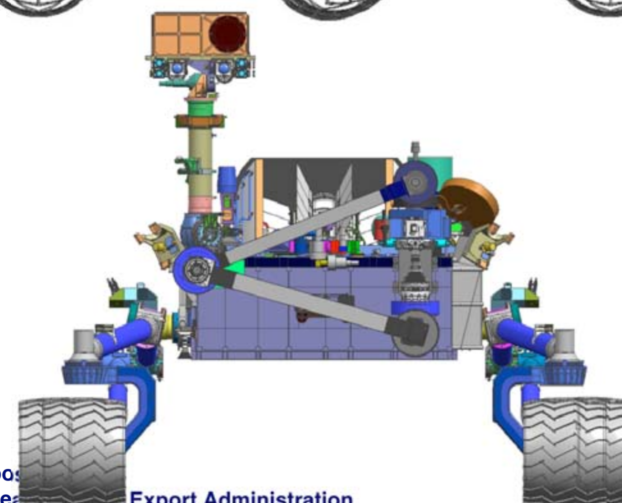
- Mission Design/Navigation/EDL Comm
- EDL
- **Surface Mobility**
- Mission Performance as function of latitude

Mobility System - Largely Unchanged

- 6 wheel independent drive, 4 corner wheel steering architecture
  - Steering rotation about vertical axis at center of wheel width
  - Rocker-bogie suspension configuration
  - Aluminum beam and machined fitting construction
- External linkage differential connects port and starboard suspension hardware
- Rover currently designed to be statically stable at a 50 degree tilt angle
- More robust to rocks/obstacles
  - Mean free path in 20% rock abundance field is about 48 m
  - Traverse >0.5 m hazard vs 0.2 for MER







Traverse Performance

Drive Mode	Operational Conditions	Rate	Per Sol
Blind (Go-To)	• Good operator visibility • No slip or slope hazards • Low obstacle density	~150m/hr	>150-200 m
AutoNav	• Low slip • No visibility or moderate position uncertainty	~50m/hr	>100 m

- Assuming disciplined (meaning almost non-stop) "Go to" traverse, exiting landing ellipse in worst case (end to end = 25 km) could take ~200 sols
  - "Pure Go To", meaning *no* prime target within ~>10km, is probably not acceptable from overall risk trade, however, rover is likely to traverse >10km during mission

Terrain Specifications - Largely unchanged

- "Performance Terrain Model" (table below) denotes 3 specific terrain types in which traverse rate and efficiency requirements must be met.
  - Other terrain models ("Minimum Mobility Terrains" and "Extreme Terrains") for mechanical design, acceptance testing, and envelope characterization.

Performance Terrain Case	Material	Slope	Structure	Rock Abundance
Rim of Bonneville crater	Sand with embedded 10-30cm rocks	0-10 degrees	N/A	20%
Columbia hills	Sand with embedded 10-30cm rocks	5-15 degrees	N/A	10%
Meridiani Ripples	Strong Soil	0-5 degrees	Sand bedforms, 1-2m wide, 5-10m long, 10-30cm high	N/A

Agenda

- Mission Design/Navigation/EDL Comm
- EDL
- Surface Mobility
- **Mission Performance as function of latitude**

