



LaRC

Mars Exploration Rover

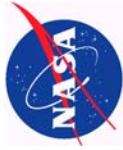
MER EDL: Overview and Reconstruction Status

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August 23, 2004





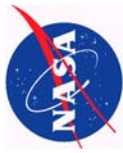
Background

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Mars Exploration Rover

- **“Spirit” and “Opportunity” landed successfully on January 4th and 25th of 2004 at two scientifically distinct sites**
- **Delivered to the surface using the Mars Pathfinder (MPF) Entry, Descent and Landing (EDL) system**
- **5 instruments to conduct remote and in-situ observations**
- **Operational life \geq 90 sols minimum for each rover**
- **Scientific objective is to search for evidence of past history of water**



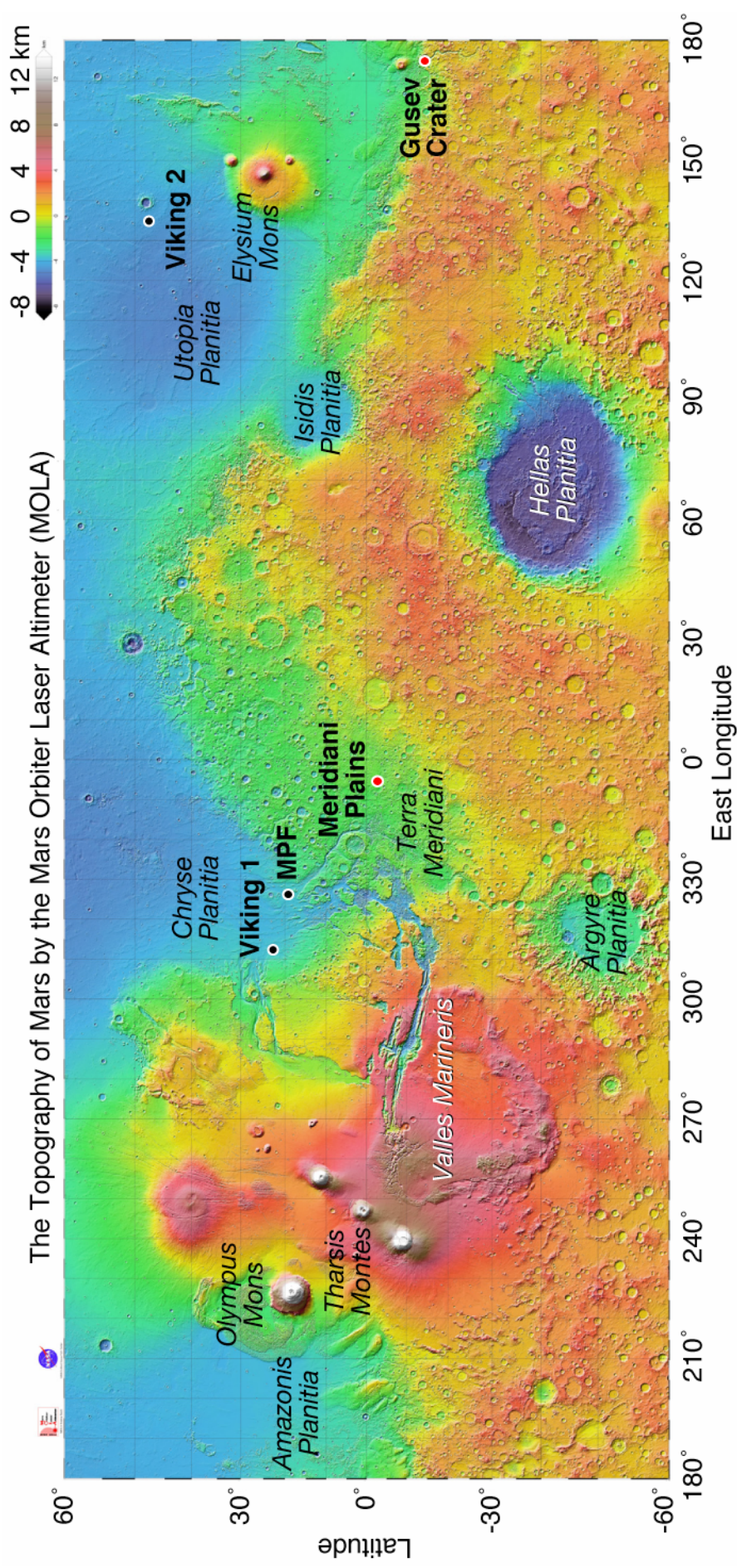


MER Candidate Landing Sites

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Landing sites will be equatorial (15° N to 15° S)



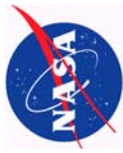


MER Entry Heritage w/Viking & Mars Pathfinder

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	Viking I. II	Mars Pathfinder	MER
Forebody geometry, deg	70	70	70
Aftbody geometry, deg	39/62 (biconic)	49	49
Relative Entry Velocity, km/s	4.5, 4.42	7.6	5.5
Relative Entry FPA, deg	-17.6	-13.8	-12
Entry Local Time	--	Pre-Dawn	Afternoon
Mass, kg	930	585	827, 832.2
$m/(C_D A)$, kg/m ²	63.7	62.3	89.8
X_{CG}/D : reference	0.221	0.27	0.27
Nominal α_T , deg	-11.1	0	0
L/D	0.18	0	0
G&C	3-axis (active)	spin stabilized	spin stabilized

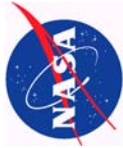


MER EDL Animation

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MER Entry, Descent, and Landing (EDL) Sequence

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Landing Times
(Mars local solar time)
 MER-A: ~2:00 PM
 MER-B: ~1:15 PM
 Earth set: ~3:30 PM

Cruise Stage Separation: E- 15m
 Entry: E- 0 s, 125 km, 5.6 km/s, $\gamma = -11.5$ deg.
 Parachute Deployment: E+ 244 s, 9.5 km, 430 m/s
 Heatshield Separation: E+ 264 s

Lander Separation: E+ 274 s

Bridle Deployed: E+ 284 s

Radar Ground Acquisition (earliest): 2.4 km (AGL)

EDL Images Taken : 1.6 km (AGL)

Airbag Inflation: 0.5 s prior to RAD firing

RAD & TIRS Rocket Firing: ~120 m

Bridle Cut: 12 m (AGL)

Bounces

L = Landing: ~E+355 s

Roll-Stop: L+10 min

Airbags Retracted: L+69 min

PND - 6

EDL Direct to Earth Communication with MFSK tones

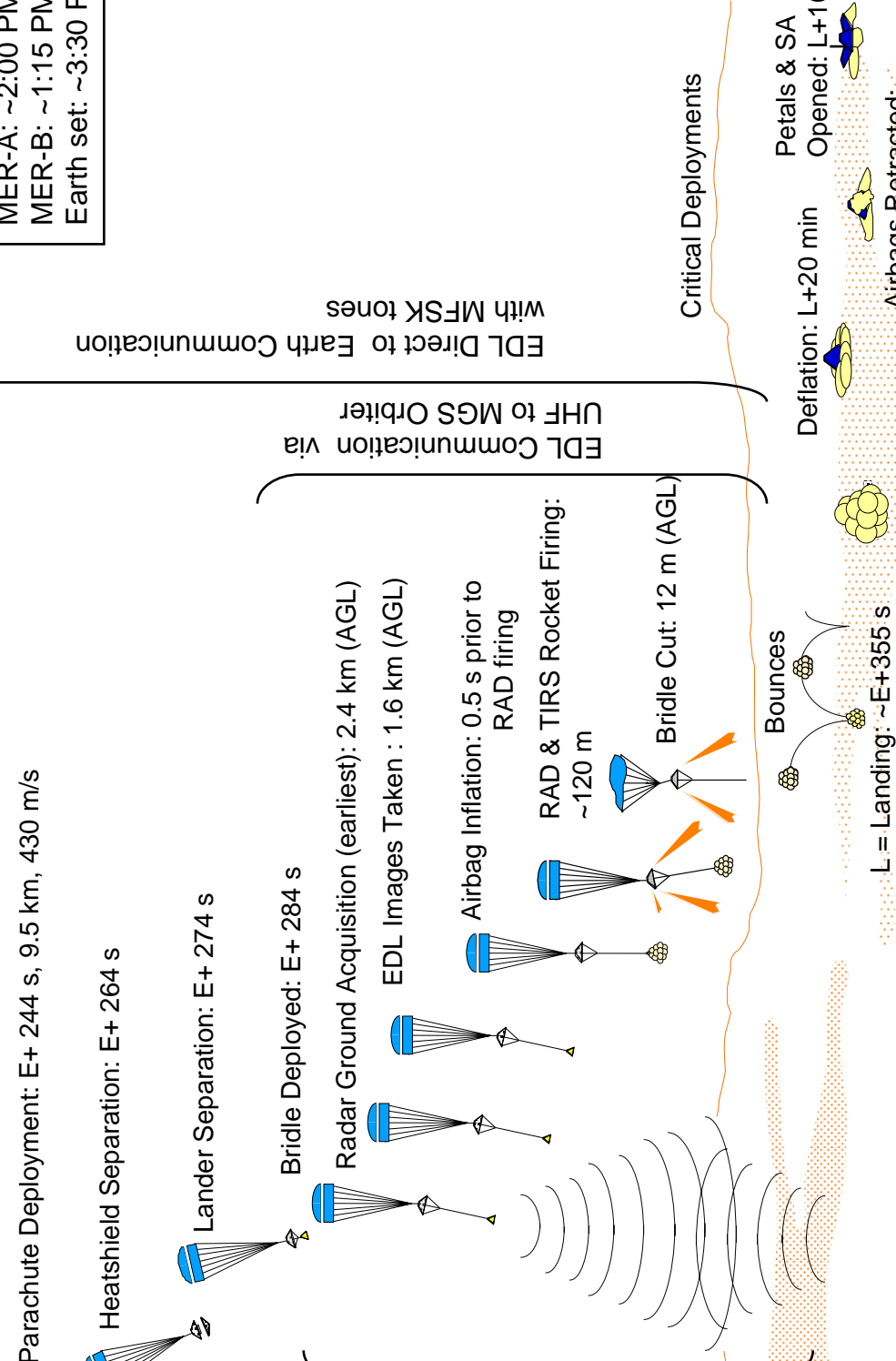
EDL Communication via UHF to MGS Orbiter

