MER EDL: Overview and Reconstruction Status

Prasun N. Desai
NASA Langley Research Center

Wayne J. Lee
Jet Propulsion Laboratory

August 23, 2004

Background

LaRC

Mars Exploration Rover

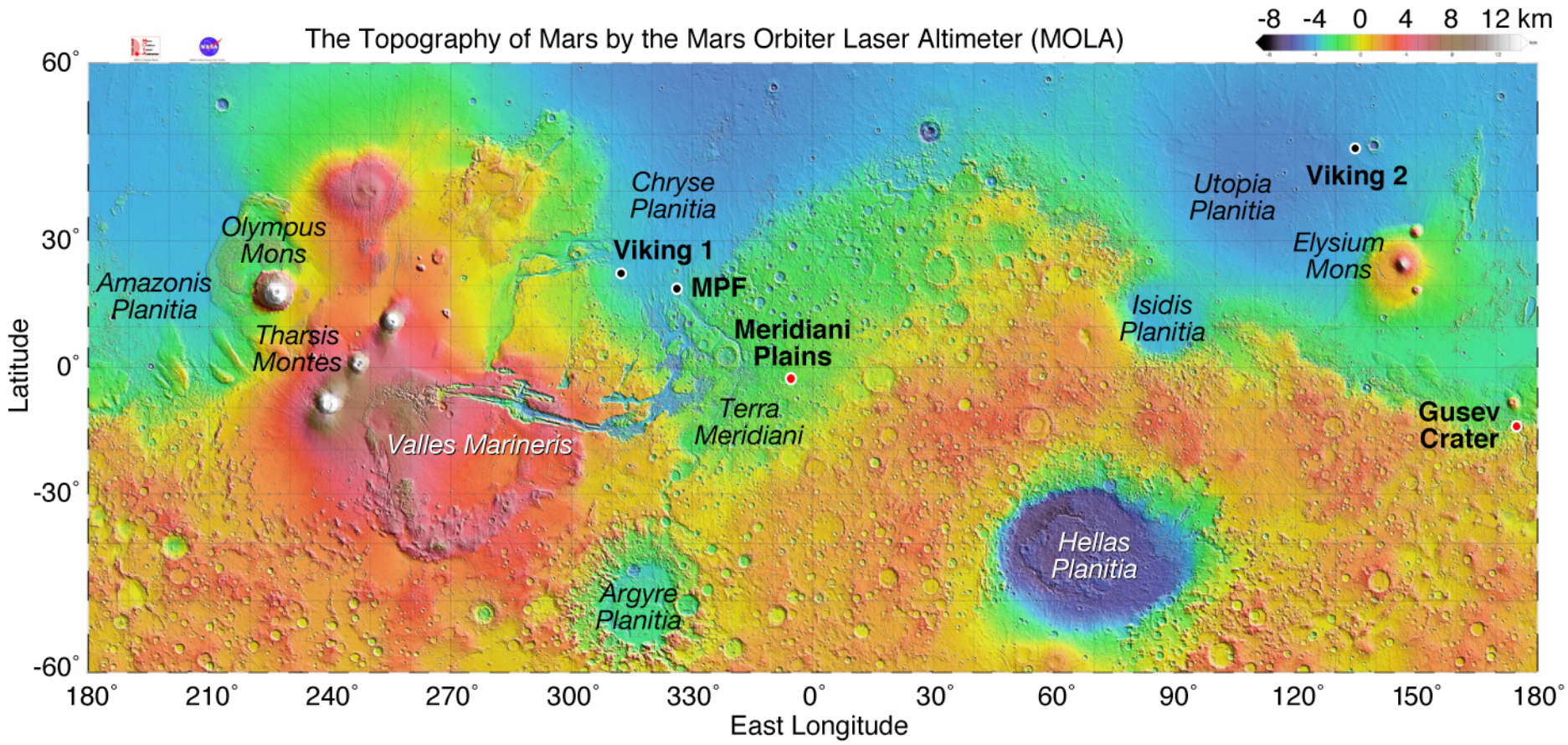
- "Spirit" and "Opportunity" landed successfully on January 4th and 25th of 2004 at two scientifically distinct sites
- Delivered to the surface using the Mars Pathfinder (MPF) Entry, Descent and Landing (EDL) system
- 5 instruments to conduct remote and in-situ observations
- Operational life ≥ 90 sols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

MER Candidate Landing Sites

LaRC

Mars Exploration Rover

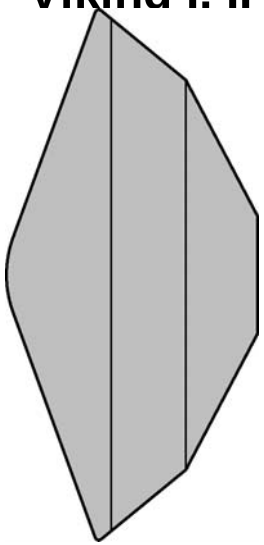
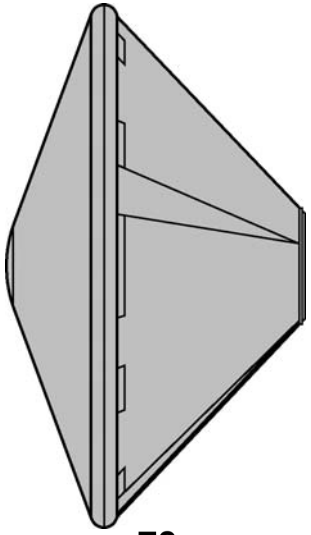
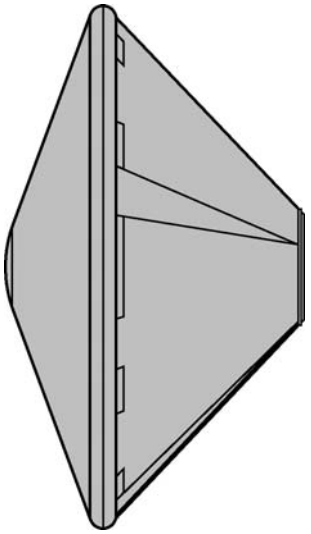
Landing sites will be equatorial (15° N to 15° S)



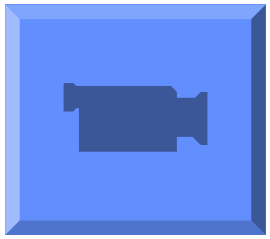
MER Entry Heritage w/Viking & Mars Pathfinder

LaRC

Mars Exploration Rover

	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
$m/(C_DA)$, 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

