Engineering Constraints on MER Landing Sites

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- **Contributors to this presentation material –**
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  - **EDL: Wayne Lee**
  - **Egress: Joel Krajewski**
  - **Surface mission resources: Jake Matijevic**
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Agenda

- **Landing targeting accuracy and ellipse sizes**
- **Landing site consequences**
- **Entry, descent, and landing constraints**
- **Egress and surface mission constraints**
- **Landing site engineering considerations**

Landing Targeting Accuracy

- **Accuracy of landing targeting can be described approximately by a Gaussian ellipse**
- **Sources of landing dispersions**
  - **Approach navigation accuracy—dominant in downtrack**
  - **Atmosphere density profile uncertainty**
  - **System drag uncertainty and variation**
  - **Winds**
- **Site characteristics are considered within central 99% of landing dispersions**
  - **Ellipses vary through launch period, so need to consider union of ellipses**
- **Improvements in ellipse sizes since last workshop**
  - **Now depending on ΔDOR due to positive MGS and Odyssey experiences**
  - **Thorough scrubbing of navigation margins, introduction of EDL margins**
  - **Using portion of benefits to allow earlier TCM-5 at two days before entry**
  - **Hematite went from 211 km to 119 km (MER-B)**
  - **Gale went from 141 km to 108 km (but not quite far enough)**
  - **Gusev went from 70 km to 103 km (hit by earlier TCM-5, EDL margins)**

Landing Site Ellipse Assumptions

- Entry dispersions are for TCM5 at Entry - 2 days [data cutoff at 2.5 days]
  - Assumes Auto-TCM capability [designed maneuver at TCM5 instead of library]
- Approach Navigation estimates include ΔDOR and updated, peer-reviewed orbit determination filter assumptions
  - A "no margin" floor capability was established, then margins were added for Navigation robustness. Sets of 2000 entry states were created for selected sites.
- LARC 6DOF and/or JPL 3DOF Monte Carlo analyses were performed for all ROTO sites plus Elysium Flow [Golombek email 9/26/2001]. 99% landing ellipses were calculated
  - Sets of 2000 entry states were provided by Nav at the following ROTO sites at launch period open and close: IP85A, TM10A, VM53A, EP55A, IP98B, TM20B, and Melas B Site
    - B-plane dispersions generated from these data, plus new nominal entry states, were used to create approximate dispersed states for Monte Carlo analyses at the other ROTO sites.
- EDL margins were added to the 99%landing ellipses to account for other potential effects on ellipse dimensions, including:
  - Sustained winds, atmosphere modeling error, potential change in targeted entry flight path angle, etc.
- Curve fits based on the ROTO site ellipses were used to provide approximate landing ellipse dimensions for the Nadir sites