Critical Deployments

Petals & SA

Deflation: L+20 min
Opened: L+100 min

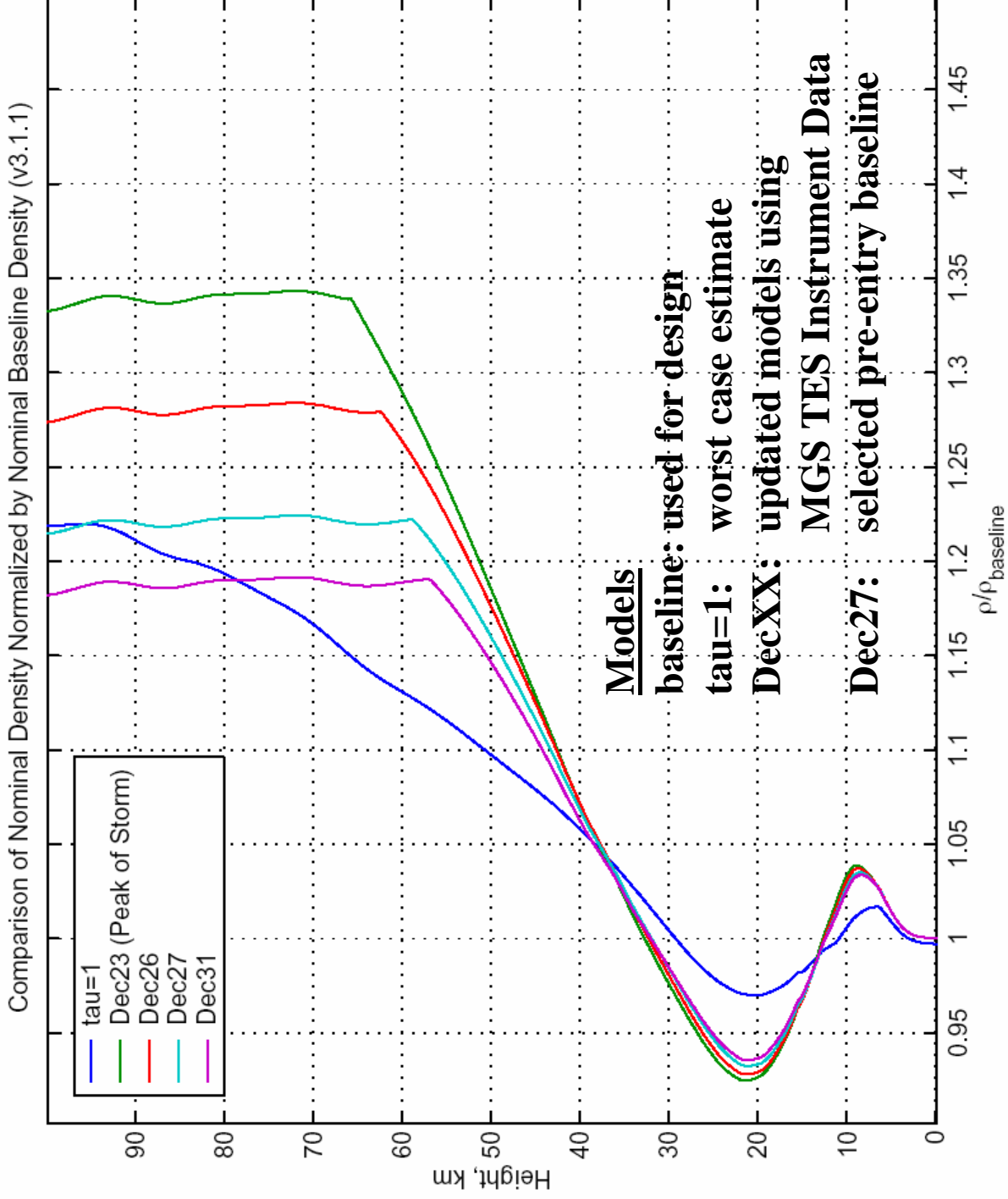
Terminal Descent Sub-Phase

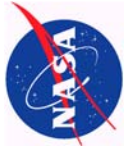




Pre-Entry ‘Spirit’ Entry Atmosphere Models LaRC

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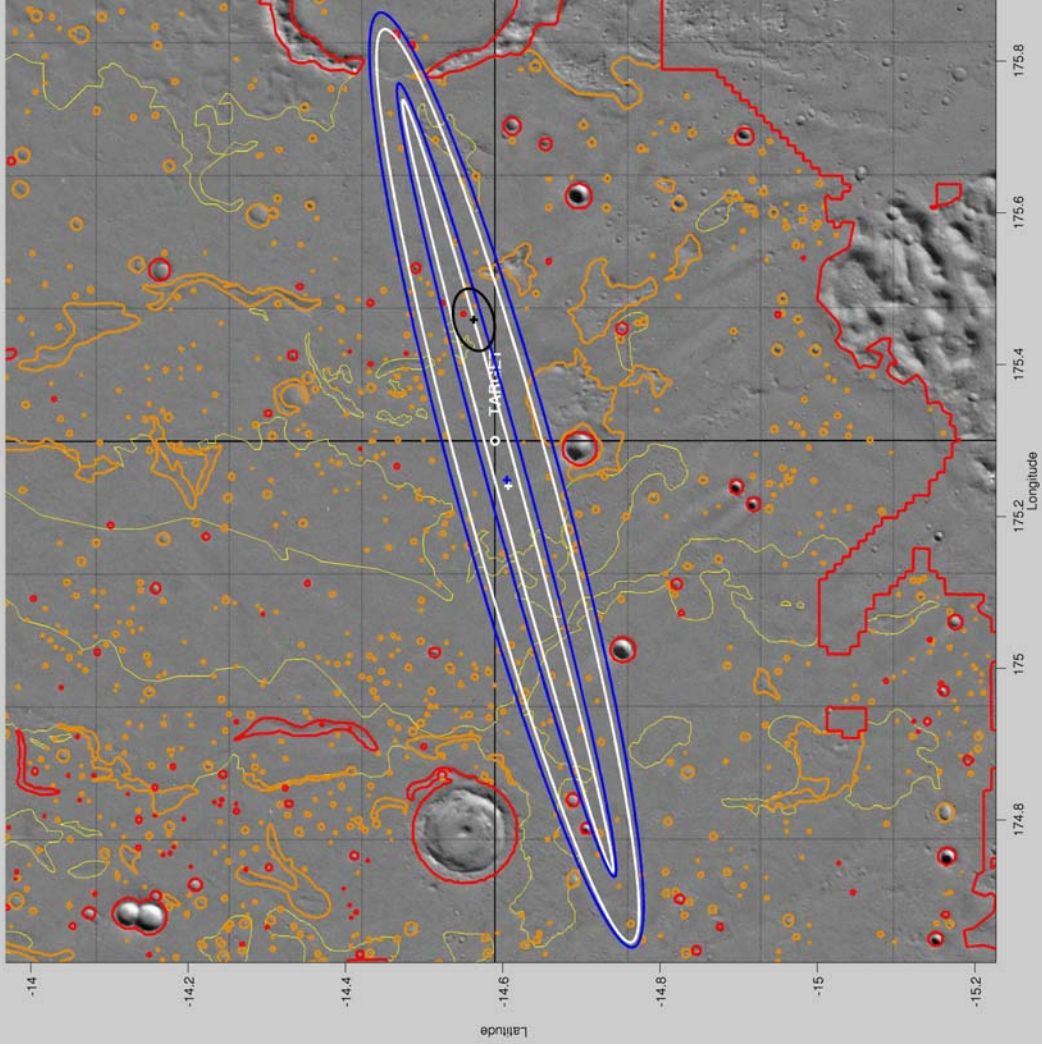




“Spirit” Landing Ellipse at Final OD, & Updated LaRC Estimate Differenced 1-way Doppler

Mars Exploration Rover

MER-A od46 & post-landing NAV Estimate 1/3/04
 Dust 4 KS3.1 Atmosphere, 725 Pa Target Blue: POST White: AEPL
 v031123 Haz, v031119 MOC /nav/home/pck/bin/MARSLS/MAPS/gusev.MOS



Legend (MarsLS v2.1)

Pts: × INFO 99 %
 mc_esf_d_a_od46_1s_cutoff_lat_long_atm
 dec27.dat (margined) CENTER = -14.605
 175.249 [Target Dist = 3.08 km]
 ELLIPSE = 72.9 x 8.0 km at 74.8 deg Az

Pts: × INFO 99 %
 mc_esf_d_a_od46_1s_cutoff_lat_long_atm
 dec27.dat (unmargined) CENTER =
 -14.605 175.249 [Target Dist = 3.08 km]
 ELLIPSE = 61.9 x 3.0 km at 74.8 deg Az