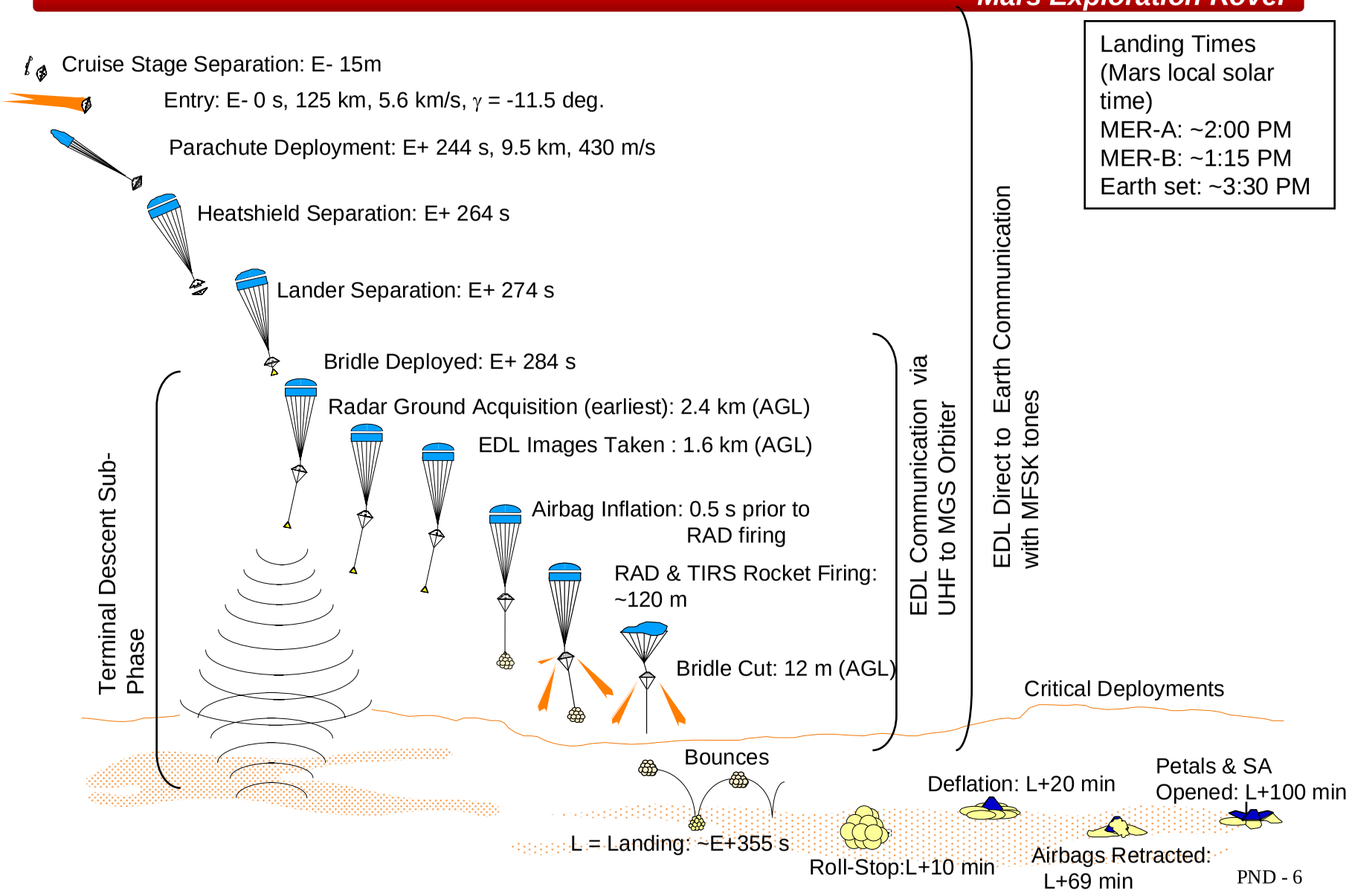
MER EDL Animation



MER Entry, Descent, and Landing (EDL) Sequence

LaRC

Mars Exploration Rover

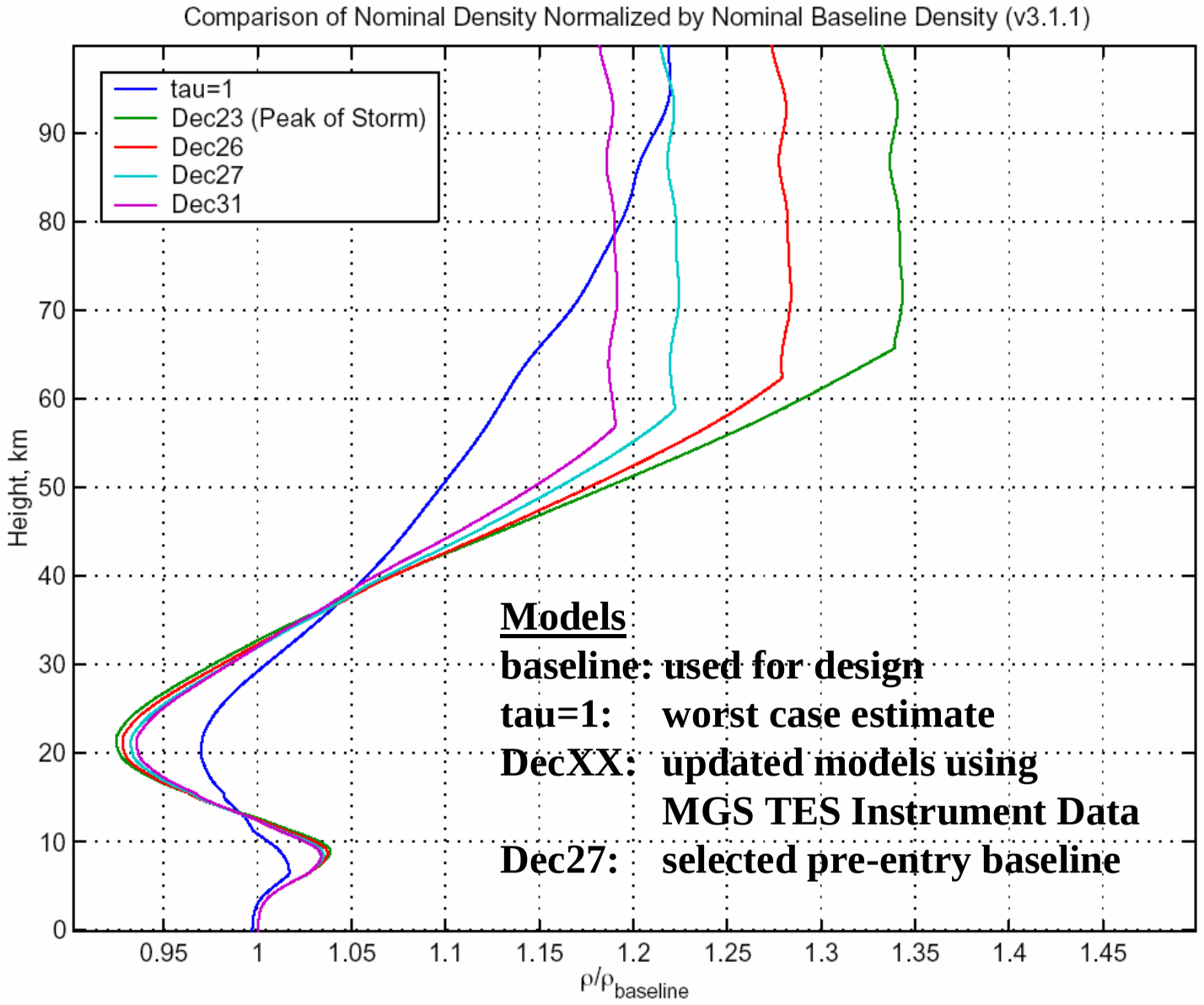


Landing Times (Mars local solar time)
MER-A: ~2:00 PM
MER-B: ~1:15 PM
Earth set: ~3:30 PM

