



**LaRC**

**Mars Exploration Rover**

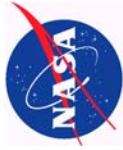
# **MER EDL: Overview and Reconstruction Status**

**Prasun N. Desai**  
**NASA Langley Research Center**

**Wayne J. Lee**  
**Jet Propulsion Laboratory**

**August 23, 2004**





## Background

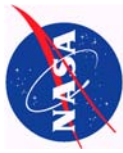
## LaRC

### 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  $\geq$  90 sols minimum for each rover**
- **Scientific objective is to search for evidence of past history of water**





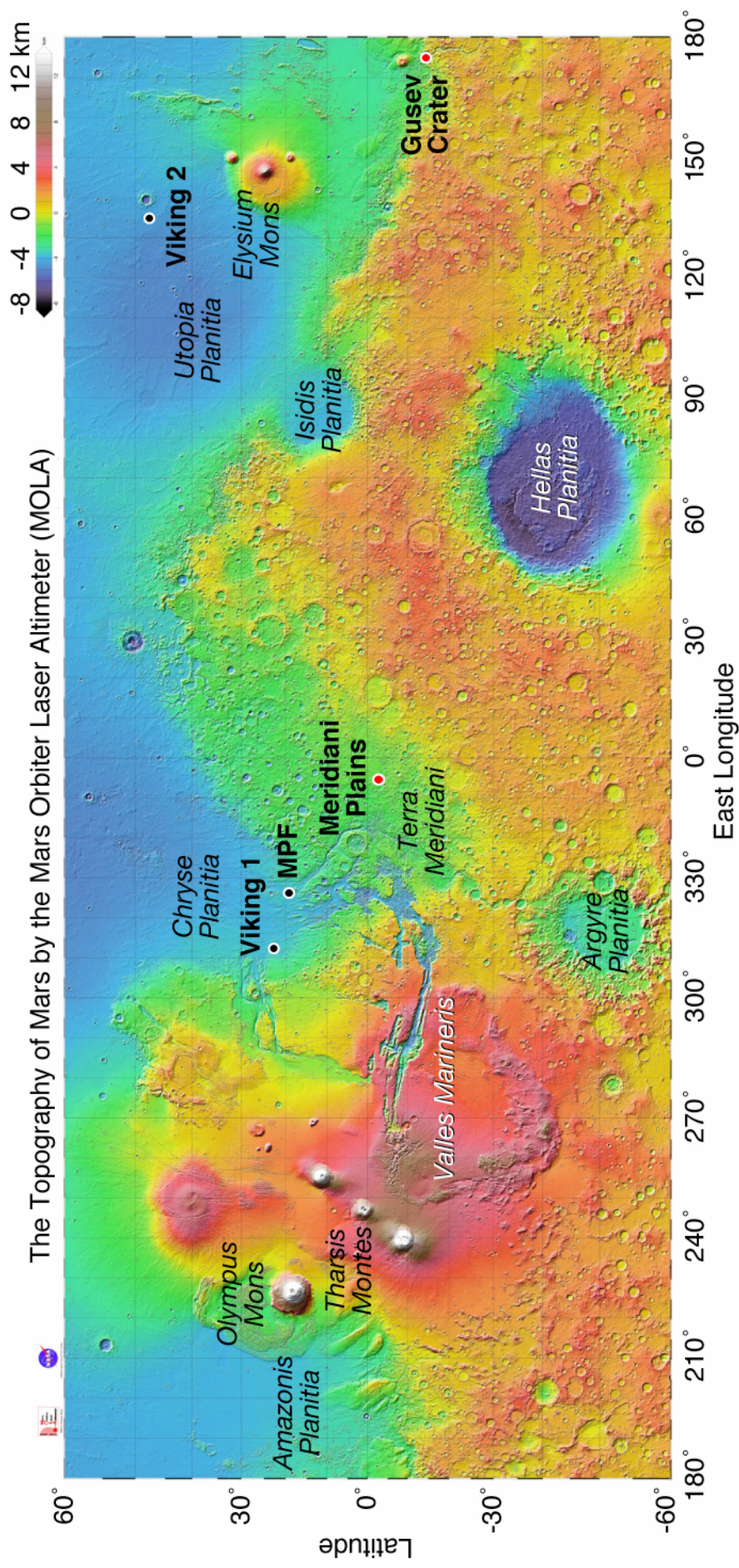


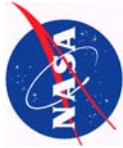
# MER Candidate Landing Sites

## LaRC

Mars Exploration Rover

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



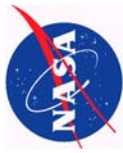


# MER Entry Heritage w/Viking & Mars Pathfinder

## LaRC

### Mars Exploration Rover

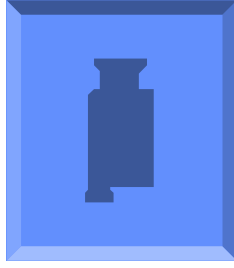
	Viking I. II	Mars Pathfinder	MER
Forebody geometry, deg	70	70	70
Aftbody geometry, deg	39/62 (biconic)	49	49
Relative Entry Velocity, km/s	4.5, 4.42	7.6	5.5
Relative Entry FPA, deg	-17.6	-13.8	-12
Entry Local Time	--	Pre-Dawn	Afternoon
Mass, kg	930	585	827, 832.2
$m/(C_D A)$ , kg/m <sup>2</sup>	63.7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

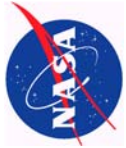


# MER EDL Animation

# LaRC

*Mars Exploration Rover*



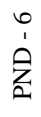
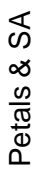
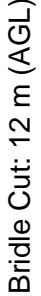
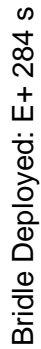
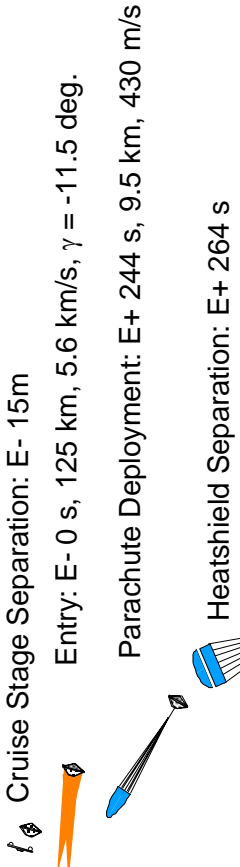