Ellipse: 99 %
 PTS.FINAL2way.esf_d_a_od46.t.ag15ad1
 5D4Wv2e.out (margined)

Ellipse: 99 %
 PTS.FINAL2way.esf_d_a_od46.t.ag15ad1
 5D4Wv2e.out (unmargined)

Ellipse: 99 %
 mc_esf_d_a_od46_1s_cutoff_lat_long_atm
 dec27.dat (margined)

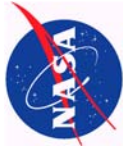
Ellipse: 99 %
 mc_esf_d_a_od46_1s_cutoff_lat_long_atm
 dec27.dat (unmargined)

Ellipse: Prelim NAV Post-Landing Estimate

Grid: 50 km solid, 10 km dotted

Loc: TARGET

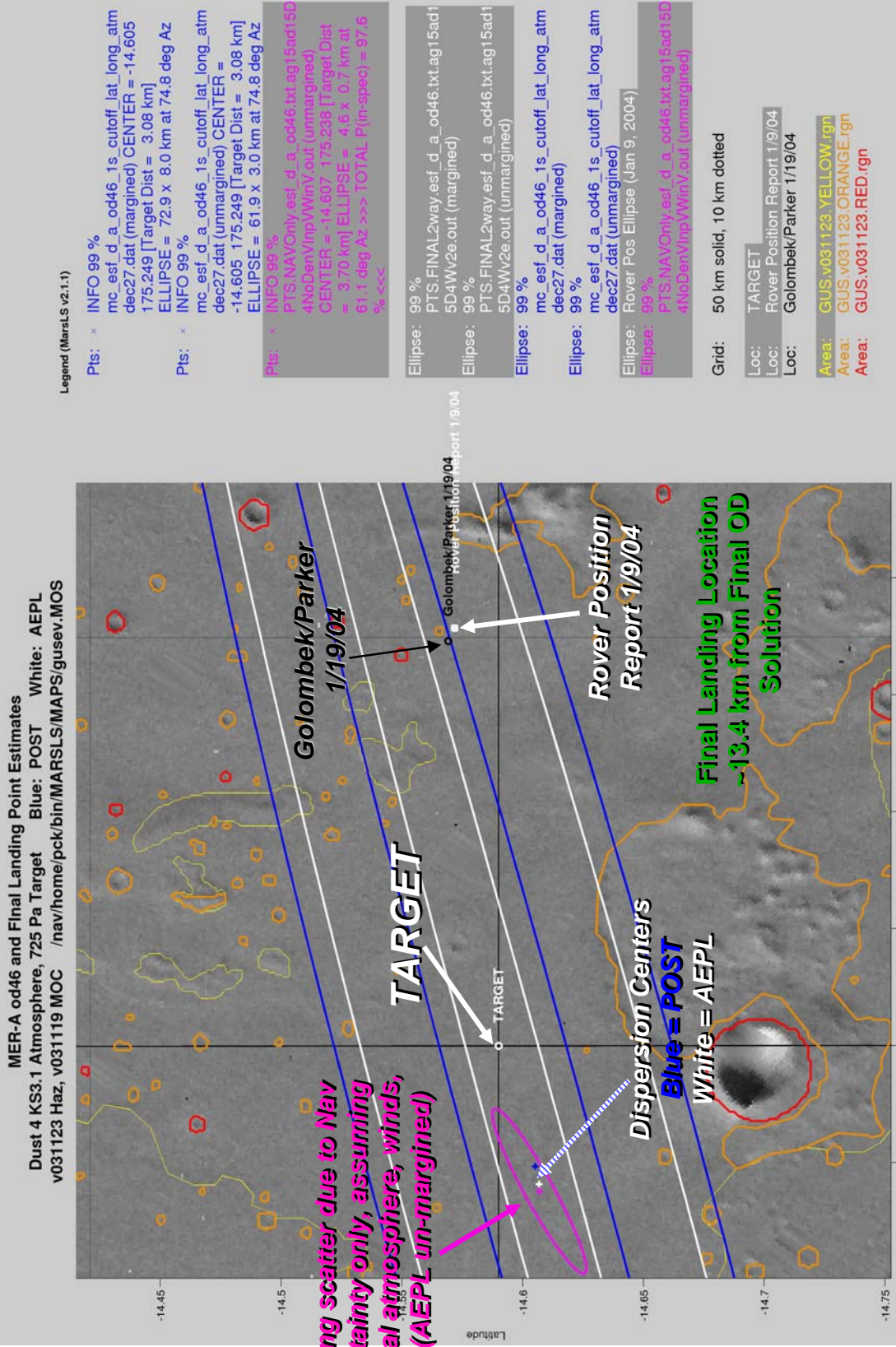
Area: GUS.v031123.YELLOW.rgn
 Area: GUS.v031123.ORANGE.rgn
 Area: GUS.v031123.RED.rgn



“Spirit” Landing Ellipse at Final OD and Final Location Estimates

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Legend (MarsLS v2.1.1)

Pts: × INFO 99 %
 mc_esf_d_a_od46_1s_cutoff_lat_long_atm
 dec27.dat (margined) CENTER = -14.605
 175.249 [Target Dist = 3.08 km]
 ELLIPSE = 72.9 x 8.0 km at 74.8 deg Az

Pts: × INFO 99 %
 mc_esf_d_a_od46_1s_cutoff_lat_long_atm
 dec27.dat (unmargined) CENTER =
 -14.605 175.249 [Target Dist = 3.08 km]
 ELLIPSE = 61.9 x 3.0 km at 74.8 deg Az

Pts: × INFO 99 %
 PTS:NAVOnly_esf_d_a_od46.txt.ag15ad1 5D
 4NobDenVinpVWinV.out (unmargined)
 CENTER = -14.607 175.238 [Target Dist
 = 3.70 km] ELLIPSE = 4.5 x 0.7 km at
 61.1 deg Az >>> TOTAL P(in-spsc) = 97.6
 % <<<<

Ellipse: 99 %
 PTS:FINAL2way_esf_d_a_od46.txt.ag15ad1
 5D4Ww2e.out (margined)

Ellipse: 99 %
 PTS:FINAL2way_esf_d_a_od46.txt.ag15ad1
 5D4Ww2e.out (unmargined)

Ellipse: 99 %
 mc_esf_d_a_od46_1s_cutoff_lat_long_atm
 dec27.dat (margined)

Ellipse: 99 %
 mc_esf_d_a_od46_1s_cutoff_lat_long_atm
 dec27.dat (unmargined)

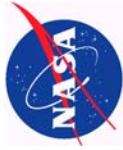
Ellipse: Rover Pos Ellipse (Jan 9, 2004)

Ellipse: 99 %
 PTS:NAVOnly_esf_d_a_od46.txt.ag15ad1 5D
 4NobDenVinpVWinV.out (unmargined)

Grid: 50 km solid, 10 km dotted

Loc: TARGET
 Loc: Rover Position Report 1/9/04
 Loc: Golombek/Parker 1/19/04

Area: GUS.v031123.YELLOW.rgn
 Area: GUS.v031123.ORANGE.rgn
 Area: GUS.v031123.RED.rgn



Monte Carlo Results for “Spirit”

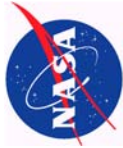
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Mars Exploration Rover

Parameter	Units	6DOF		3DOF		Reconstructed
		Mean	3- σ Range	Mean	3- σ Range	
Hypersonic Flight						
Peak Heating Rate	W/cm ²	39.9	38.1-41.7	45.0 ^b	42.9 ^b -47.1 ^b	
Attitude @ Peak Heat Rate	deg	0.6	0-2.2	\check{S} ^a	\check{S} ^a	1.8
Peak Acceleration	Earth g	5.9	5.5-6.3	5.9	5.5-6.3	5.6
Peak Stag Pressure	N/m ²	9984	9263-10705	9955	9253-10657	
Total Heat Load	J/cm ²	2770	2669-2870	3247 ^b	3136 ^b -3358 ^b	
Parachute Deployment						
Time from Entry	sec	245.6	237.3-253.8	245.5	237.9-253.1	251
Height	km	8.6	6.1-11.1	8.7	6.3-11.1	7.54
Wind-Relative Velocity	m/s	417.7	389.9-445.6	407.0 ^c	377.5 ^c -436.5 ^c	411
Mach Number		1.78	1.71-1.85	1.78	1.71-1.85	
Dynamic Pressure	N/m ²	724.2	654.5-794.0	725.6	654.8-796.3	730
Planet-Relative FPA	deg	-28.2	-30.0- -26.4	-28.1	-29.9- -26.3	
Attitude	deg	1.1	0-4.9	\check{S} ^a	\check{S} ^a	7
Heatshield Jettison						
Time from Entry	sec	265.6	257.3-273.8	265.5	257.9-273.1	271
Height	km	6.4	3.9-8.9	6.4	4.0-8.8	
Wind-Relative Velocity	m/s	112.2	94.1-130.3	108.9 ^c	88.7 ^c -129.1 ^c	
Planet-Relative FPA	deg	-49.6	-55.6- -43.6	-49.6	-55.7- -43.5	
Dynamic Pressure	N/m ²	60.8	45.2-76.4	\check{S} ^a	\check{S} ^a	
Mach number		0.47	0.4-0.54	0.47	0.4-0.53	

^aComputed in 6DOF only, ^bDifferent calculation method used, ^cPlanet-relative velocity listed,

^dResults obtained from 24DOF multi-body POST simulation.