Pre-Entry "Spirit" Entry Atmosphere Models

LaRC

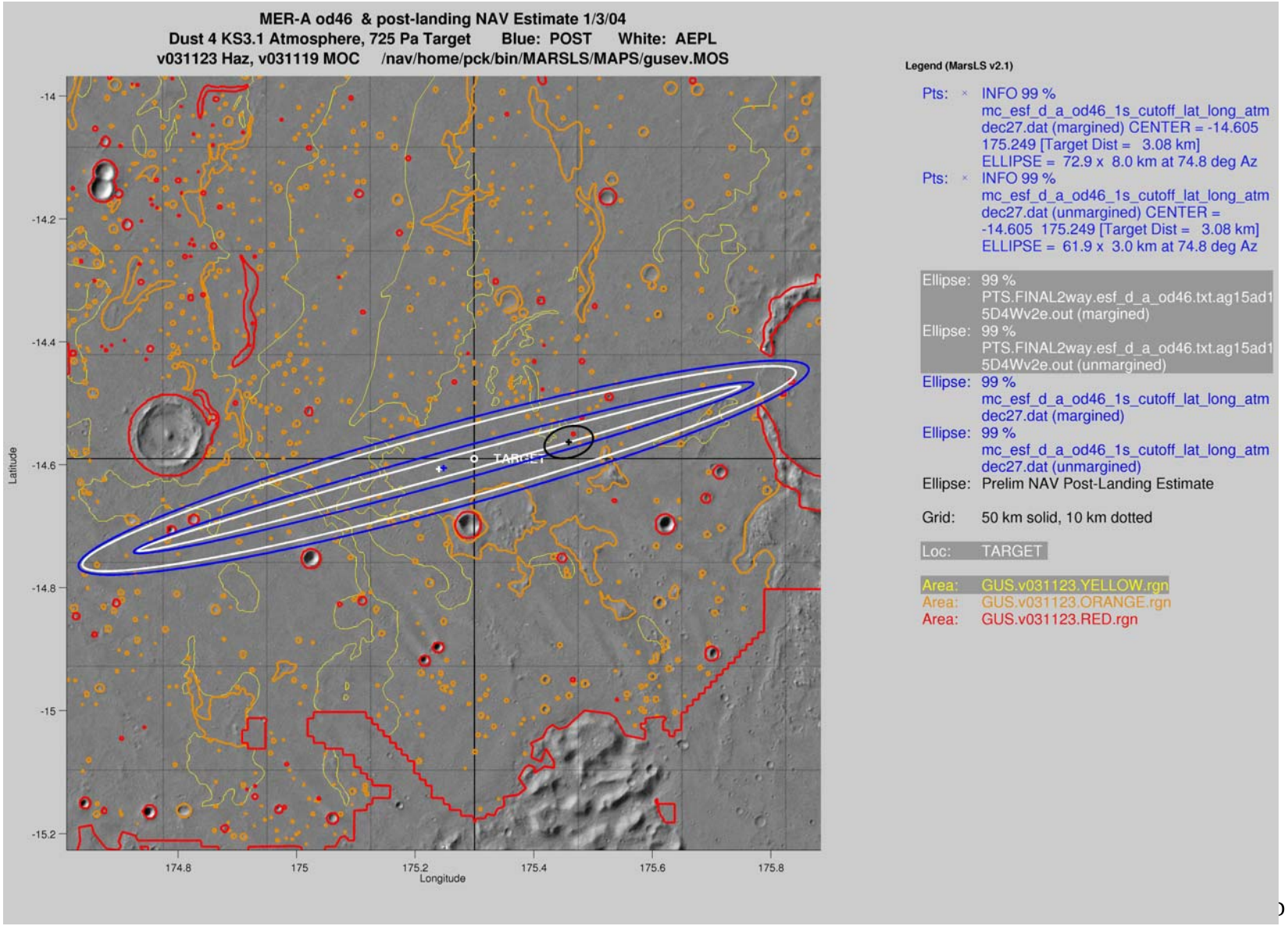
Mars Exploration Rover



"Spirit" Landing Ellipse at Final OD, &Updated Estimate Differenced 1-way Doppler

LaRC

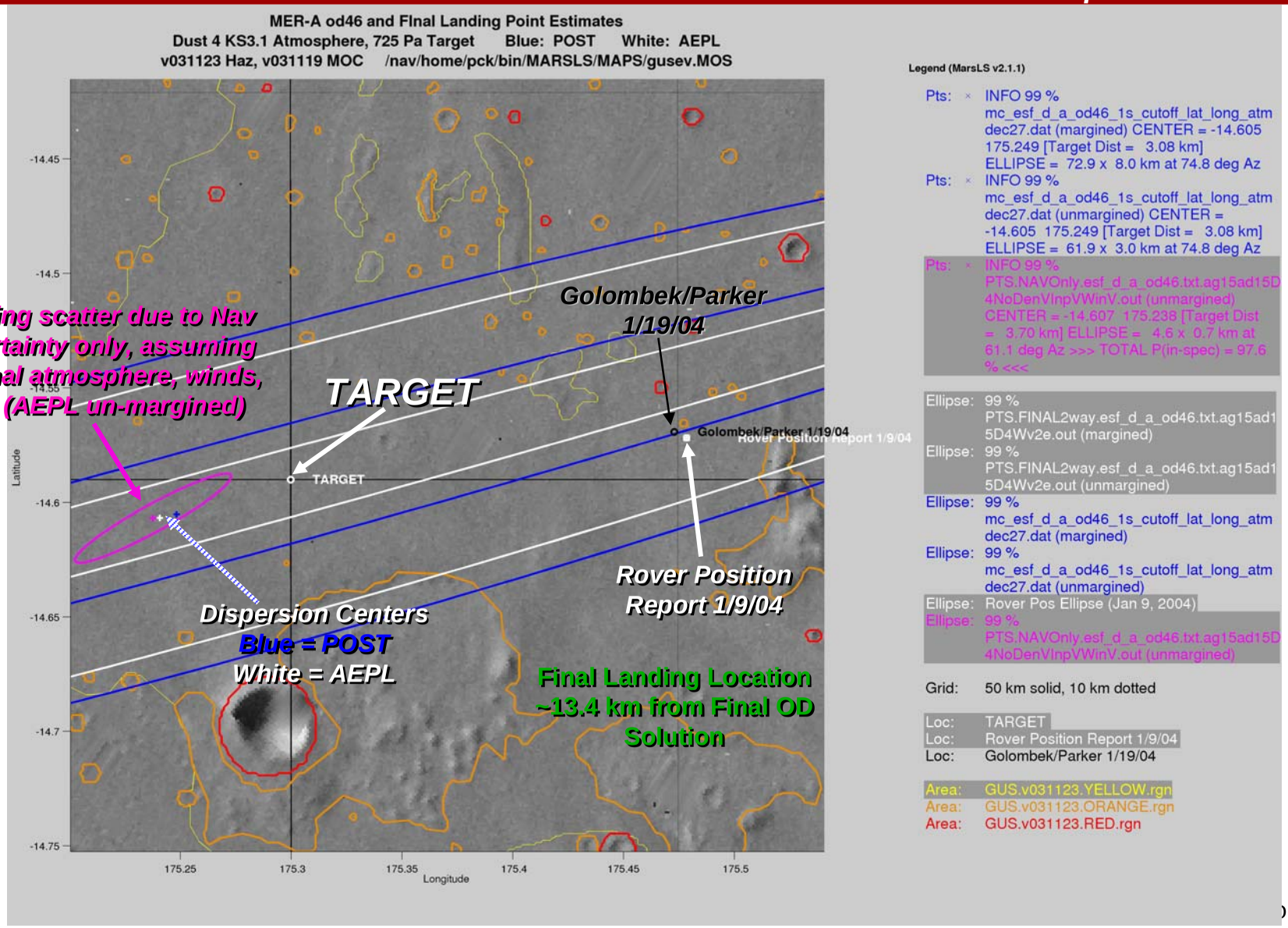
Mars Exploration Rover



"Spirit" Landing Ellipse at Final OD and Final Location Estimates

LaRC

Mars Exploration Rover



Monte Carlo Results for "Spirit"

LaRC

Mars Exploration Rover

Parameter	Units	6DOF Mean	6DOF 3-σ Range	3DOF Mean	3DOF 3-σ Range	Reconstructed
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	Š[a]	Š[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**	**Š[a]**	**Š[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	Š[a]	Š[a]	
Mach number		0.47	0.4-0.54	0.47	0.4-0.53	

[a]Computed in 6DOF only, [b]Different calculation method used, [c]Planet-relative velocity listed,
[d]Results obtained from 24DOF multi-body POST simulation.