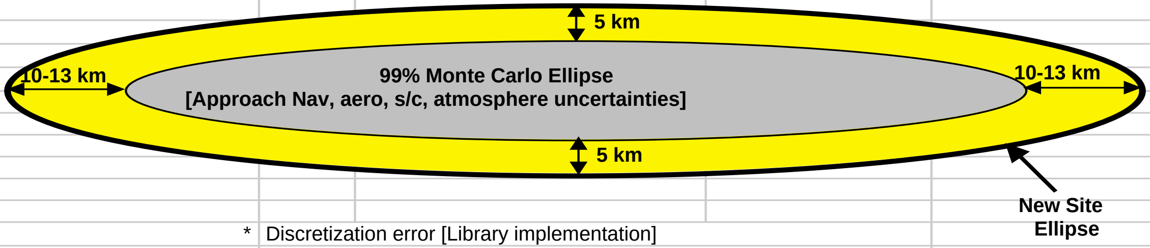
Approach Navigation Assumptions

- **New orbit determination [OD] filter assumptions include appropriate margin with respect to "no margin" [best performance] assumptions and flight system requirements, as recommended by the Navigation Advisory Group [NAG]**
  - **Resulting approach dispersions are significantly smaller than earlier estimates used to generate the original site ellipses**
- **Key OD filter assumptions:**
  - **ΔDOR points every two days, with last point at least two days before data cutoff**
  - **ACS event ΔV: 3 mm/s 1σ per axis (FS requirement: 2 mm/s 1σ per axis)**
  - **ACS event frequency: 1 every 8 days (mission plan: 1 every 12 days)**
  - **Non-grav accelerations: $2x10^{12}$ km/s^2**
  - **10% of solar radiation pressure acceleration at Entry - 60 days**
  - **Doppler, range, and ΔDOR accuracies per NAG recommendations**
  - **Platform and media calibrations per NAG recommendations**
- **Navigation delivery capabilities strongly dependent on spacecraft dynamics**
  - **ACS events, non-grav acceleration uncertainty, maneuver execution errors**
- **Navigation accuracy does not apply in the event of a thruster cluster failure**
  - **Unbalanced turns would produce non-zero net ΔV from each ACS event, resulting in degraded performance**

EDL Margins

No Discretization [Assumes Auto-TCM]*

Factor	Factor Value	Rationale	Effect on Total Downtrack [km]	Effect on Total Crosstrack [km]
Sustained Winds	20 m/s	Mesoscale models show winds up to 24 m/s - 30 m/s	4	4
Atmos Density	+/-5%	Dust storm requirement; Additional modeling uncertainty	12	0
Impact to Roll Stop	1 km	Max roll distance [MPF]	1	1
		RSS:	**13**	**4**
Crosstrack Control Limit	5 km	MPL ops experience	0	5
		Subtotal	**13**	**9**
Targeted Entry FPA	-0.2°	Chute load reduction; Reduced angle of attack at chute deploy; Additional atmosphere robustness	10% of Monte Carlo ellipse length	0
EDL Margin added to 99% Monte Carlo Ellipse:			**13 + 10%**	**10**



* Discretization error [Library implementation] could add > 30 km to total downtrack, TBD crosstrack