# MER Entry, Descent, and Landing (EDL) Sequence

## 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

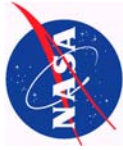


EDL Direct to Earth Communication with MFSK tones

EDL Communication via UHF to MGS Orbiter

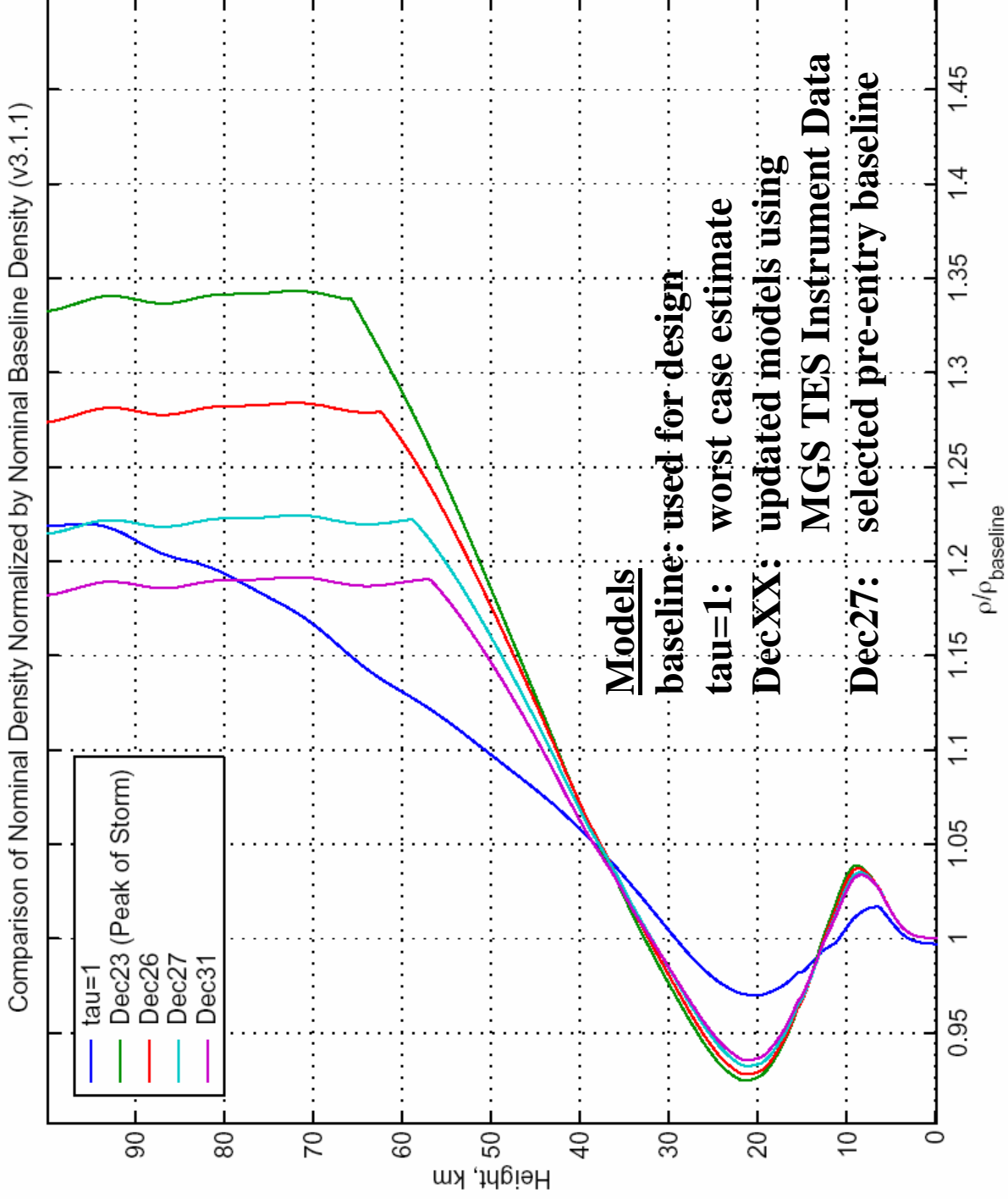
Critical Deployments

Terminal Descent Sub-Phase

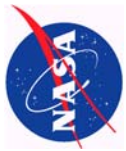


# Pre-Entry ‘Spirit’ Entry Atmosphere Models LaRC

Mars Exploration Rover



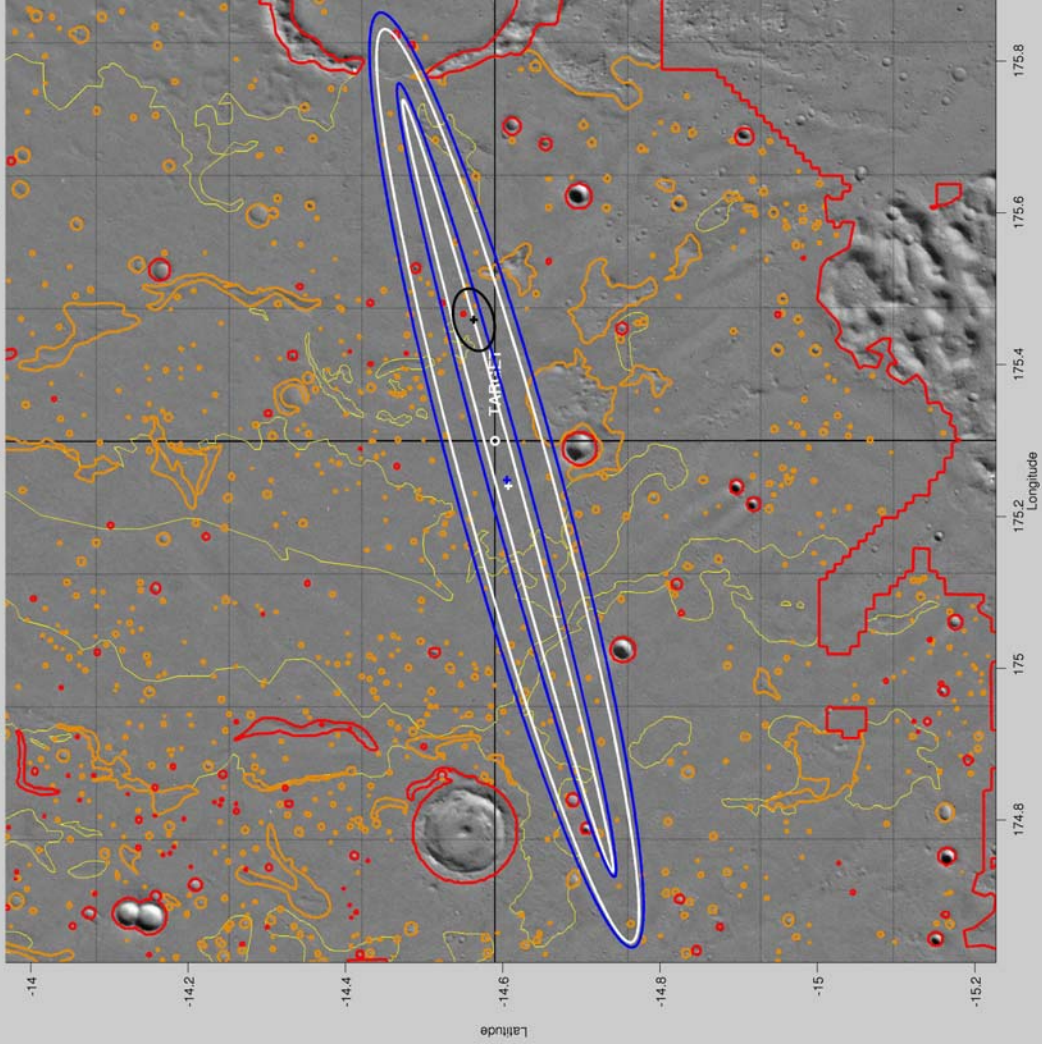




# “Spirit” Landing Ellipse at Final OD, & Updated LaRC Estimate Differenced 1-way Doppler

## 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 (margin) 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 (unmargin) 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 (margin)

Ellipse: 99 %  
 PTS.FINAL2way.esf\_d\_a\_od46.t.ag15ad1  
 5D4Wv2e.out (unmargin)

Ellipse: 99 %  
 mc\_esf\_d\_a\_od46\_1s\_cutoff\_lat\_long\_atm  
 dec27.dat (margin)

Ellipse: 99 %  
 mc\_esf\_d\_a\_od46\_1s\_cutoff\_lat\_long\_atm  
 dec27.dat (unmargin)

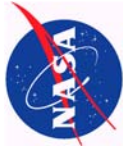
Ellipse: Prelim NAV Post-Landing Estimate