Monte Carlo Results for "Spirit" (cont'd)

LaRC

Mars Exploration Rover

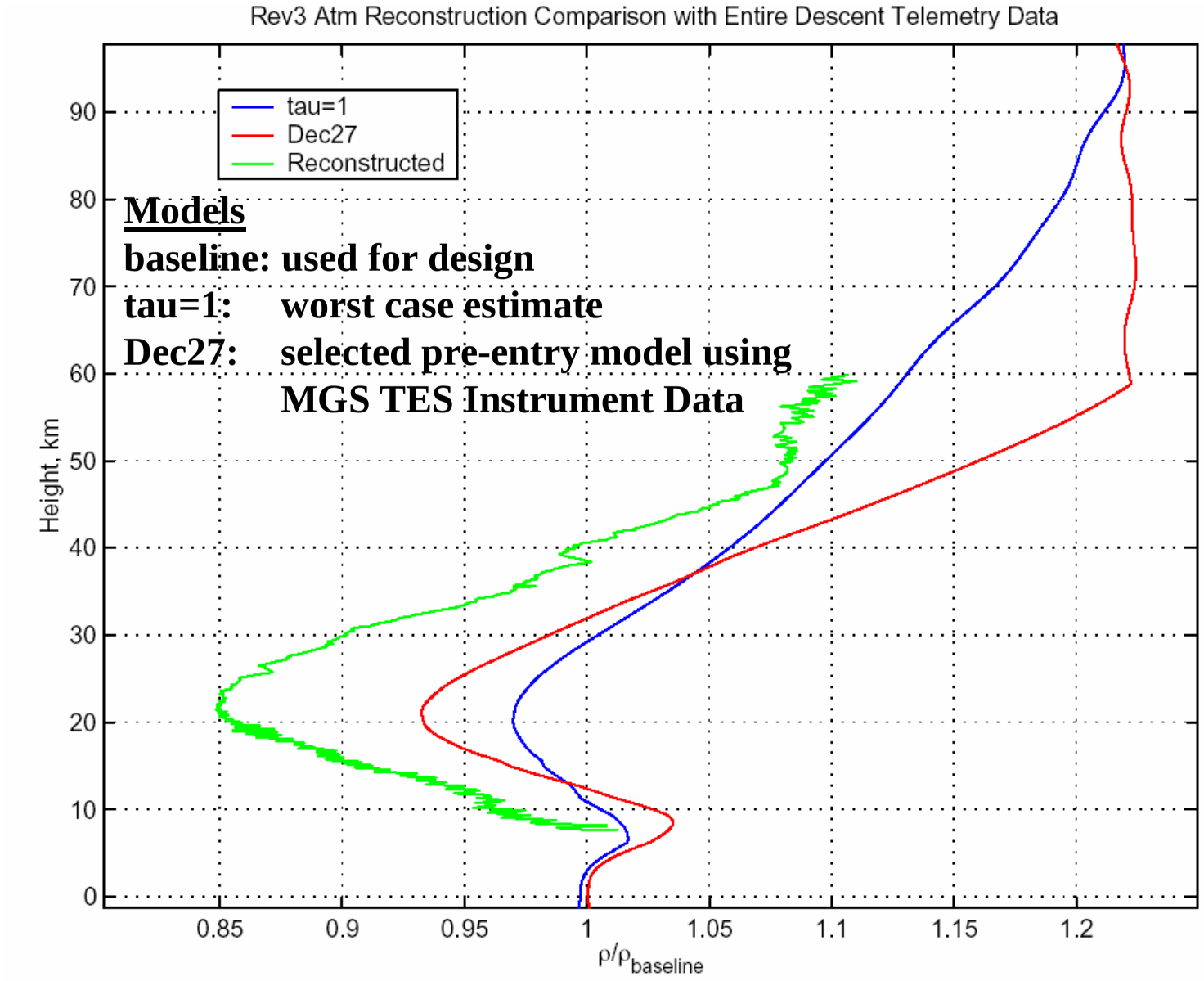
Parameter	Units	6DOF Mean	6DOF 3-σ Range	3DOF Mean	3DOF 3-σ Range	Reconstructed
Lander Descent Initiation						
Time from Entry	sec	275.6	267.3-283.8	275.5	267.9-283.1	281
Height	km	5.6	3.1-8.1	5.6	3.2-8.1	
Wind-Relative Velocity	m/s	90.6	77.4-103.9	90.5[c]	75.1[c]-105.8[c]	
Planet-Relative FPA	deg	-62.0	-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

[a]Computed in 6DOF only, [b]Different calculation method used, [c]Planet-relative velocity listed,
[d]Results obtained from 24DOF multi-body POST simulation.