Monte Carlo Results for “Spirit” (cont’d) LaRC

Mars Exploration Rover

Parameter	Units	6DOF		3DOF		Reconstructed
		Mean	3- σ Range	Mean	3- σ Range	
Lander Descent Initiation						
Time from Entry	sec	275.6	267.3-283.8	275.5	267.9-283.1	281
Height	km	5.6	3.1-8.1	5.6	3.2-8.1	
Wind-Relative Velocity	m/s	90.6	77.4-103.9	90.5 ^c	75.1 ^c -105.8 ^c	
Planet-Relative FPA	deg	-62.0	-70.4- -53.6	-62.1	-70.7- -53.5	
Dynamic Pressure	N/m ²	41.8	31.8-51.8	Š ^a	Š ^a	
Sensed Acceleration	Earth g	0.43	0.39-0.46	0.43	0.39-0.46	
RAD Initiation						
Time from Entry	sec	345.8	316.2-375.3	346.7	317.3-376.2	339.4
Time from Chute Deploy	sec	100.2	64.4-136.0	101.3	65.3-137.2	88.4
Height	m	123.1	91.3-154.7	118.4	87.1-149.6	99.4
Wind-Relative Velocity	m/s	73.1	61.6-84.5	73.0 ^c	61.8 ^c -84.2 ^c	69.2
Planet-Relative FPA	deg	-83.9	-89.9- -76.3	-84.1	-89.6- -77.4	
Mach number	0.29	0.24-0.34	0.29	0.24-0.33		
Bridle Cut						
Time from Entry	sec	348.2 ^d	319.7 ^d -376.3 ^d	349.7	320.6-378.7	
Height	m	12.4^d	4.2^d-20.1^d	13.6	11.1-16.1	8.5
Wind-Relative Velocity	m/s	9.8 ^d	0.2 ^d -25.3 ^d	9.3 ^c	0.3 ^c -20.4 ^c	11.8
Landing						
Time from Entry	sec	350.5 ^d	321.0 ^d -379.5 ^d	352.3	322.9-381.5	
Wind-Relative Velocity	m/s	13.9 ^d	7.2 ^d -25.0 ^d	13.9 ^c	6.7 ^c -21.2 ^c	14.0

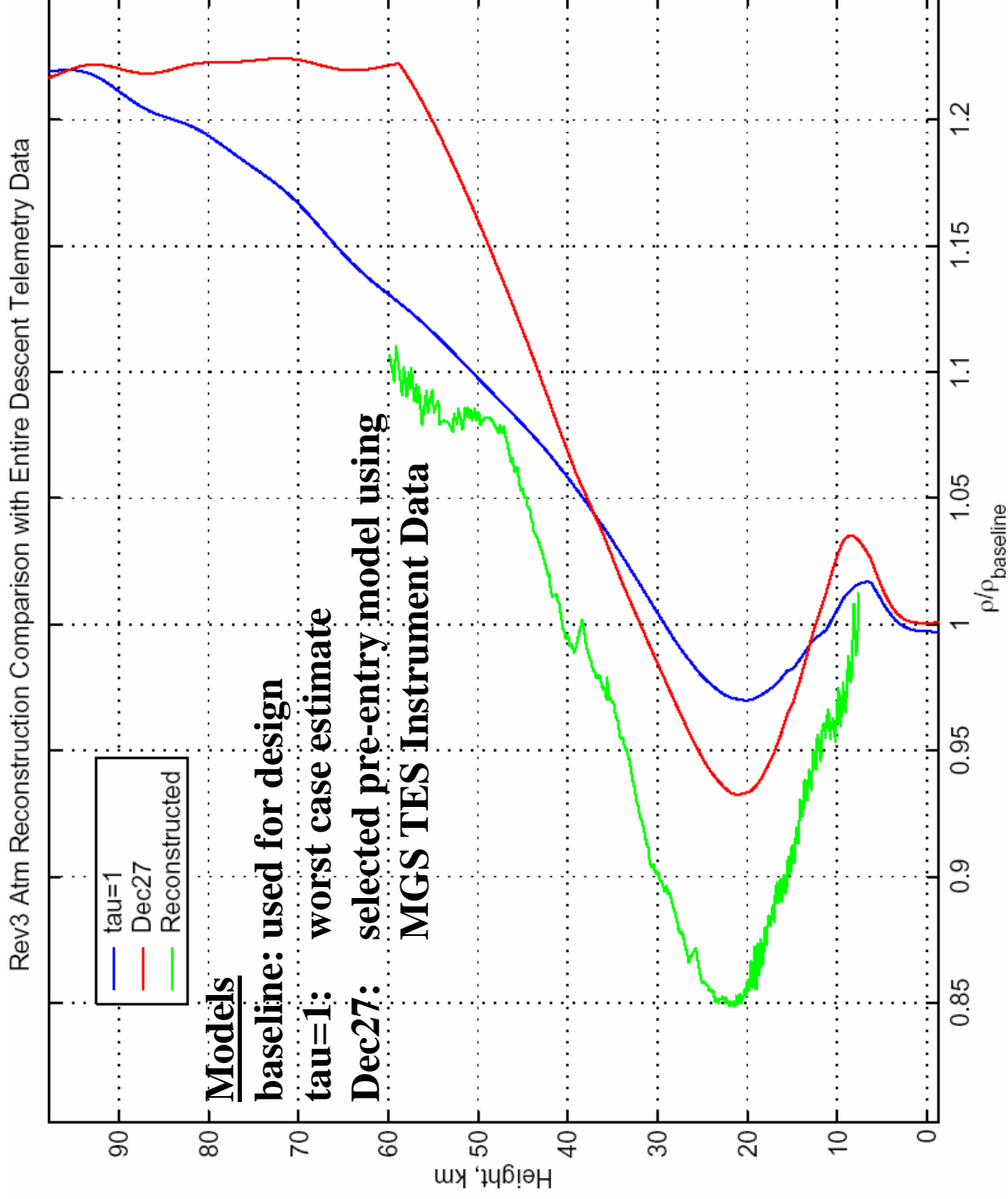
^aComputed in 6DOF only, ^bDifferent calculation method used, ^cPlanet-relative velocity listed,

^dResults obtained from 24DOF multi-body POST simulation.