Grid: 50 km solid, 10 km dotted

Loc: TARGET

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

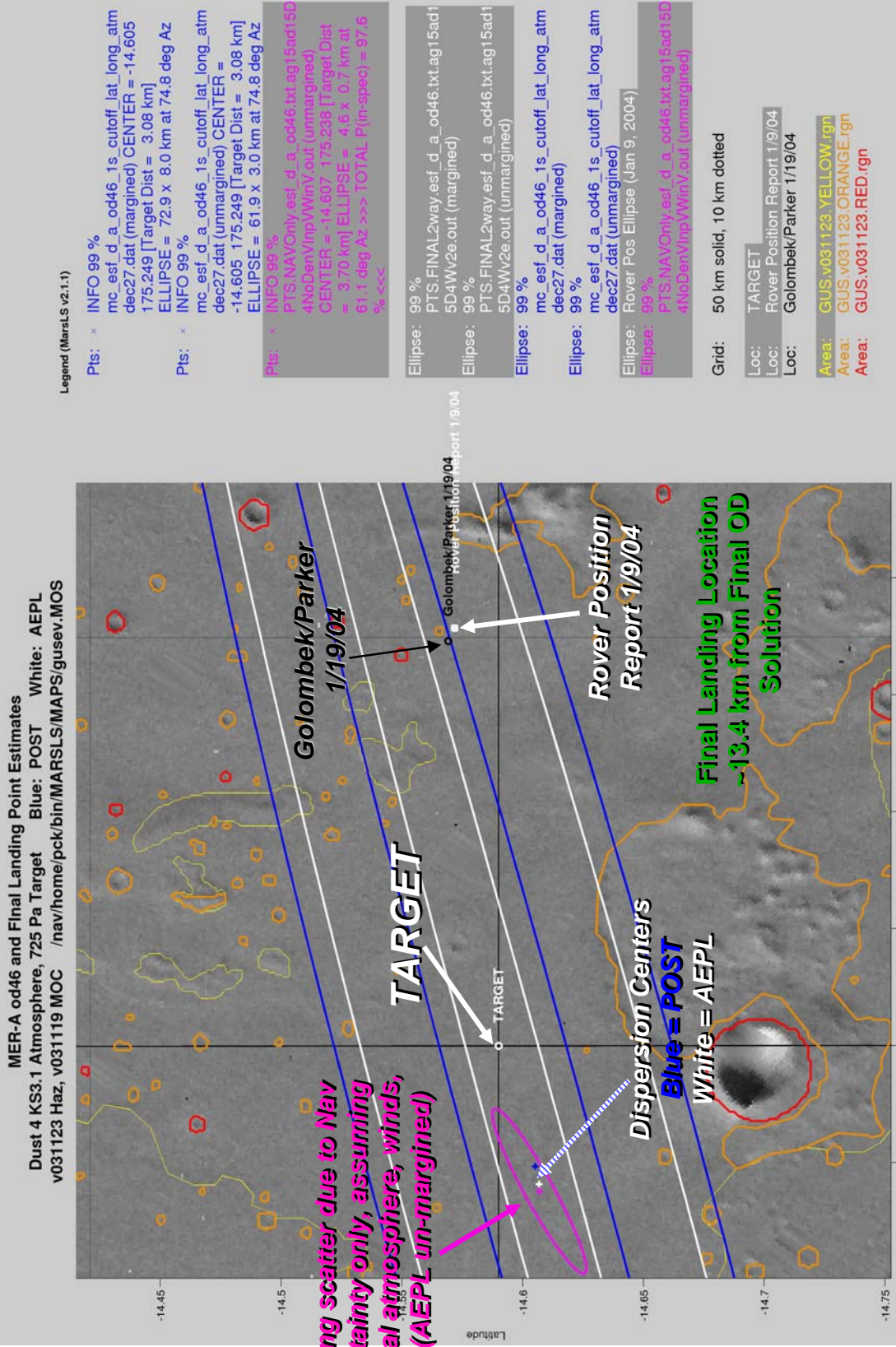




# “Spirit” Landing Ellipse at Final OD and Final Location Estimates

## LaRC

### Mars Exploration Rover



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-spcc) = 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)

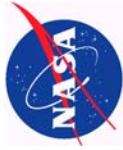
Ellipse: Rover Pos Ellipse (Jan 9, 2004)

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”

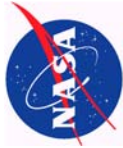
LaRC

## Mars Exploration Rover

Parameter	Units	6DOF		3DOF		Reconstructed
		Mean	3- $\sigma$ Range	Mean	3- $\sigma$ Range	
<b>Hypersonic Flight</b>						
Peak Heating Rate	W/cm <sup>2</sup>	39.9	38.1-41.7	45.0 <sup>b</sup>	42.9 <sup>b</sup> -47.1 <sup>b</sup>	
Attitude @ Peak Heat Rate	deg	0.6	0-2.2	$\check{S}$ <sup>a</sup>	$\check{S}$ <sup>a</sup>	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 <sup>2</sup>	9984	9263-10705	9955	9253-10657	
Total Heat Load	J/cm <sup>2</sup>	2770	2669-2870	3247 <sup>b</sup>	3136 <sup>b</sup> -3358 <sup>b</sup>	
<b>Parachute Deployment</b>						
Time from Entry	sec	<b>245.6</b>	<b>237.3-253.8</b>	<b>245.5</b>	<b>237.9-253.1</b>	<b>251</b>
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 <sup>c</sup>	377.5 <sup>c</sup> -436.5 <sup>c</sup>	411