Reconstructed "Spirit" Entry Density Profile

LaRC

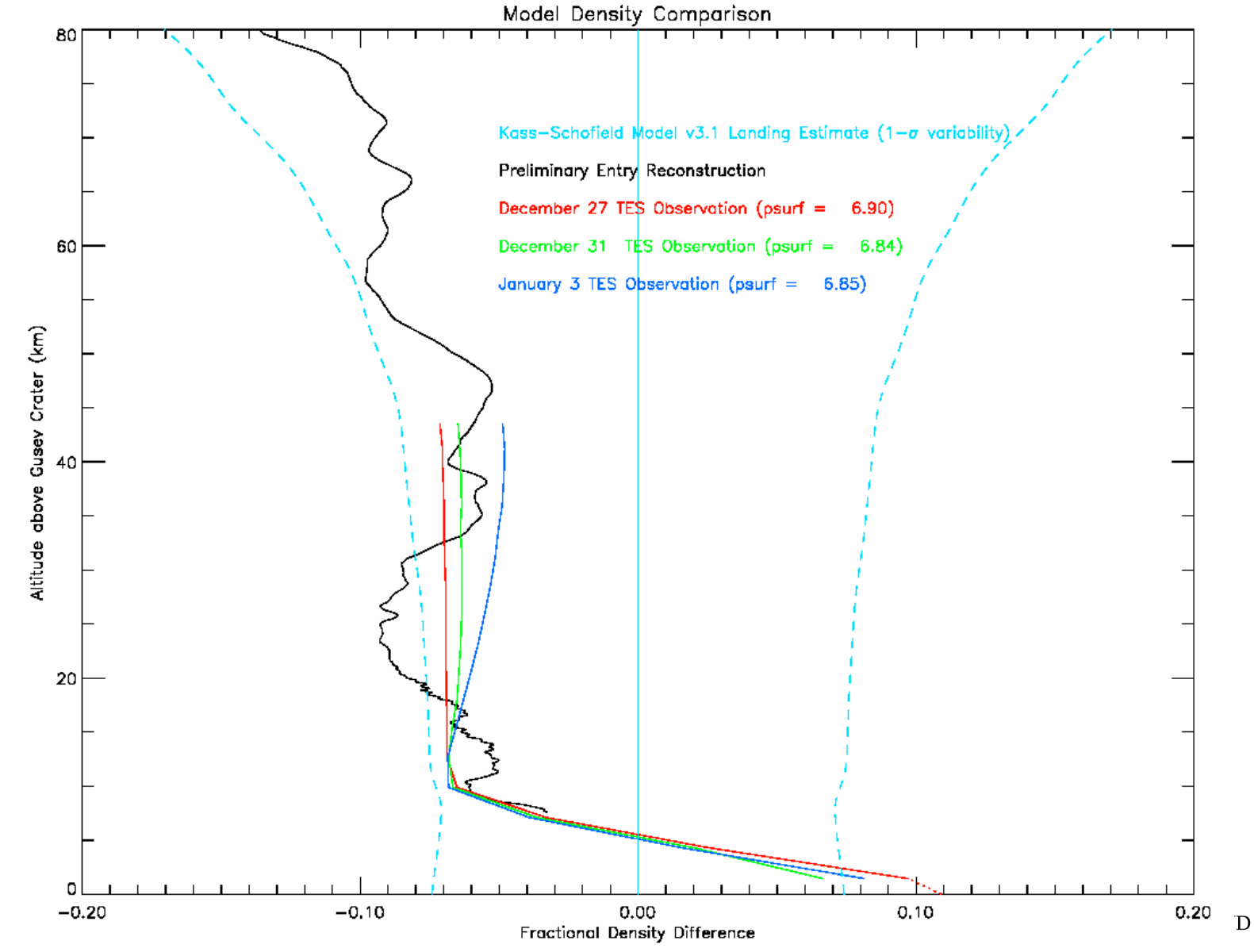
Mars Exploration Rover



Refined Reconstructed "Spirit" Entry Density Profile

LaRC

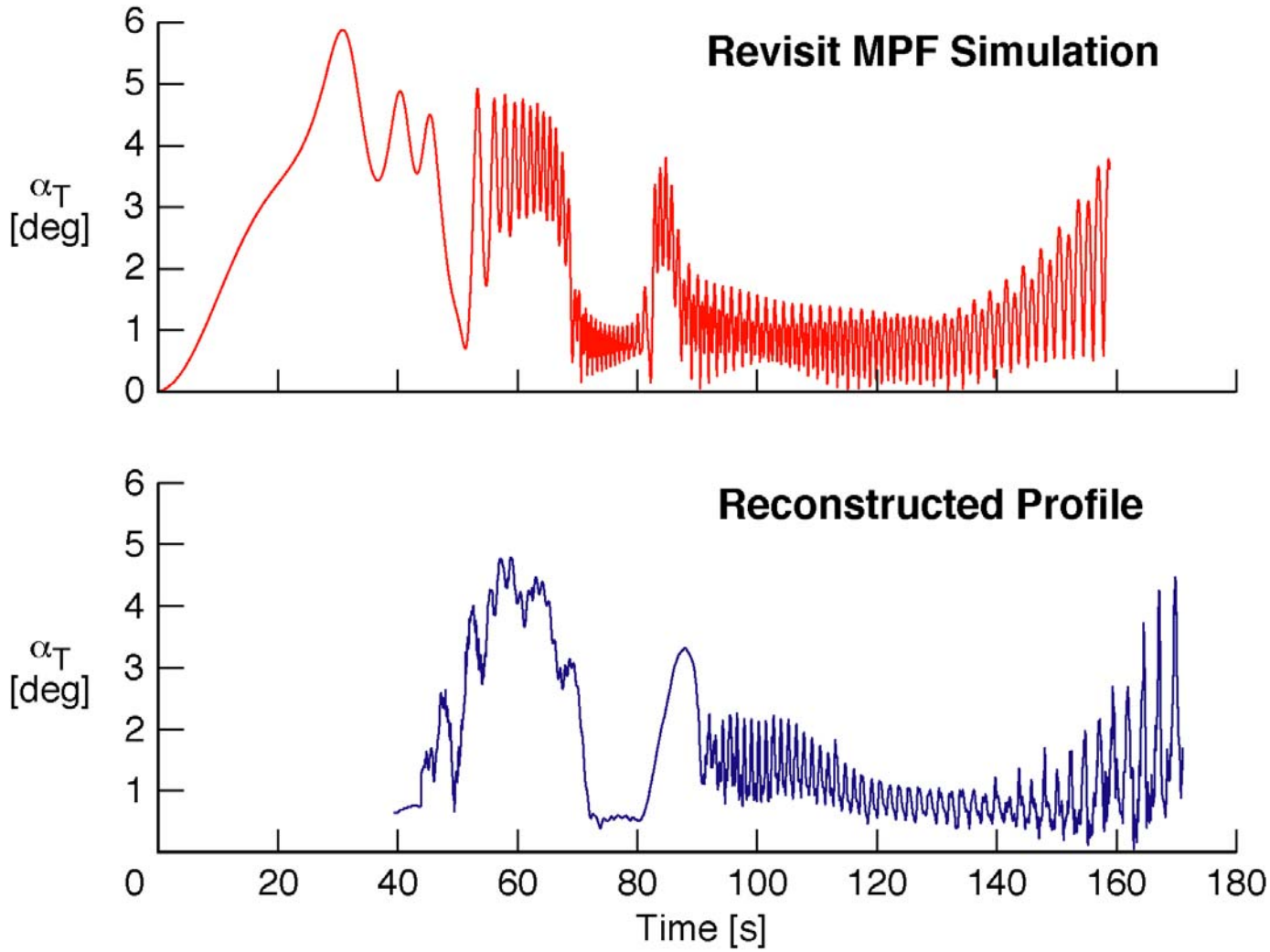
Mars Exploration Rover



Mars Pathfinder Attitude Reconstruction

LaRC

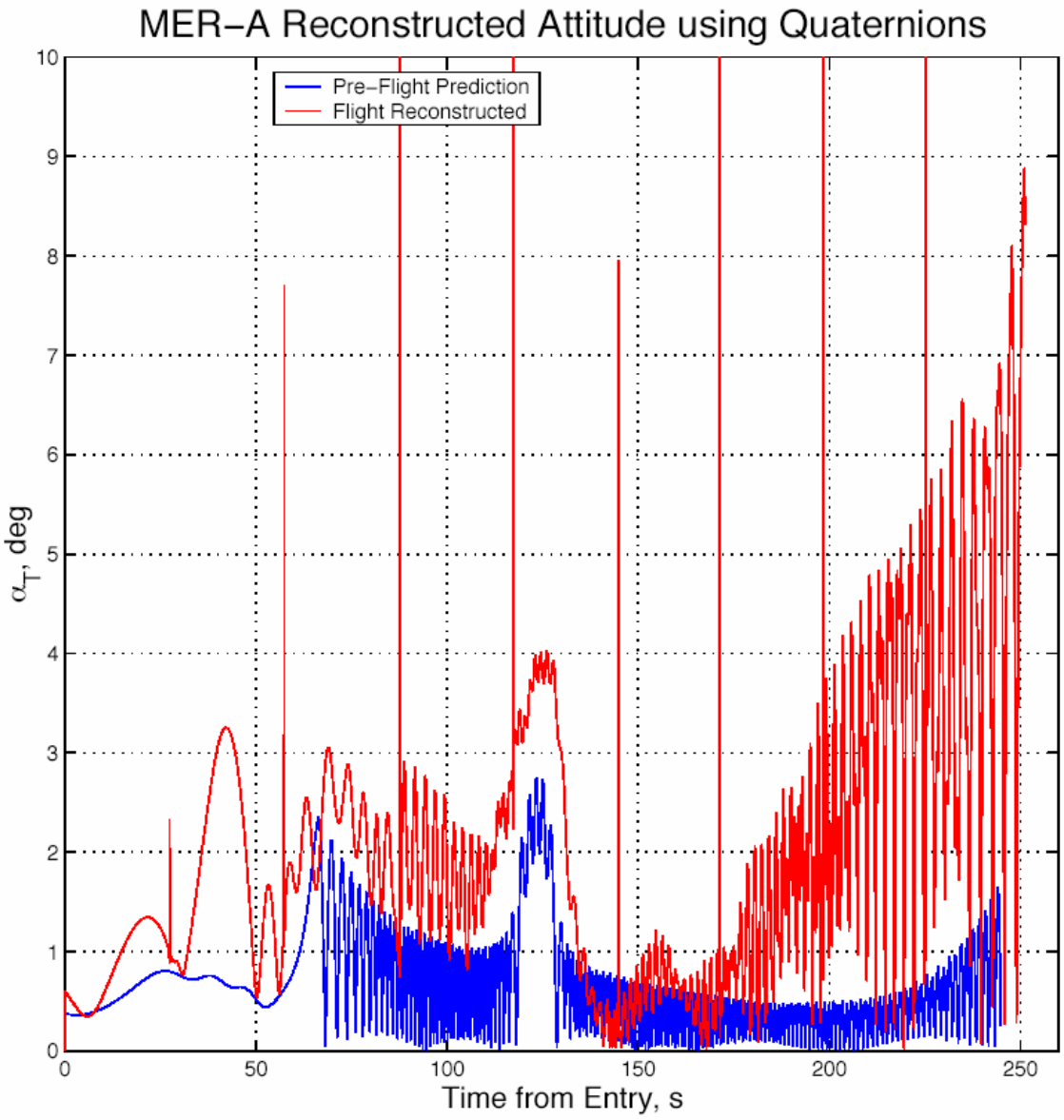
Mars Exploration Rover