Reconstructed ‘Spirit’ Entry Density Profile LaRC

Mars Exploration Rover

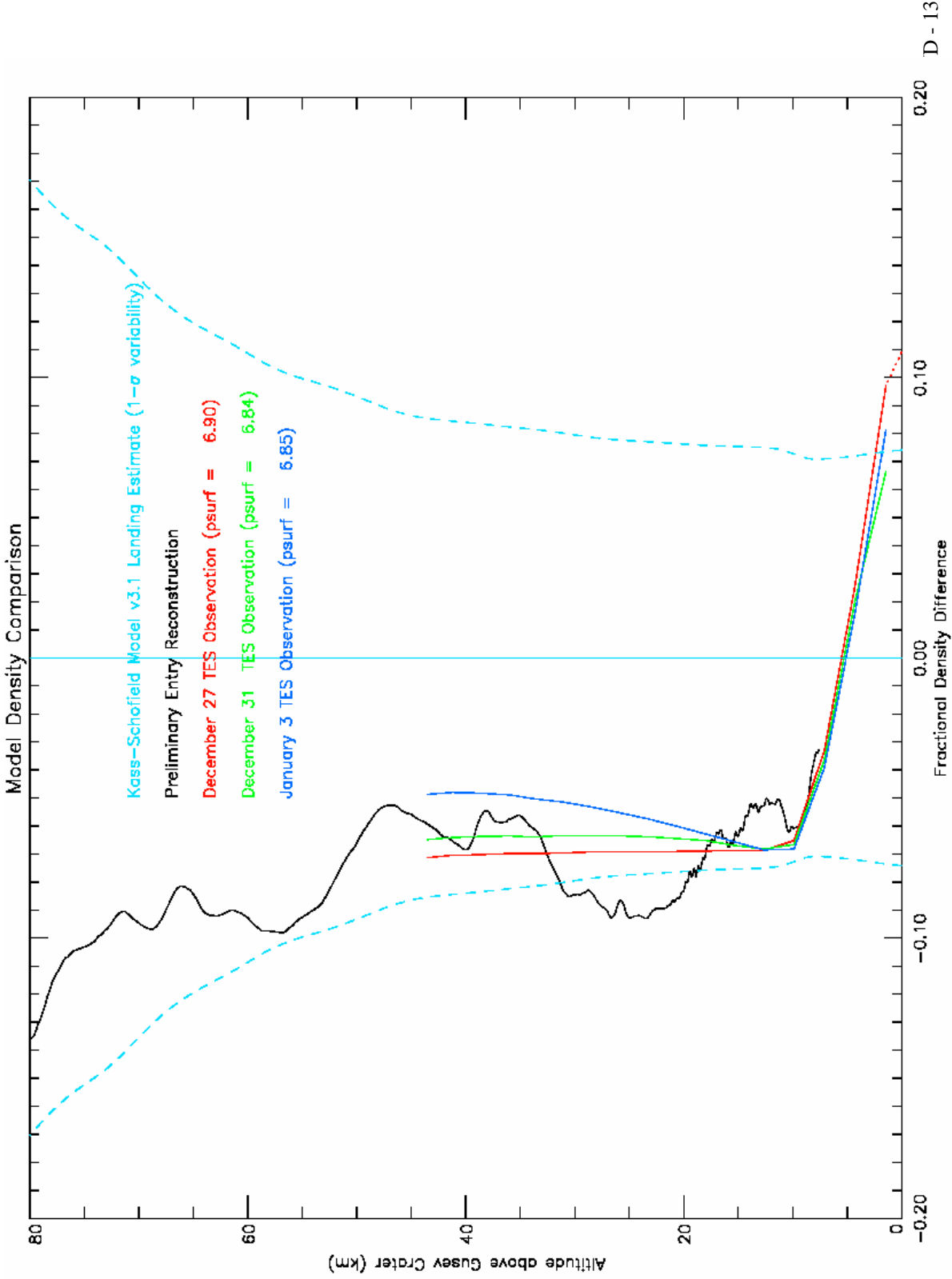


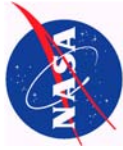


Refined Reconstructed “Spirit” Entry Density Profile

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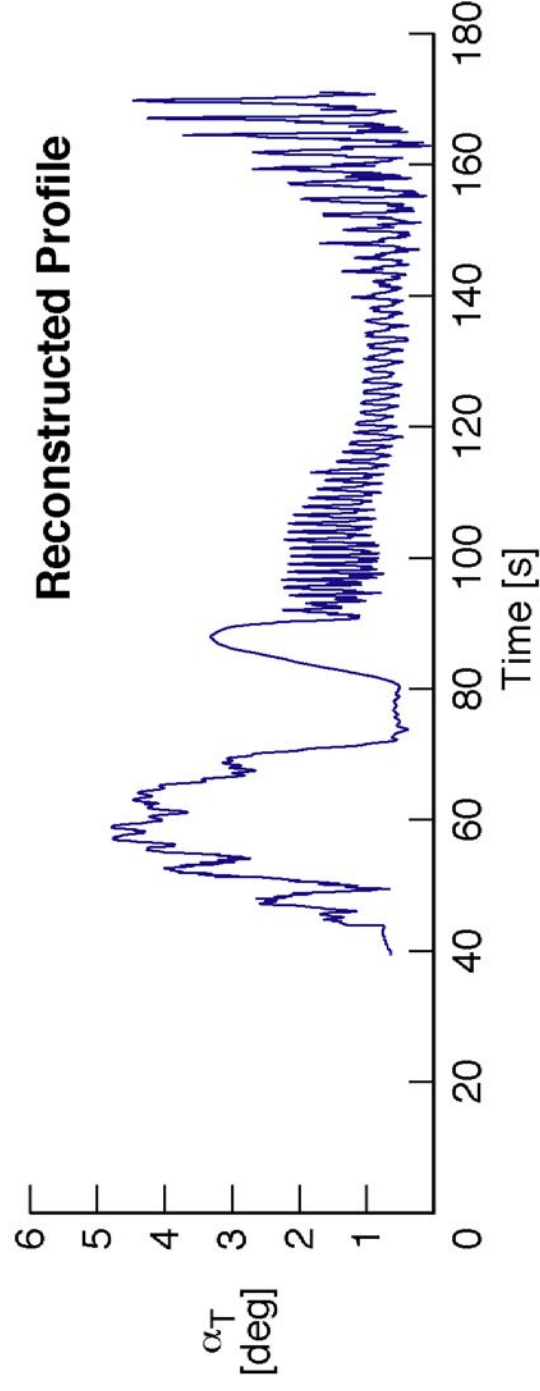
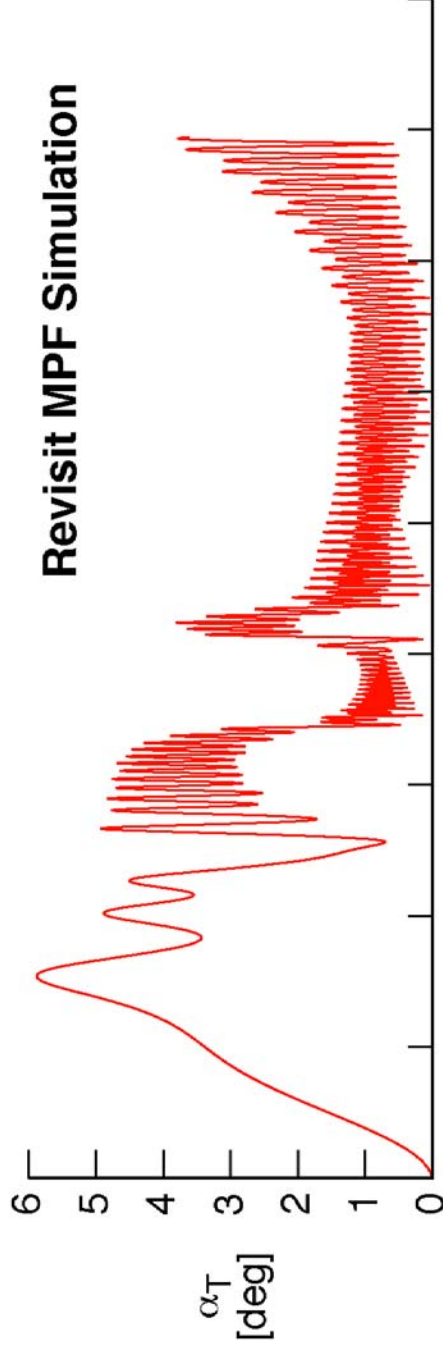
Mars Exploration Rover