Site Ellipse Sizes

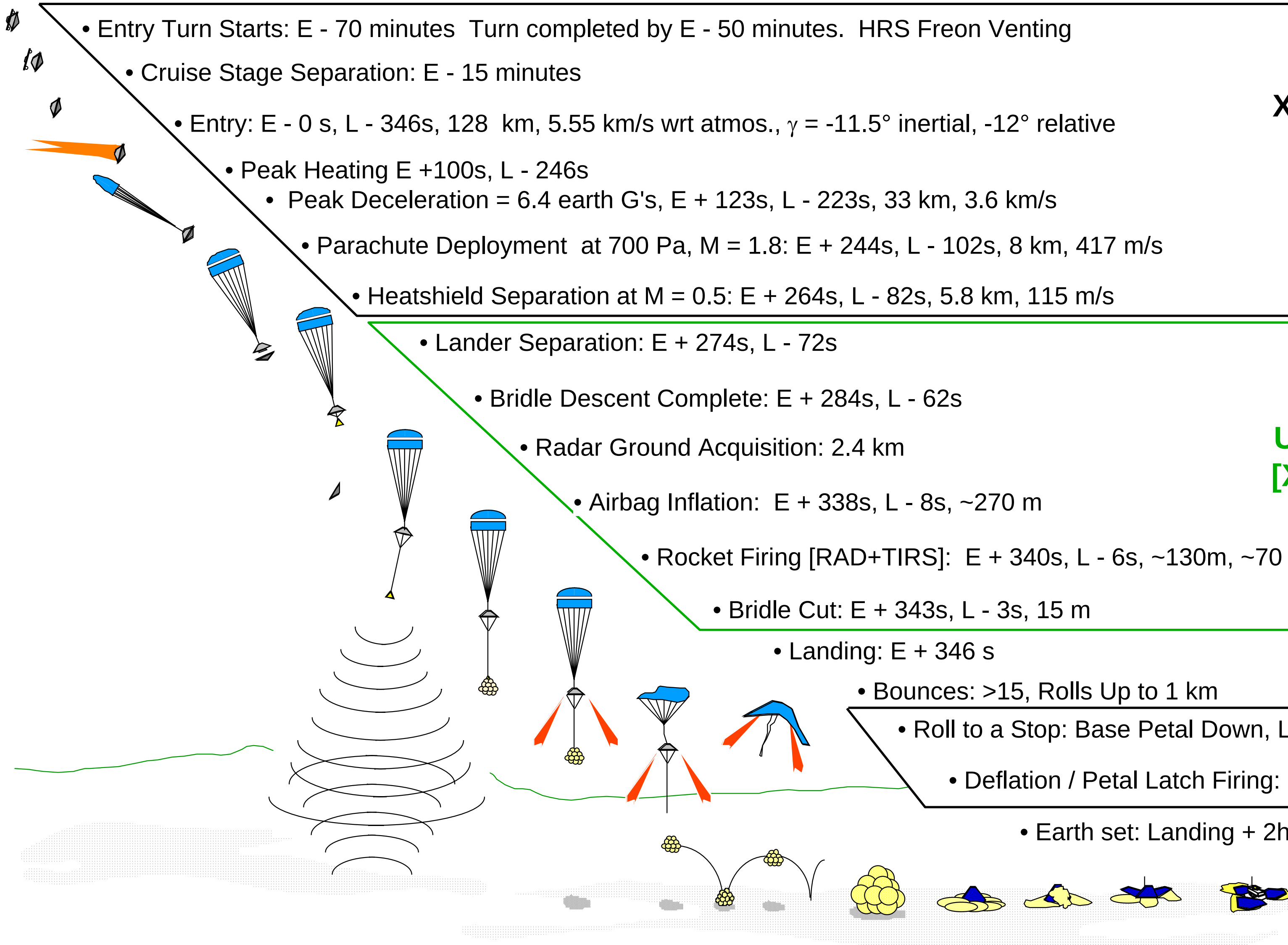
Site	Planetocentric Latitude [deg.]	East Longitude [deg.]	MER-A Open Total Downtrack [km]	MER-A Open Total Crosstrack [km]	MER-A Open Azimuth [deg.]	MER-A Close Total Downtrack [km]	MER-A Close Total Crosstrack [km]	MER-A Close Azimuth [deg.]
Isidis IP85A	4.62	85.21	**132**	16	88	**127**	17	85
Hematite TM9A	-1.2	354.23	**119**	17	84	**114**	17	81
Hematite TM10A	-2.2	353.23	**119**	17	84	**113**	17	81
Gale EP82A	-5.76	137.66	**108**	18	81	**106**	18	79
Melas VM53A	-8.68	282.07	**103**	18	80	**100**	19	78
Eos VM41A	-13.2	318.46	**98**	19	78	**103**	19	75
Gusev EP55A	-14.67	175.75	**96**	19	76	**103**	19	74

Site	Planetocentric Latitude [deg.]	East Longitude [deg.]	MER-B Open Total Downtrack [km]	MER-B Open Total Crosstrack [km]	MER-B Open Azimuth [deg.]	MER-B Close Total Downtrack [km]	MER-B Close Total Crosstrack [km]	MER-B Close Azimuth [deg.]
Isidis IP98B	4.55	84.01	**140**	16	91	**133**	17	86
Hematite TM19B	-1.2	354.53	**119**	18	87	**112**	18	82
Hematite TM20B	-1.98	353.82	**117**	18	86	**112**	19	82
Melas B Site	-8.68	282.07	**105**	20	82	**103**	20	79
Elysium Flow EP49B	9.16	155.47	**152**	16	95	**148**	17	89

Landing Site Selection Consequences

- **Landing site-related mission failures would result from:**
  - **Failure to properly complete required events before impact**
    - **Altitude**
    - **RADAR reflectance**
  - **Adverse conditions for landing impacts and roll**
    - **Winds increasing impact velocity**
    - **Slopes causing shear on bags, spoofing RADAR, or adding energy on roll**
    - **Rocks tearing bags or impacting lander structure**
  - **Obstacles to deployment and egress due to immediate slope and rocks**
  - **Surface mission lifetime**
    - **Solar latitude over surface mission**
    - **Night-time temperatures and required energy to maintain thermal control**
- **Landing site engineering considerations include:**
  - **Landing latitudes and landing day (MER-A or MER-B)**
    - **Total available energy for surface mission**
    - **Energy cost of direct-to-Earth data return**
    - **Orbiter relay asset conflicts between MER-A and MER-B**
    - **Direct-to-Earth session conflicts between MER-A and MER-B**
      - **Hematite PM overlaps Melas AM sessions**
    - **Potential for extended mission**
  - **Rover trafficability with respect to rocks**