“Spirit” Attitude Reconstruction

LaRC

Mars Exploration Rover

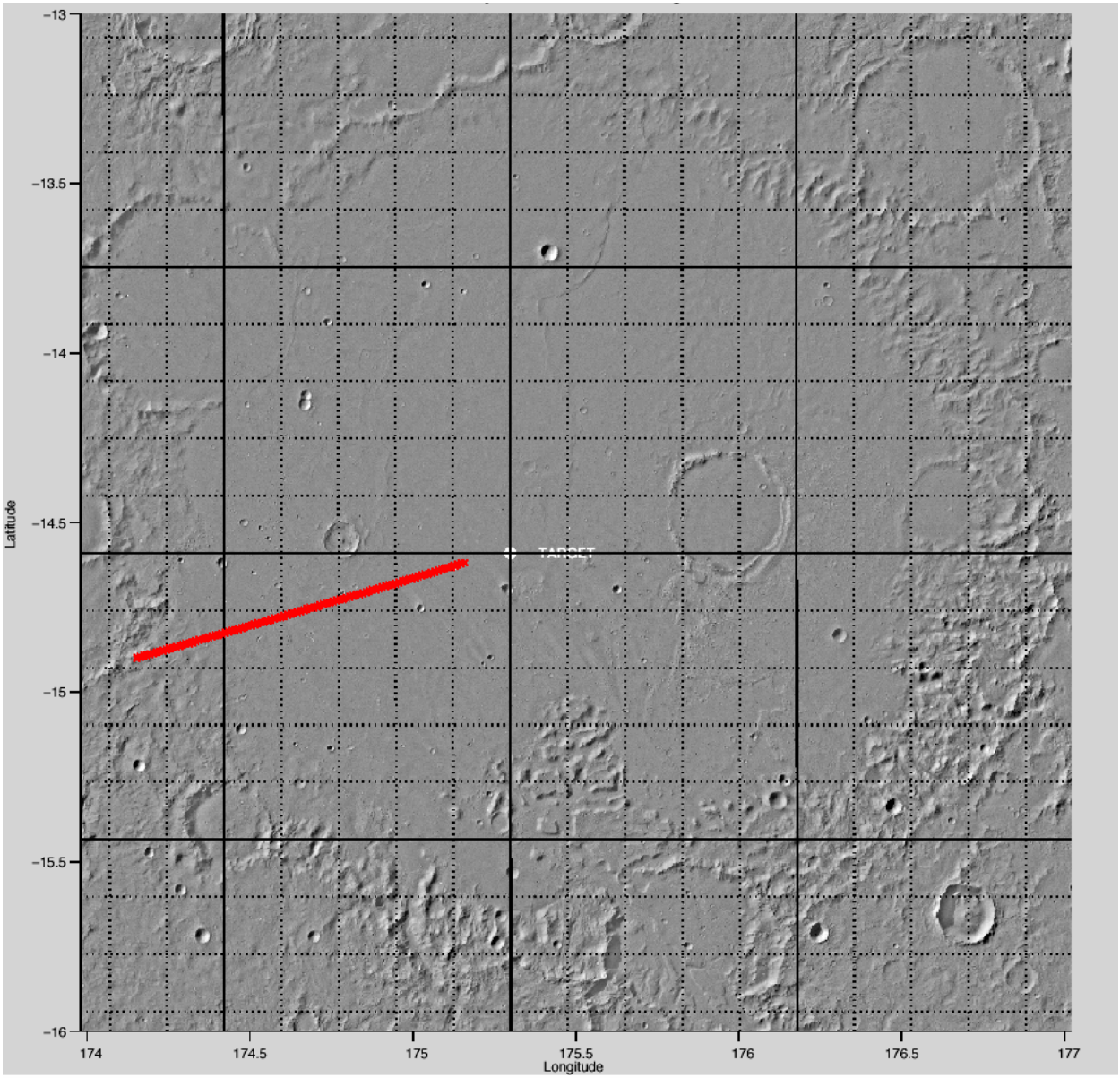


Attitude Growth at ~170s (Mach 6) theorized due to atmosphere turbulence arising from Spirit flying over western rim of Gusev Crater (next slide)

“Spirit” Entry Ground Track

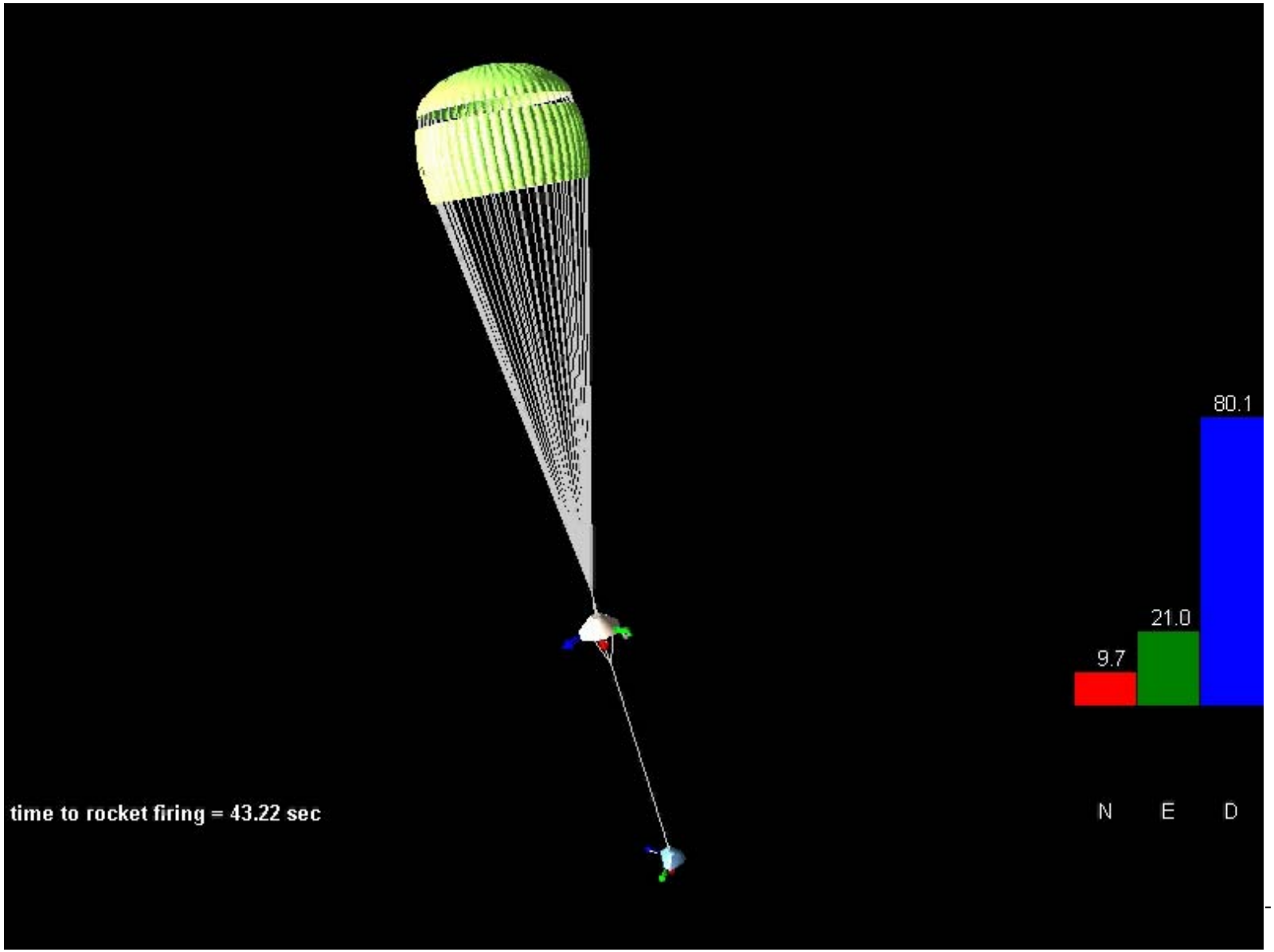
LaRC

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)