Mars Pathfinder Attitude Reconstruction LaRC

Mars Exploration Rover



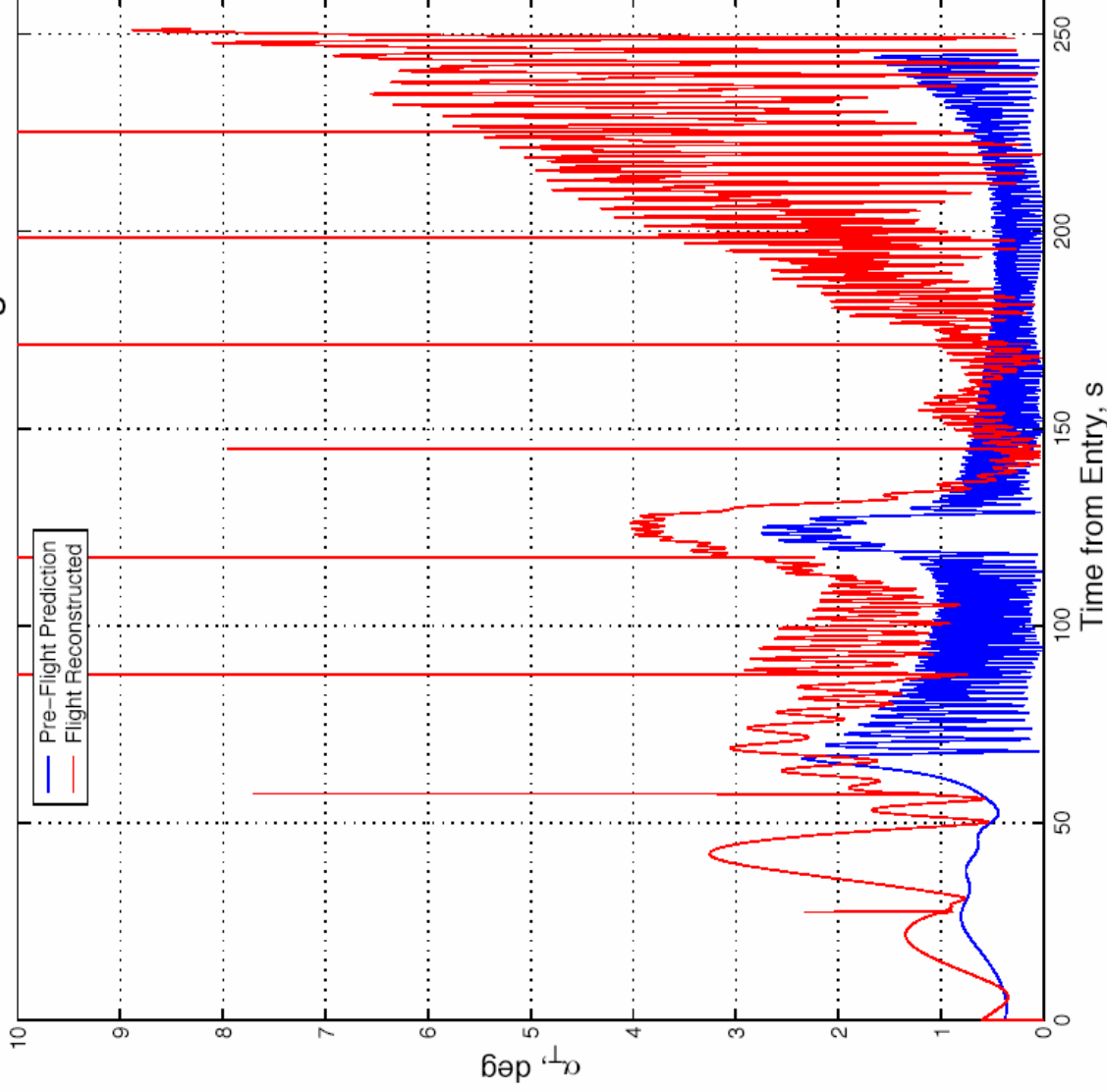


“Spirit” Attitude Reconstruction

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Mars Exploration Rover

MER-A Reconstructed Attitude using Quaternions



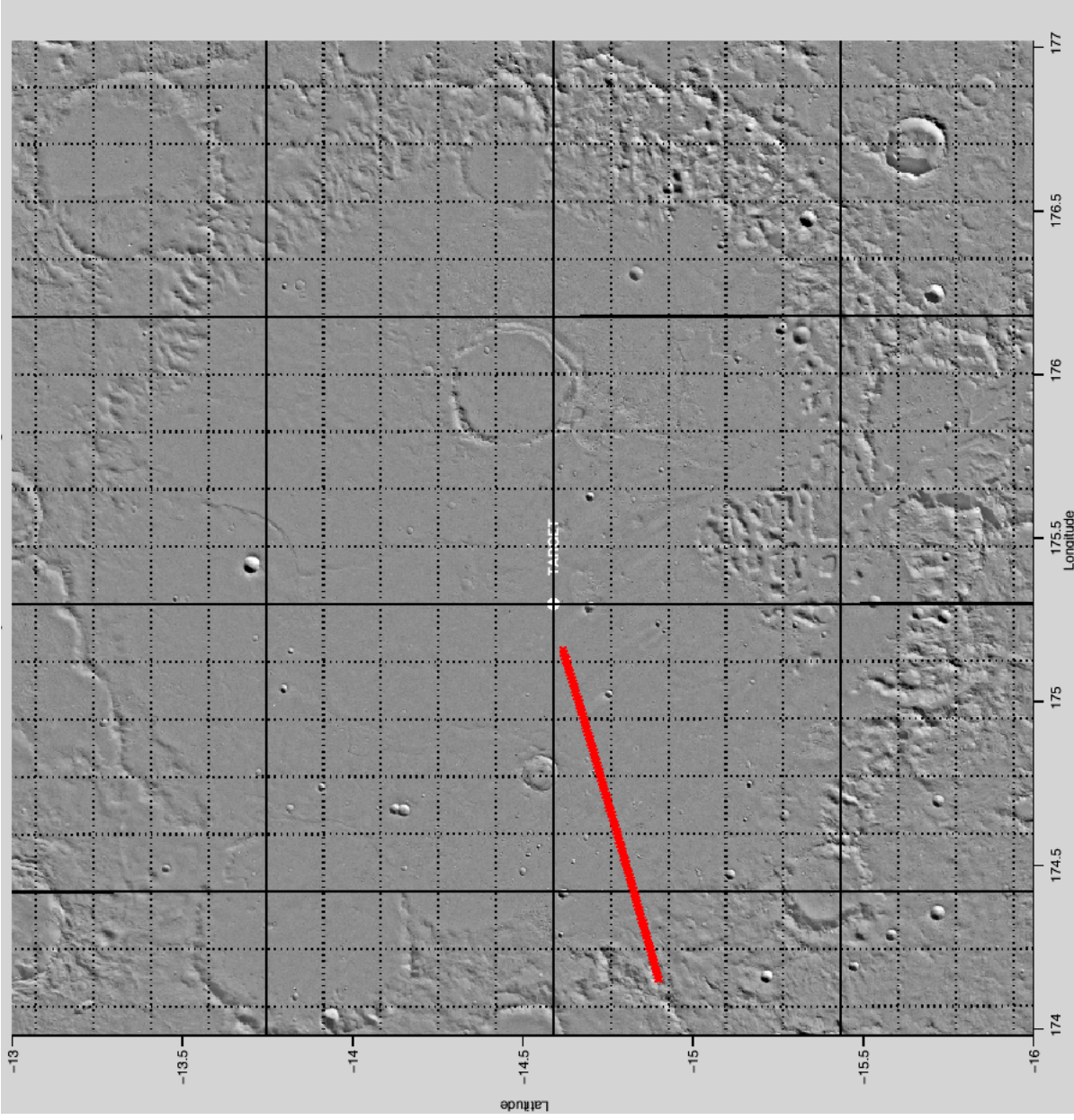
Attitude Growth at ~170s (Mach 6) theorized due to atmosphere turbulence arising from Spirit flying over western rim of Gusev Crater (next slide)



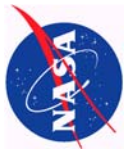
“Spirit” Entry Ground Track

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Mars Exploration Rover



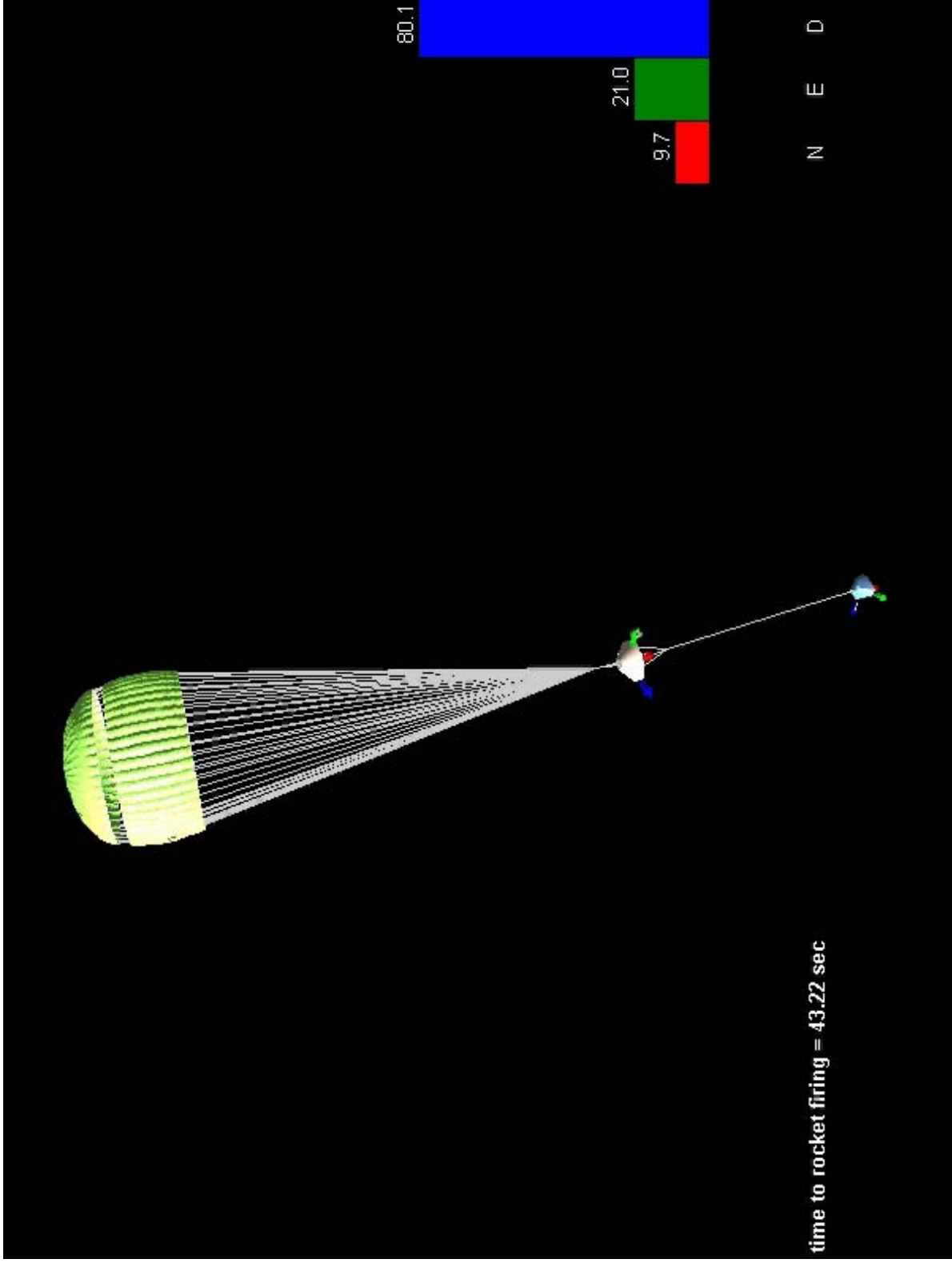
Spirit flight path plotted over western rim of Gusev Crater. Displaying portion of trajectory where attitude growth begins (time of 170s - 250s)

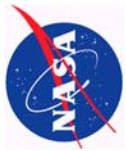


Reconstructed “Spirit” Terminal Descent Dynamics (Side View)