Entry, Descent, and Landing



- Entry Turn Starts: E - 70 minutes Turn completed by E - 50 minutes. HRS Freon Venting
- Cruise Stage Separation: E - 15 minutes
- Entry: E - 0 s, L - 346s, 128 km, 5.55 km/s wrt atmos., γ = -11.5° inertial, -12° relative
- Peak Heating E +100s, L - 246s
- Peak Deceleration = 6.4 earth G's, E + 123s, L - 223s, 33 km, 3.6 km/s
- Parachute Deployment at 700 Pa, M = 1.8: E + 244s, L - 102s, 8 km, 417 m/s
- Heatshield Separation at M = 0.5: E + 264s, L - 82s, 5.8 km, 115 m/s

X-band DTE

- Lander Separation: E + 274s, L - 72s
- Bridle Descent Complete: E + 284s, L - 62s
- Radar Ground Acquisition: 2.4 km
- Airbag Inflation: E + 338s, L - 8s, ~270 m
- Rocket Firing [RAD+TIRS]: E + 340s, L - 6s, ~130m, ~70 m/s
- Bridle Cut: E + 343s, L - 3s, 15 m

UHF to MGS [X-band DTE Backup]

- Landing: E + 346 s
- Bounces: >15, Rolls Up to 1 km

X-band DTE

- Roll to a Stop: Base Petal Down, Landing + 2 min
- Deflation / Petal Latch Firing: Landing + 90 min
- Earth set: Landing + 2h 40 min

EDL Constraints (1)

- **Assure adequate drag to reach EDL event conditions before impact**
  - ***The altitudes at a landing site shall be less than -1.3 km relative to the MOLA geoid***
- **Assure adequate RADAR reflectivity to get range to actual surface**
  - **(thermal inertia constraint covered by temperature requirement)**
- **Limit variation between RADAR surface altitude eight seconds before landing (used for rocket-firing solution), and actual landing altitude**
  - ***On a 100 m topographic grid horizontal scale, the slopes between grid points shall be less than 5°***
- **Control total impact energy and surface-tangential velocity component**
  - ***The horizontal velocity at impact shall be predicted to be less than 20 m/s***
  - **The landing site characteristic that drives the horizontal velocity is wind**
  - **Sustained winds add directly and cannot be detected by the landing system**
  - **Wind shears can induce horizontal velocity by tilting the rockets at firing**
  - **Rocket tilt can be detected, and is partly compensated for by small rockets**
  - **Insufficient data at this workshop for wind to be a site discriminator**

EDL Constraints (2)

- **Limit shear on bags from surface-tangential component of impact velocity**
  - ***On a 5 m topographic grid horizontal scale, the slopes between grid points shall be less than 15°***
- **Avoid severe air-bag damage before roll-stop, and avoid stroke failure of bags where rocks impact lander structure**
  - ***The rock abundances at a landing site shall be less than 20%***
  - **The 20% limit is a Mars Pathfinder heritage number**
  - **New analyses with expected impact velocities and survival of 0.5 m high rocks suggests that 20% is not survivable with high enough probability**
  - **Test program of air-bag system performance envelope underway**
  - **Likely that 20% rock abundance will be reduced**
- **Assure an overall decrease in kinetic energy with time while rolling**
  - ***On a 1 km horizontal scale, slopes shall be less than 2°***
  - **2° provides reasonable assurance of decelerating roll**