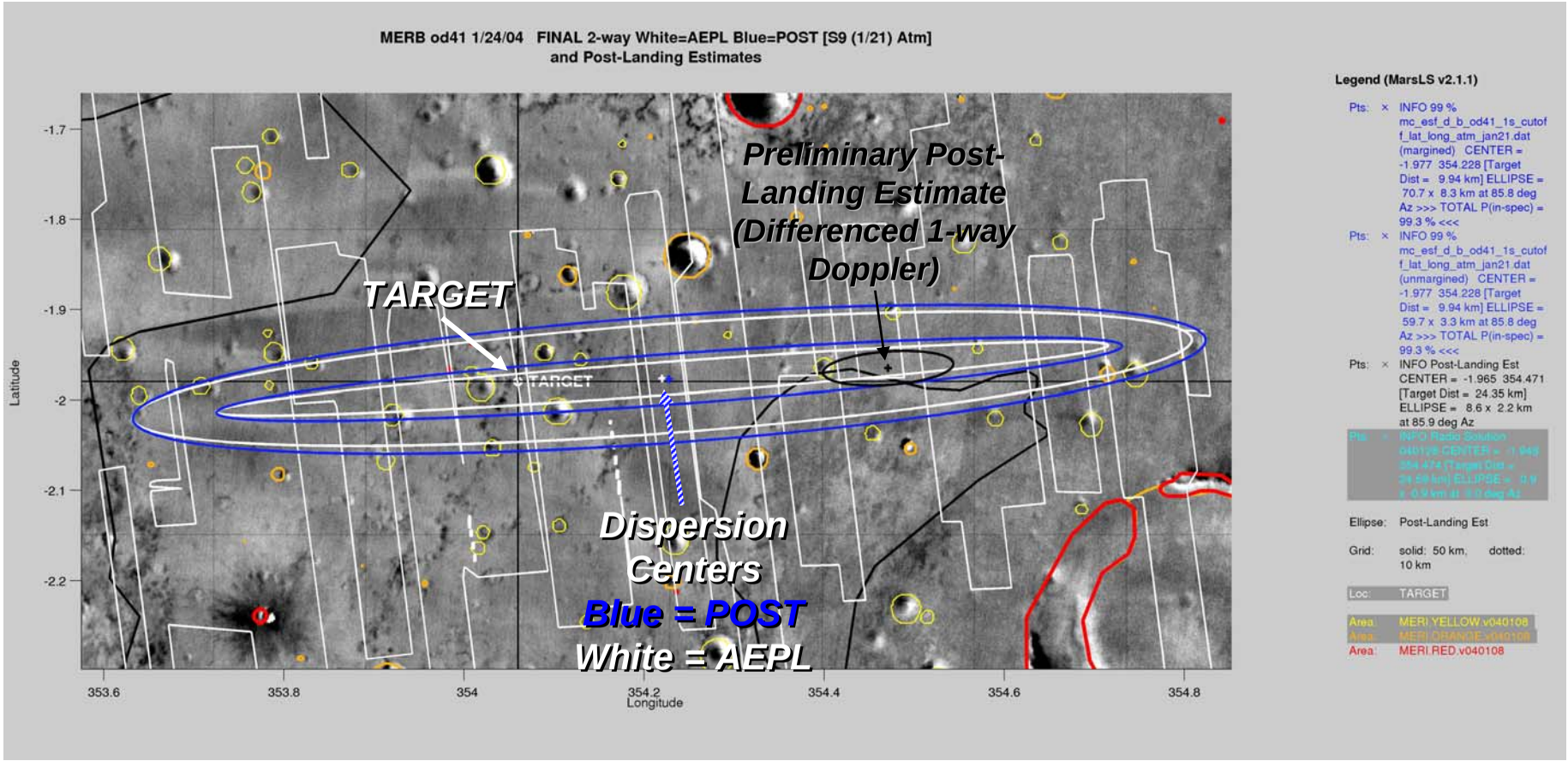
Reconstructed “Spirit” Terminal Descent Dynamics (Side View)



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

LaRC

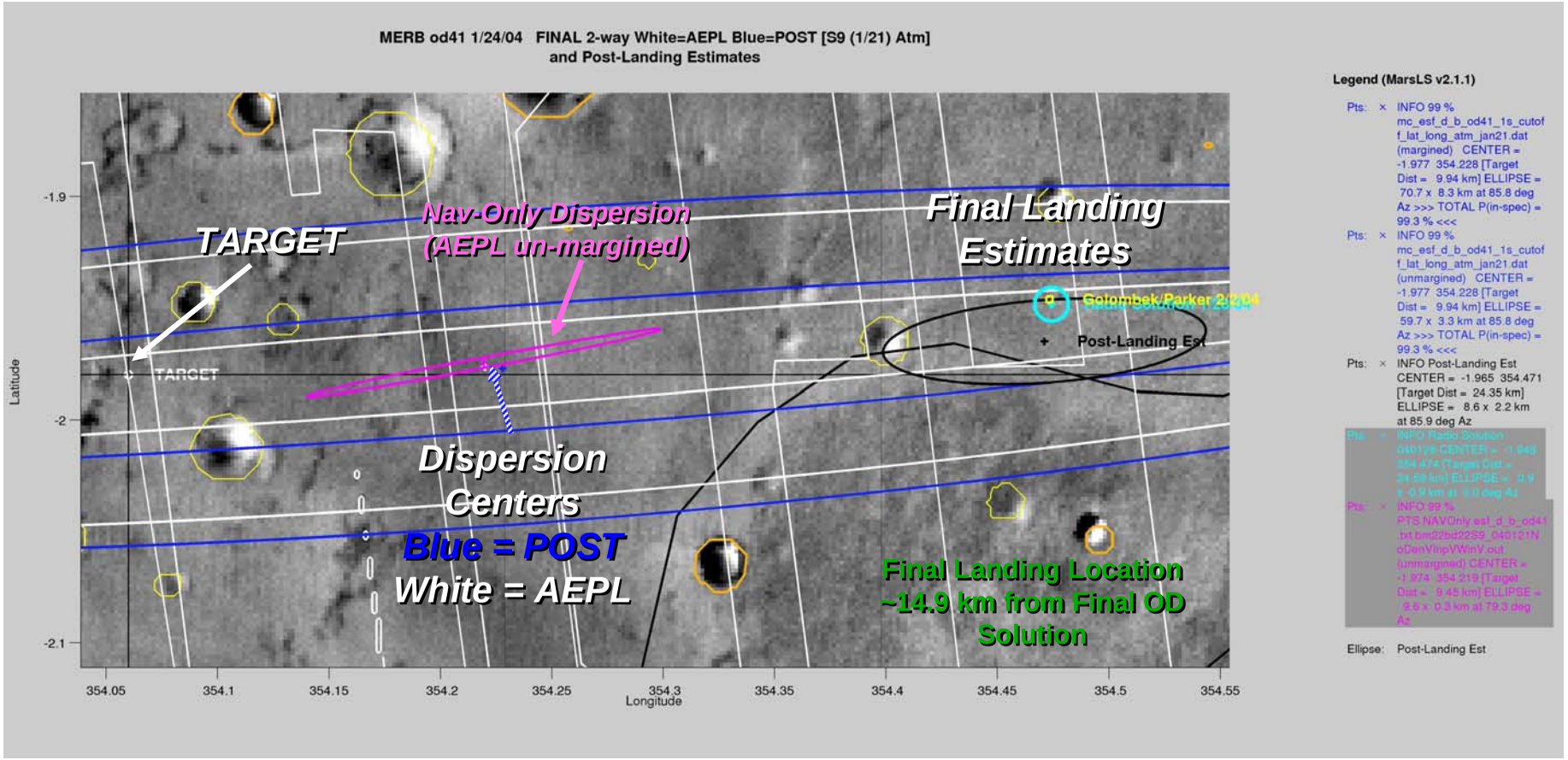
Mars Exploration Rover



"Spirit" Landing Ellipse at Final OD and Final Location Estimates

LaRC

Mars Exploration Rover



Monte Carlo Results for "Opportunity"

LaRC

Mars Exploration Rover

Parameter	Units	6DOF Mean	6DOF 3-σ Range	3DOF Mean	3DOF 3-σ Range	Reconstructed
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	Š[a]	Š[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**	**Š[a]**	**Š[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	Š[a]	Š[a]	
Mach number	0.49	0.42-0.56	0.49	0.42-0.56		

[a]Computed in 6DOF only, [b]Different calculation method used, [c]Planet-relative velocity listed,

[d]Results obtained from 24DOF multi-body POST simulation.