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Mars Exploration Rover

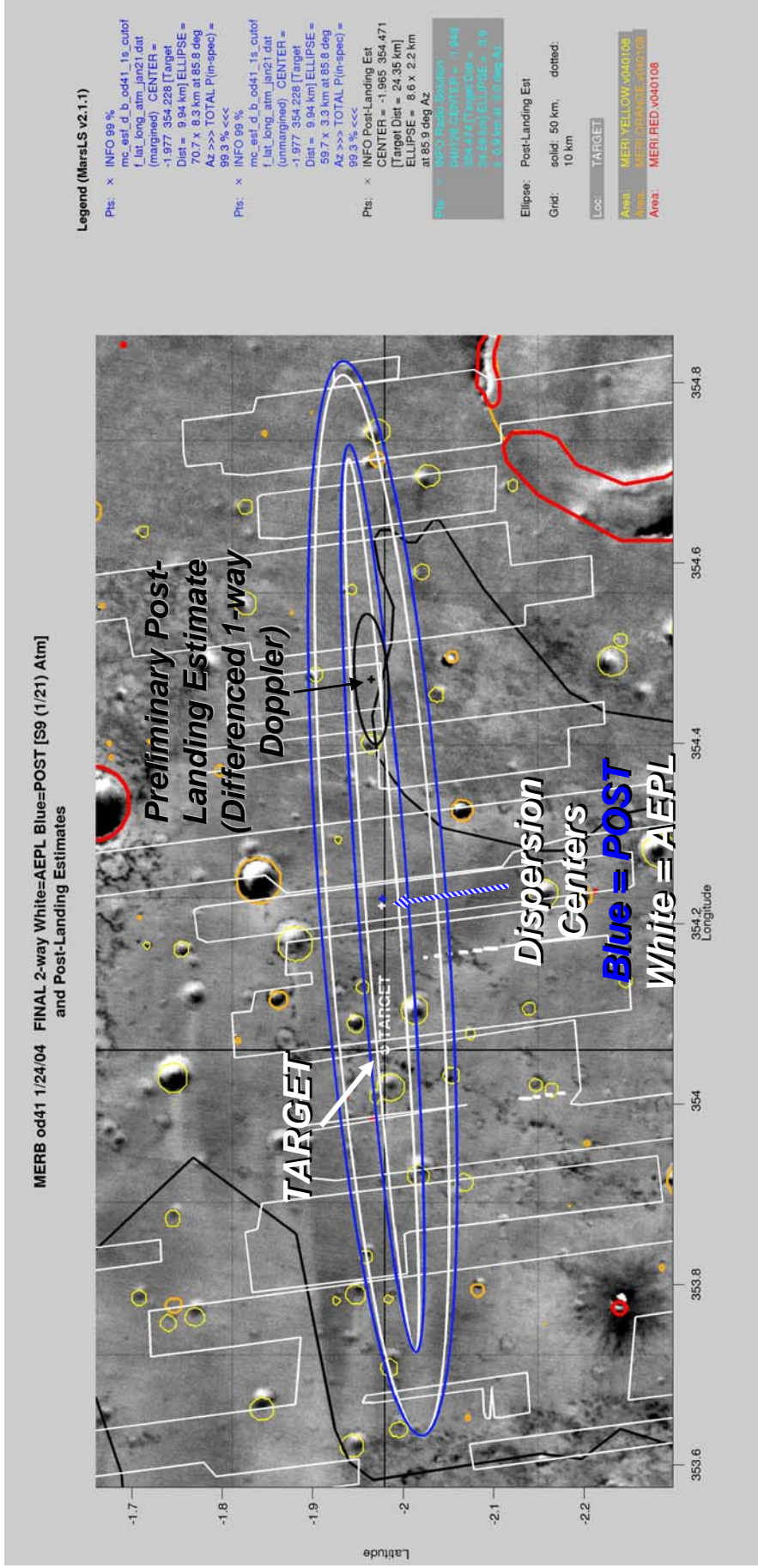




“Opportunity” Landing Ellipse at Final OD, & Updated Estimate Differenced 1-way Doppler

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Mars Exploration Rover

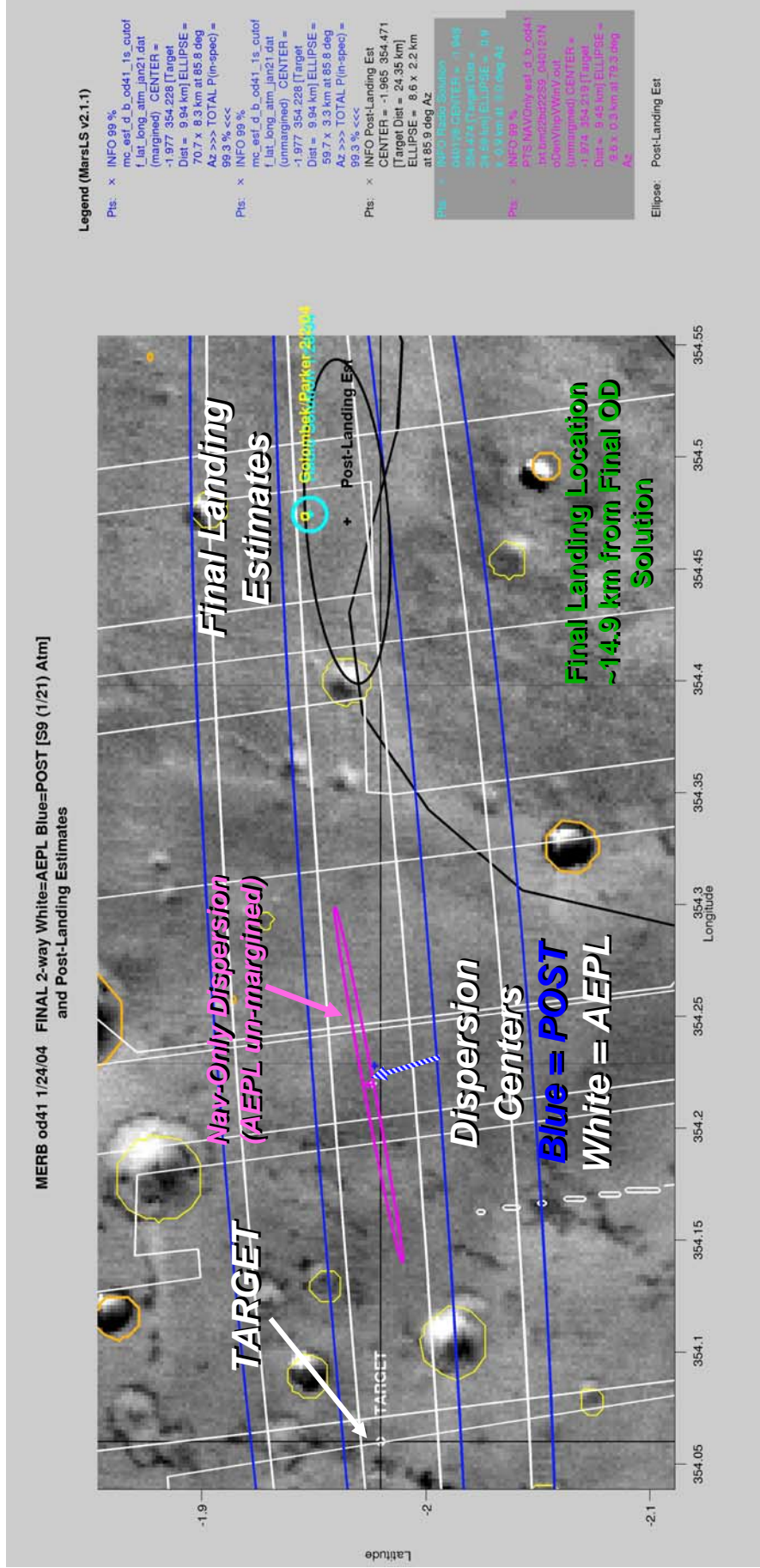




“Spirit” Landing Ellipse at Final OD and Final Location Estimates

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Mars Exploration Rover





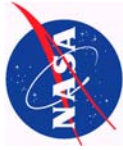
Monte Carlo Results for “Opportunity” LaRC

Mars Exploration Rover

Parameter	Units	6DOF		3DOF		Reconstructed
		Mean	3- σ Range	Mean	3- σ Range	
Hypersonic Flight						
Peak Heating Rate	W/cm ²	42.2	39.3-45.2	47.9 ^b	44.6 ^b -51.1 ^b	
Attitude @ Peak HeatRate	deg	0.6	0-2.1	\check{S} ^a	\check{S} ^a	2.1
Peak Acceleration	Earth g	6.4	5.9-7.0	6.4	5.9-7.0	6.3
Peak Stag Pressure	N/m ²	10835	9868-11803	10812	9863-11760	
Total Heat Load	J/cm ²	2711	2595-2826	3190 ^b	3064 ^b -3317 ^b	
Parachute Deployment						
Time from Entry	sec	242.1	234.5-249.7	242.1	235.2-249.0	250.3
Height	km	8.7	6.4-11.0	8.8	6.6-11.0	7.52
Wind-Relative Velocity	m/s	438.0	411.8-464.2	425.3 ^c	395.4 ^c -455.2 ^c	434
Mach Number		1.86	1.78-1.94	1.86	1.79-1.94	
Dynamic Pressure	N/m ²	747.0	674.7-819.3	749.1	676.3-821.9	764
Planet-Relative FPA	deg	-26.8	-28.4- -25.1	-26.7	-28.3- -25.2	
Attitude	deg	1.0	0-4.4	\check{S} ^a	\check{S} ^a	8
Heatshield Jettison						
Time from Entry	sec	262.2	254.6-269.8	262.1	255.2-269.0	270.3
Height	km	6.5	4.2-8.8	6.5	4.3-8.8	
Wind-Relative Velocity	m/s	116.9	99.3-134.5	113.1 ^c	94.1 ^c -132.1 ^c	
Planet-Relative FPA	deg	-47.6	-53.0- -42.2	-47.6	-53.3- -42.0	
Dynamic Pressure	N/m ²	63.5	47.1-80.0	\check{S} ^a	\check{S} ^a	
Mach number	0.49	0.42-0.56	0.49	0.42-0.56		

^aComputed in 6DOF only, ^bDifferent calculation method used, ^cPlanet-relative velocity listed,

^dResults obtained from 24DOF multi-body POST simulation.