EDL Performance Validation

- **Major Tests Completed to Date:**
  - **Airbag Performance Envelope Exploration Drops**
  - **Airbag Abrasion vs. Denier Count Exploration Drops**
  - **Airbag/Radar Interaction Test**
  - **Ballistic Range Test of Entry Vehicle**
  - **Parachute Rate of Descent Characterization Drops**
  - **Parachute Stability and Drag Wind Tunnel Test**
  - **Subsonic Aerodynamics Wind Tunnel Test**
  - **DRL Deployment Development Testing**
  - **Zylon Material Characterization Testing (Bridle and Parachute)**
  - **TIRS Cover Ejection Tests**
- **Upcoming Major Tests**
  - **Airbag Qualification and Performance Envelope Exploration**
  - **Radar Performance Drop Test**
  - **Rocket (RAD/TIRS) Performance Characterization Firings**
  - **Terminal Descent Dynamics Characterization**
  - **TPS Performance Arc Jet Test**
  - **TRAD Performance Drop Test**

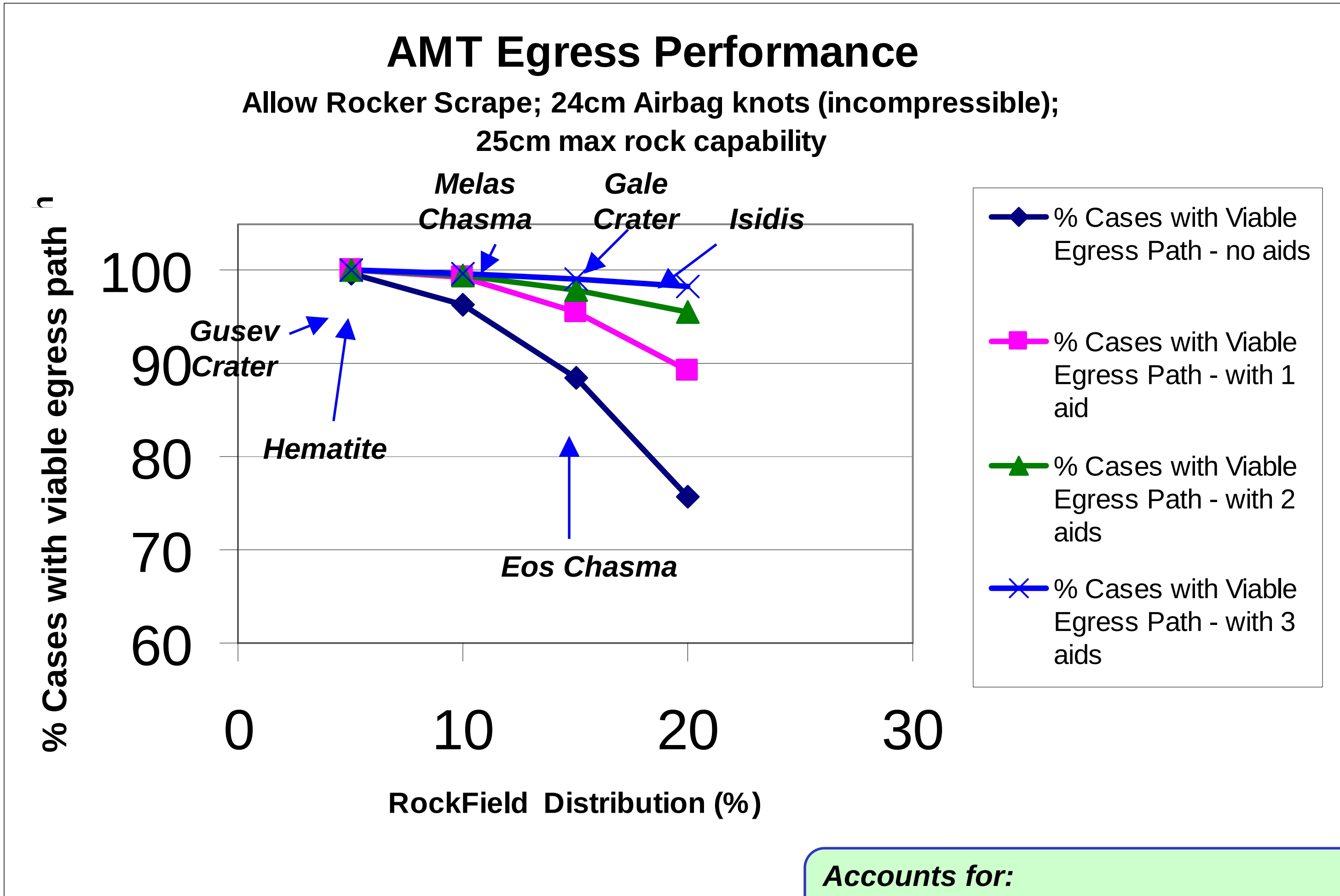
Wind Modeling Status

- **Site-specific mesoscale wind models in development**
  - **Experimental development, requires validation before use**
  - **Mesoscale models common in terrestrial studies, but new for Mars**
  - **Best approach for the wind characteristics of importance to EDL**
- **Two independent models being developed, based on independent terrestrial mesoscale models**
  - **MRAMS, Scot Rafkin at San Jose State University (Ames MGCM)**
  - **Mars MM5, Anthony Tiogo at Cornell and Mark Richardson at Caltech (GFDL MGCM)**
- **Intended qualitative and quantitative applications of models**
  - **Relative ranking of regions and sites within regions with respect to wind**
  - **Generation of new random wind model for EDL simulations**
- **Model validation approaches**
  - **Comparison with boundary layer theory and atmospheric physics**
  - **Comparison with Viking and Pathfinder observations**
  - **Comparison of independent predictions**
  - **Peer-review by terrestrial and Martian boundary layer specialists (Jan 2002)**

Surface Mission Constraints

- **Adequate reliability of deployment and rover egress off of lander**
  - **Affected by immediate slopes and rock abundance**
  - **Controlled by EDL rock abundance and 5 m scale slope requirements**
  - **Assumes three egress aids**
- **Surface mission lifetime and adequate energy for mission success**
  - **Solar latitude needs to be close to landing latitude over surface mission**
  - ***The center of the MER-A landing ellipse shall be within 15°S to 5°N latitude***