Thermal Situation – Operations

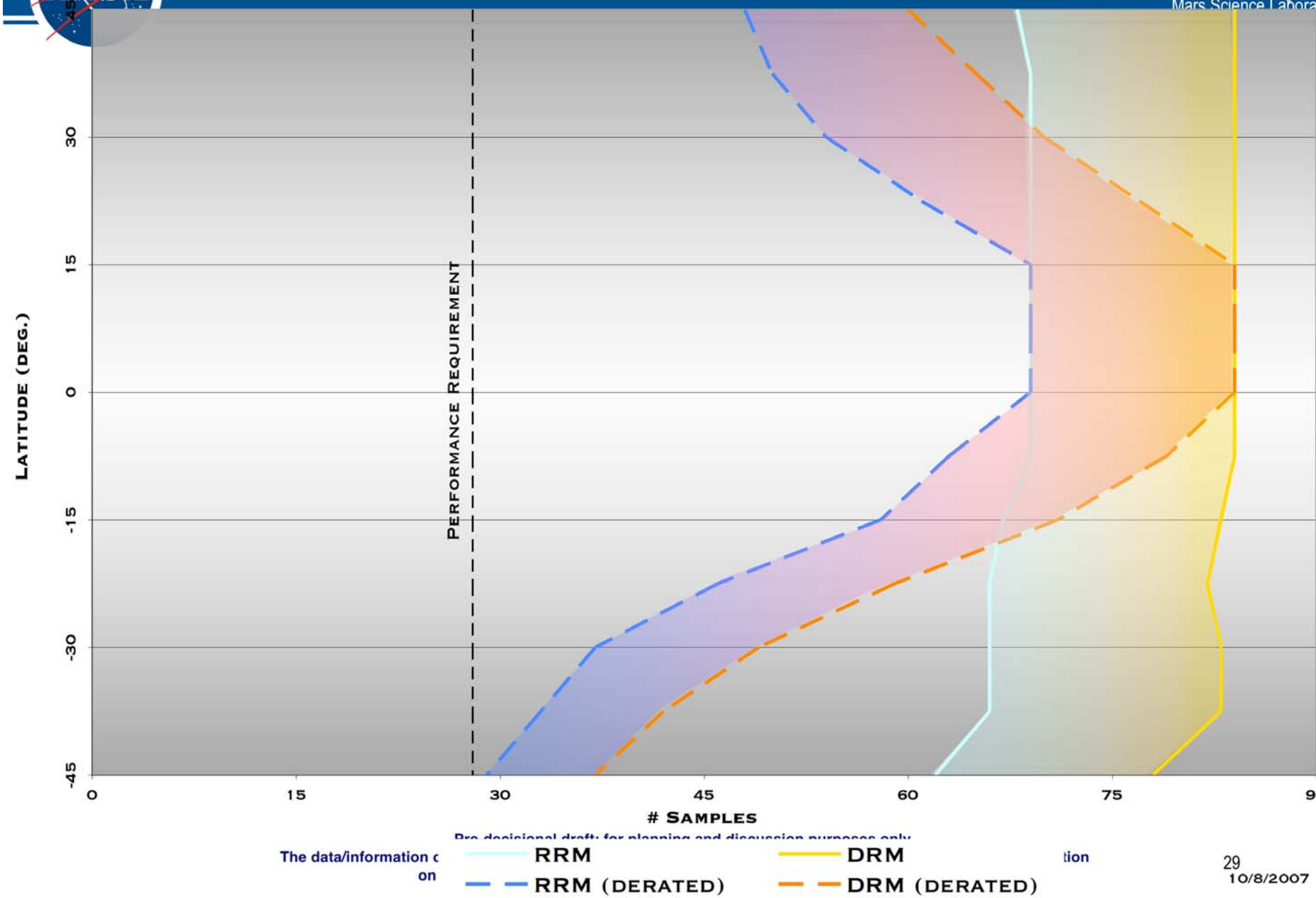
- MSL had originally baselined a dry lube system that would have allowed operation of major actuators down below -100C
  - Dry lube failed during life test and was dropped after Tiger Team study
  - Replaced by more conventional wet lube system (and steel gearboxes)

- Use of wet lube requires higher operating temperatures
  - Two options exist for achieving these temperatures
    - Wait for rover to warm up in sun
    - Use elective battery power to heat actuators
  - Focusing on conservative -50C cold operating limit
  - Focusing on conservative wait-to-use (no heaters)

- Strong function of Martian season and latitude of landing site
  - Thermal team has modeled major actuator temps over diurnal and seasonal cycles based on ***conservative*** (but not stacked worst case) ambient temps
  - Analyze performance of above options across range of potential landing site latitude on Mars
  - Analyze impacts on Earth operations scenario

MSL Mission Performance

Heat Actuators to -55 C



Actuator: Ops Impact Summary

- Under these conservative analyses:
  - Rover can operate between 5S-15N over entire Mars year with virtually no loss of performance
  - Rover can operate between 5S-10S, or 15N-25N with only minor degradation in performance, degradation becoming significant from 15S on
  - 28 sample rqmt still met to 45S but significant winter stand-down
  - ***Note poor arrival conditions at 25-45S***

- We need to examine performance for southerly sites in greater detail:
  - 5-10 degrees C of temp can improve mission return noticeably
  - Specific site thermal conditions
  - Actuator heating effectiveness and qual capability

AFT:	-50°C	-60°C	-70°C
45ºN	0.53	0.63	0.70
30ºN	0.79	0.94	1.00
22.5ºN	1.00	1.00	1.00
15ºN	1.00	1.00	1.00
0º	1.00	1.00	1.00
15ºS	0.75	0.96	1.00
22.5ºS	0.65	0.75	0.95
30ºS	0.57	0.65	0.74
45ºS	0.43	0.49	0.55

"derating factor" based on cold stand-down hours

Summary

- Our understanding of the MSL system capabilities and constraint has matured significantly since the first landing site workshop
  - MSL continues to represent a significant improvement in accessing scientifically important sites on Mars and brings an extraordinarily capable payload
  - Performance in EDL and operations can be a strong function of altitude and latitude which need to be kept in mind for landing site selection

- **Engineering constraints have matured, but are under continual evaluation and refinement**
  - Risk trade requires understanding and modelling of system performance as function of constraint variables
  - We are willing to retain high science value sites which have yellow* safety evaluations in some engineering categories as of now (Oct 2007) in order to allow this trade to play out to the benefit of science

    Yellow due to uncertainty about final MSL engineering capability
  - There is value in post-processing this workshop's science evaluations against engineering to come up with actual list of "final candidates" for detailed evaluations in upcoming year
  - We'll talk more about this near close of the workshop….