Monte Carlo Results for “Opportunity” (cont’d) LaRC

Mars Exploration Rover

Parameter	Units	6DOF		3DOF		Reconstructed
		Mean	3- σ Range	Mean	3- σ Range	
Lander Descent Initiation						
Time from Entry	sec	272.1	264.6-279.8	272.1	265.2-281.8	280.3
Height	km	5.7	3.3-8.0	5.7	3.5-8.2	
Wind-Relative Velocity	m/s	91.0	81.0-106.9	92.1 ^c	78.6 ^c -113.9 ^c	
Planet-Relative FPA	deg	-60.6	-67.5- -53.8	-60.7	-67.8- -53.6	
Dynamic Pressure	N/m ²	43.6	33.0-54.3	\bar{S} ^a	\bar{S} ^a	
Sensed Acceleration	Earth g	0.44	0.40-0.49	0.44	0.40-0.48	
RAD Initiation						
Time from Entry	sec	343.7	315.9-371.5	344.7	317.1-372.2	336.3
Time from Chute Deploy	sec	101.5	68.2-134.8	102.5	69.1-136.0	86
Height	m	123.1	91.3-154.7	118.5	85.4-151.7	127.1
Wind-Relative Velocity	m/s	72.7	61.4-84.1	72.7 ^c	61.1 ^c -84.4 ^c	71.1
Planet-Relative FPA	deg	-86.8	-89.9- -80.9	-86.8	-89.9- -80.7	
Mach number		0.29	0.25-0.33	0.29	0.24-0.33	
Bridle Cut						
Time from Entry	sec	347.9 ^d	318.6 ^d -377.2 ^d	347.6	320.4-374.8	
Height	m	13.1^d	4.5^d -21.7^d	13.4	11.4-15.4	6.9
Wind-Relative Velocity	m/s	9.6 ^d	0.7 ^d -23.6 ^d	7.1 ^c	0.6 ^c -18.5 ^c	9.3
Landing						
Time from Entry	sec	348.6 ^d	320.3 ^d -376.9 ^d	350.1	322.8-383.3	
Wind-Relative Velocity	m/s	13.8 ^d	6.9 ^d -23.5 ^d	12.6 ^c	5.7 ^c -19.5 ^c	

^aComputed in 6DOF only, ^bDifferent calculation method used, ^cPlanet-relative velocity listed,

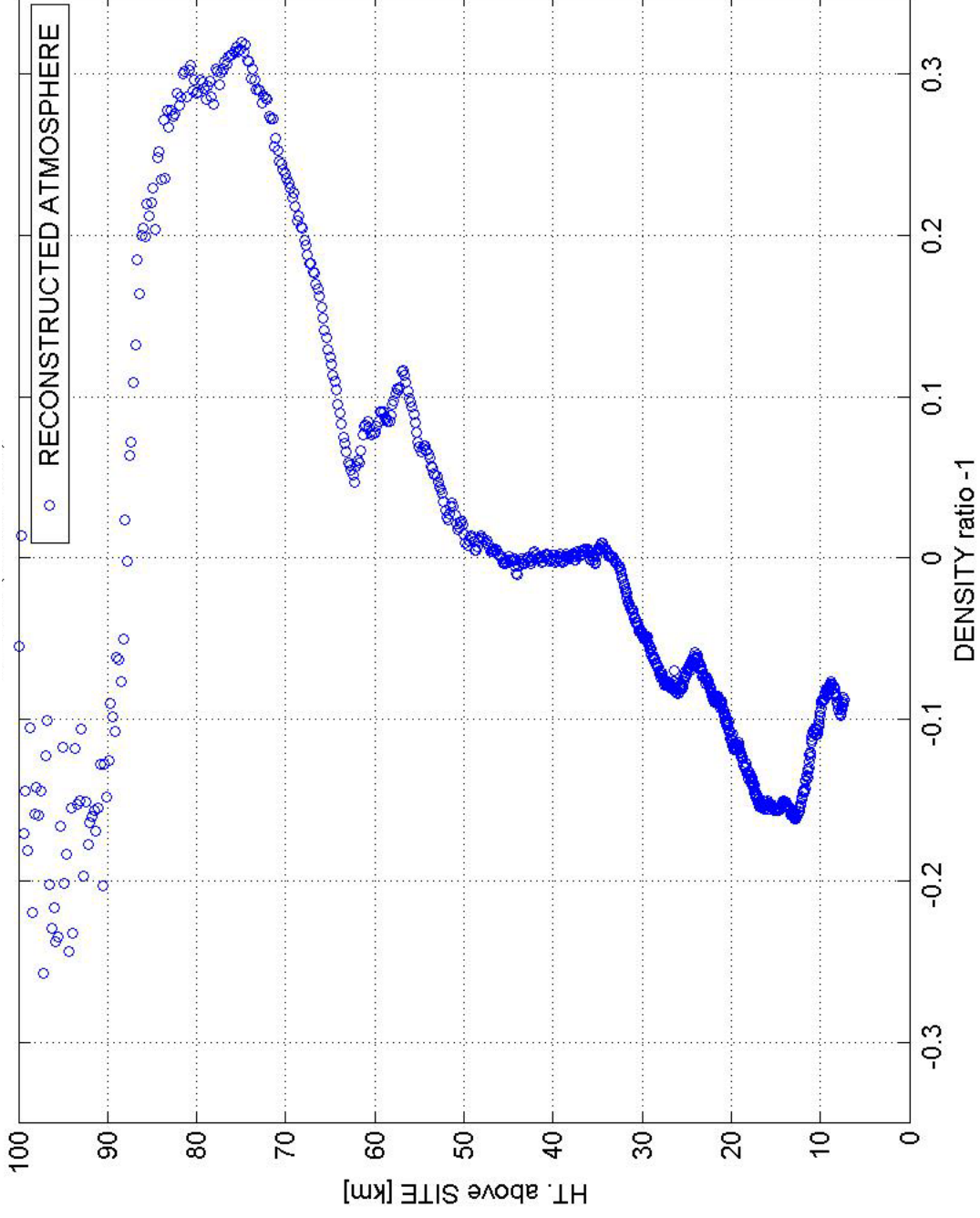
^dResults obtained from 24DOF multi-body POST simulation.



Reconstructed “Opportunity”’ Entry Density Profile

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Mars Exploration Rover

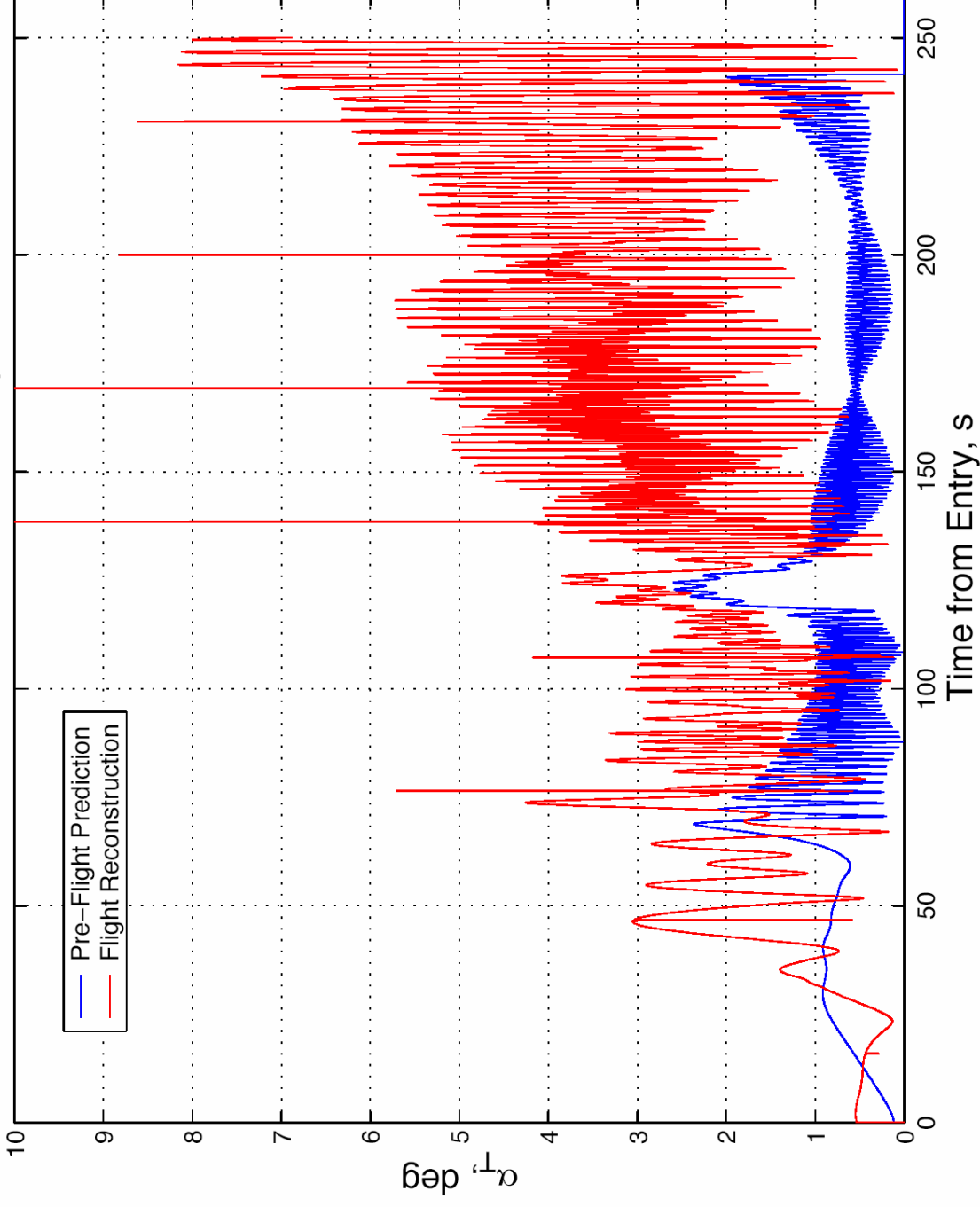




“Opportunity” Attitude Reconstruction LaRC

Mars Exploration Rover

MER-B Reconstructed Attitude using Quaternions



Attitude Growth starts earlier ~130s (Mach 16) than for Spirit. Behavior still not understood. Analysis is ongoing.



Summary

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Mars Exploration Rover

- “Spirit” EDL went very well
- “Opportunity” EDL went very well also
- Preliminary reconstruction indicates EDL for both entries were within pre-entry predictions
- Time of parachute deployment was later than predicted near $+3\text{-}\sigma$ bound
 - Late deployment time was a result of a lower density experienced during EDL
- No clear explanation as of yet for higher angle of attack
- Reconstruction work on-going