  - ***The center of the MER-B landing ellipse shall be within 10°S to 10°N latitude***
  - **Limit energy needed to maintain thermal control overnight**
  - ***The minimum atmospheric temperature at one meter above the surface of a landing site as determined by the measured albedo and thermal inertia shall be greater than –97C***
- **Adequate UHF data return**
  - **Avoid MER-A and MER-B seeing the same orbiter at the same time**
  - ***The centers of the MER-A and MER-B landing site ellipses shall be separated by a central angle of at least 37°***

Preliminary Egress Capability Estimate



Accounts for:
- Rover Capability vs. Lander Deck Height/tilt
- Large Rocks blocking potential Egress Paths

Egress Performance Testing Plans

- **Update Performance Estimate in Early November based on**
  - **Egress Rover performance tests**
  - **Lander/Airbag Model Calibration tests**
- **Test driving capability on MER-like Lander during November '01**
  - **May discover "wheel traps" that preclude some Egress directions**
    - **Hence, may degrade Egress Performance estimate**
- **MTM / DTM Rovers currently scheduled for assembly in March '02**
  - **Improved insight into "as-built" suspension capabilities may result in an update to estimated Egress performance**

Landing Site Engineering Considerations

- **Total mission energy**
  - **Landing latitude and mission (A/B) determines total energy available for surface activities and communication, and survival lifetime**
    - **10% to 35% more planning energy for MER-A than MER-B at same latitude**
    - **Greatest planning energy in the middle of a latitude band (A or B)**
    - **Lifetime increases as you go North (Sun is moving North at this time)**
  - **Mission (A/B) determines energy cost of direct-to-Earth communication as a function of time**
    - **25% to 15% less efficient data return for MER-B compared to MER-A**
    - **70m DSN antenna energy cost of data ranges from 4.5 Whr/Mb to 14 Whr/Mb**
    - **UHF energy cost of data constant at 0.8 Whr/Mb**
    - **UHF volume mediates A/B data return differences**
      - **Typical mission scenarios return 4.7 Gb for MER-A at Gusev, 4.4 Gb for MER-B at Isisdis**
- **Trafficability**
  - **Landing site rock abundance affects rover traverse capability**
  - **High rock abundances would result in shorter planned traverses, overall lower traverse capability**