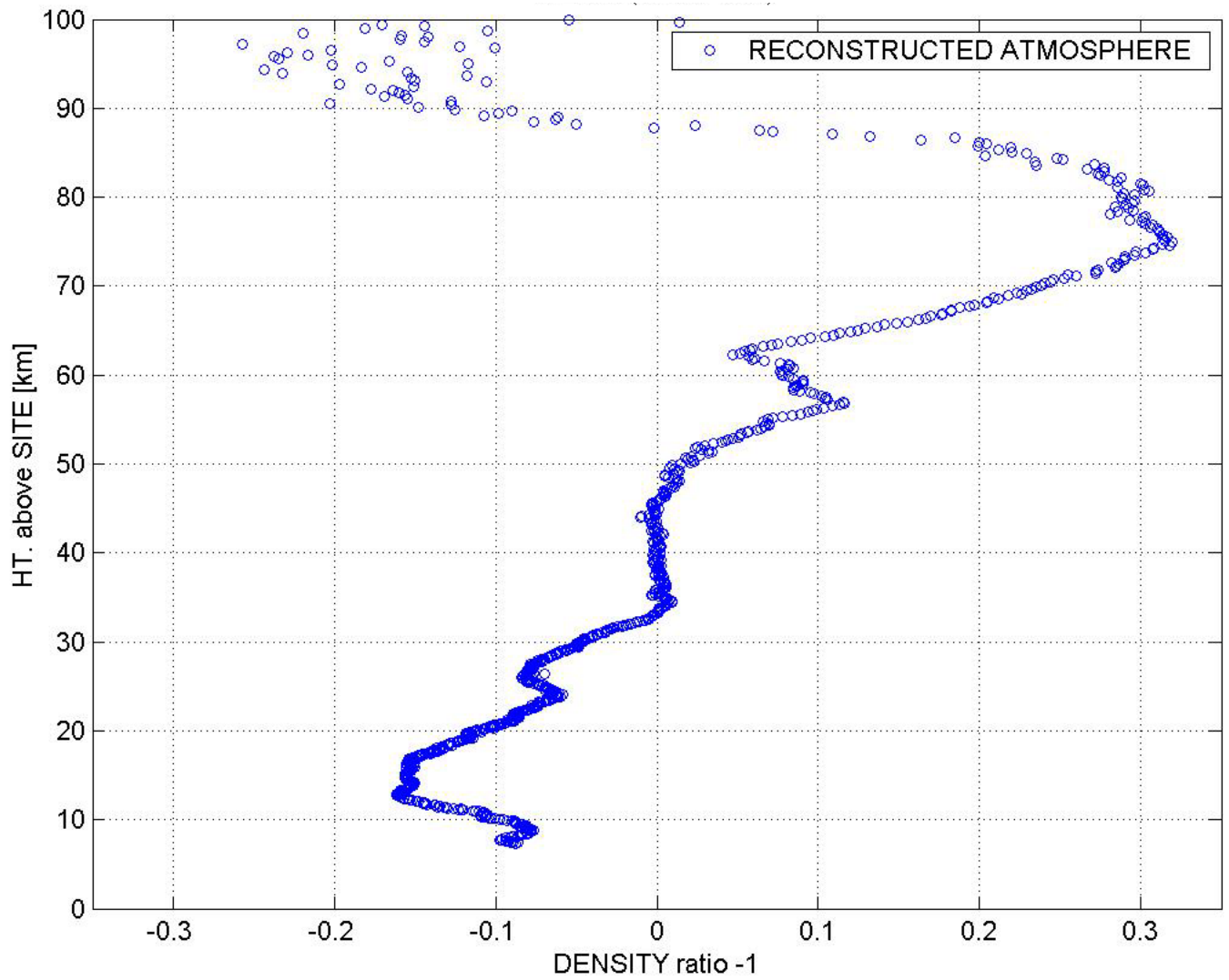
Monte Carlo Results for "Opportunity" (cont'd) *LaRC*

Mars Exploration Rover

		6DOF		3DOF		Reconstructed
Parameter	**Units**	**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	Š[a]	Š[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]	

[a]Computed in 6DOF only, [b]Different calculation method used, [c]Planet-relative velocity listed,
[d]Results obtained from 24DOF multi-body POST simulation.

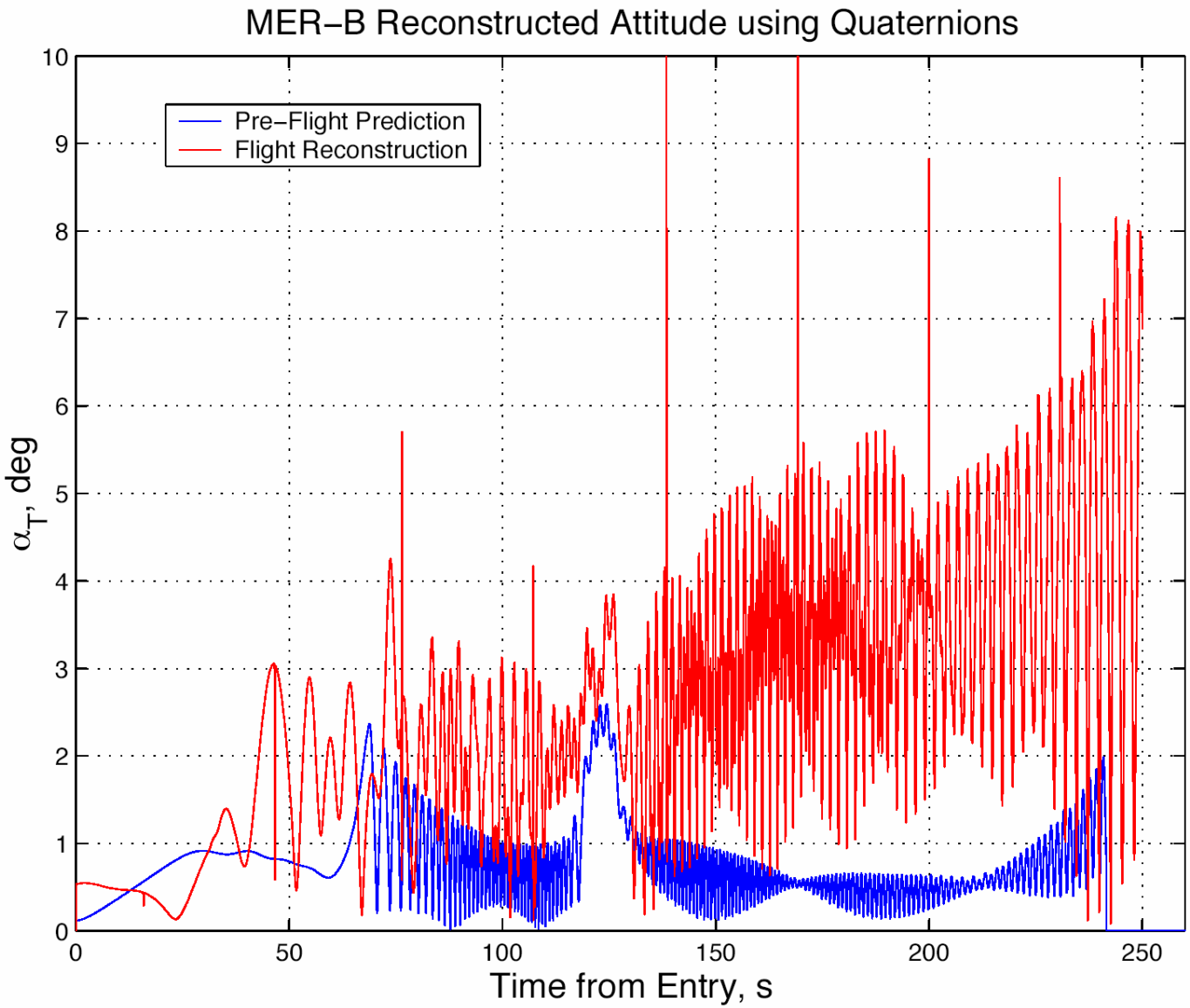
Reconstructed “Opportunity” Entry Density Profile



"Opportunity" Attitude Reconstruction

LaRC

Mars Exploration Rover



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

Summary

- "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-σ 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