					Last Sol of Survival		Total Planning Energy	
							Through 92Sols (kWhr)	
	Designation	**Site Lat/Long**			**MERA 34 string 1/4/04 arrival**	**MERB 34 string 1/25/04 arrival**	**MERA 34 string 1/4/04 arrival**	**MERB 34 string 1/25/04 arrival**
Roto Sites								
	Hematite							
	TM20B	1.99S, 6.01W			120	104	24.1	20.5
	TM19B	1.20S, 5.30W			120	104	23.7	20.4
	TM10A	2.20S, 6.30W			120	104	24.1	20.5
	TM9A	1.20S, 5.60W			120	104	23.7	20.4
	Melas Chasma							
	VM53A	8.8S, 77.8W			108	92	25.7	20.5
	B Site	8.8S, 77.8W			108	92	25.7	20.5
	Gale							
	EP82A	5.81S, 222.23W			112	96	25.3	20.8
	Gusev							
	EP55A (S)	14.85S, 184.16W			96	80	25.3	18.7
	Eos Chasma							
	VM41A	13.34S, 41.39W			100	84	25.6	19.4
	Isidis							
	IP98B	4.64N, 275.88W			132	120	21.9	19.9
	IP85A	4.7N, 274.68W			132	120	21.9	19.9

Trafficability

- **Analytic formulation of MER rover traverse capability uses rock model of Golombek and Rapp**
  - **Computes distance required for rover to autonomously traverse a planned distance to destination**
  - **Applies a constant overhead for rock hazard avoidance**
  - **Assumes rock height of ≥ 0.2 m is a hazard to rover traverse**
  - **Poisson distribution of rocks matching model cumulative rock coverage**
- **Define 'trafficability factor' as expected distance / planned distance**
  - **Planned distance is lines connecting waypoints**
  - **Expected distance is what on-board rover navigation should do to maneuver around rocks when trying to get to waypoints**
  - **Trafficability factor ≥ 1**
- **Trafficability factor ≥ 2 impacts mobility**
  - **Requires shorter commanded drives to avoid wandering**
  - **Would likely take more advantage of rover clearance to allow traverses directly over larger rocks, e.g. up to 0.23 m**

Landing Site Trafficability

	Designation	Site Lat/Long	IRTM Rock Mean	Traffic Fact
Roto Sites				
	Hematite			
	TM20B	1.99S, 6.01W	5.5	1.004
	TM19B	1.20S, 5.30W	6.33	1.011
	TM10A	2.20S, 6.30W	6.33	1.011
	TM9A	1.20S, 5.60W	6.33	1.011
	Melas Chasma			
	VM53A	8.8S, 77.8W	11.6	1.264
	B Site	8.8S, 77.8W	11.6	1.264
	Gale			
	EP82A	5.81S, 222.23W	15	2.029
	Gusev			
	EP55A (S)	14.85S, 184.16W	5.75	1.006
	Eos Chasma			
	VM41A	13.34S, 41.39W	14.67	1.897
	Isidis			
	IP98B	4.64N, 275.88W	16.33	2.907
	IP85A	4.7N, 274.68W	16	2.615

Backup Slides

Nadir Site Ellipse Sizes

Mars Exploration Rover

Approximate Dimensions as a function of Latitude, based on Curve Fits using ROTO Site Data

Uncertainties ~ +/- 5 km Downtrack, +/- 1 km Crosstrack, +/- 1 deg Azimuth

	Planetocentric Latitude [deg.]	E. Longitude [deg.]	Mission	Open Tot Downtrack [km]	Open Tot Crosstrack [km]	Open Azimuth [deg.]	Close Tot Downtrack [km]	Close Tot Crosstrack [km]	Close Azimuth [deg.]
Hematite									
TM11A	-3.4	352.94	A	114	17	83	109	18	80
TM22B	-3.4	352.64	B	116	18	85	110	19	81
TM12A	-3.6	356.94	A	113	17	83	109	18	80
TM23B	-3.1	356.73	B	116	18	85	110	19	81
TM21B	-2.5	356.54	B	118	18	86	112	18	82
NE Valles Marineris Outflow									
VM37A	-10.925	321.84	A	101	18	78	102	18	76
Meridiani Highlands									
TM13A	-2.95	349.81	A	115	17	83	110	18	81
TM24B	-2.77	349.71	B	117	18	86	111	19	81
Meridiani Crater									
TM15A	-8.5	352.72	A	104	18	80	103	18	78
TM16A	-9.25	353.06	A	103	18	79	103	18	77
EP69A Crater									
EP69A	-9.08	150.299	A	104	18	79	103	18	77
Central Valles Marineris									
VM44A	-12.93	297.399	A	98	19	77	102	19	75
Boedickker Crater									
EP64A	-15.11	162.45	A	95	19	76	103	19	74
Isidis Planitia Sites									
IP84A	4.41	87.98	A	133	16	88	127	17	85
IP96B	4.38	88.28	B	136	16	91	129	17	86

Nadir Site Lifetime and Planning Energy

					Last Sol of Survival		Total Planning Energy	
							Through 92sols (kWhr)	
	Designation	Site Lat/Long			MERA 34 string 1/4/04 arrival	MERB 34 string 1/25/04 arrival	MERA 34 string 1/4/04 arrival	MERB 34 string 1/25/04 arrival
Nadir Sites								
	Hematite							
	TM21B	2.50S, 3.30W			116	104	24.4	20.7
	TM22B	3.40S, 7.20 W			116	104	24.4	20.7
	TM23B	3.10S, 3.10W			116	104	24.4	20.7
	TM12A	3.60S, 2.90W			116	104	24.4	20.7
	TM11A	3.40S, 6.90W			116	104	24.4	20.7
	Boedickker Crater							
	EP64A	15.30S, 197.44W			96	80	25.3	18.7
	Un-named Crater							
	EP69A	9.20S, 209.60W			108	92	25.7	20.5
	Isidis							
	IP84A	4.50N, 271.90W			132	120	21.9	19.9
	IP96B	4.48N, 271.60W			132	120	21.9	19.9
	Meridiani Crater							
	TM15A	8.60S, 7.1W			108	92	25.7	20.5
	TM16A	9.36S, 6.76W			108	92	25.7	20.5
	Meridiani Highlands							
	TM13A	3.00S, 10.00W			116	104	24.4	20.7
	TM24B	2.80S, 10.10W			116	104	24.4	20.7
	NE Valles Marineris Outflow							
	VM37A	11.10S, 38.05W			104	88	25.8	20.1
	Central Valles Marineris							
	VM44A	13.10S, 62.50W			100	84	25.6	19.4

Nadir Site Trafficability

	Designation	Site Lat/Long	IRTM Rock Mean	Traffic Fact
Nadir Sites				
	Hematite			
	TM21B	2.50S, 3.30W	6.4	1.012
	TM22B	3.40S, 7.20 W	7	1.02
	TM23B	3.10S, 3.10W	8	1.042
	TM12A	3.60S, 2.90W	8	1.042
	TM11A	3.40S, 6.90W	7	1.02
	Boedickker Crater			
	EP64A	15.30S, 197.44W	4	1
	Un-named Crater			
	EP69A	9.20S, 209.60W	6	1.008
	Isidis			
	IP84A	4.50N, 271.90W	15.25	2.145
	IP96B	4.48N, 271.60W	17.83	6.33
	Meridiani Crater			
	TM15A	8.60S, 7.1W	8	1.042
	TM16A	9.36S, 6.76W	7	1.02
	Meridiani Highlands			
	TM13A	3.00S, 10.00W	12	1.311
	TM24B	2.80S, 10.10W	12	1.311
	NE Valles Marineris Outflow			
	VM37A	11.10S, 38.05W	20	-
	Central Valles Marineris			
	VM44A	13.10S, 62.50W	18	7.364