Mach Number		1.78	1.71-1.85	1.78	1.71-1.85	
Dynamic Pressure	N/m <sup>2</sup>	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	
<b>Attitude</b>	<b>deg</b>	<b>1.1</b>	<b>0-4.9</b>	$\check{S}$ <sup>a</sup>	$\check{S}$ <sup>a</sup>	<b>7</b>
<b>Heatshield Jettison</b>						
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 <sup>c</sup>	88.7 <sup>c</sup> -129.1 <sup>c</sup>	
Planet-Relative FPA	deg	-49.6	-55.6- -43.6	-49.6	-55.7- -43.5	
Dynamic Pressure	N/m <sup>2</sup>	60.8	45.2-76.4	$\check{S}$ <sup>a</sup>	$\check{S}$ <sup>a</sup>	
Mach number		0.47	0.4-0.54	0.47	0.4-0.53	

<sup>a</sup>Computed in 6DOF only, <sup>b</sup>Different calculation method used, <sup>c</sup>Planet-relative velocity listed,

<sup>d</sup>Results 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- $\sigma$ Range	Mean	3- $\sigma$ Range	
<b>Lander Descent Initiation</b>						
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 <sup>c</sup>	75.1 <sup>c</sup> -105.8 <sup>c</sup>	
Planet-Relative FPA	deg	-62.0	-70.4- -53.6	-62.1	-70.7- -53.5	
Dynamic Pressure	N/m <sup>2</sup>	41.8	31.8-51.8	Š <sup>a</sup>	Š <sup>a</sup>	
Sensed Acceleration	Earth g	0.43	0.39-0.46	0.43	0.39-0.46	
<b>RAD Initiation</b>						
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 <sup>c</sup>	61.8 <sup>c</sup> -84.2 <sup>c</sup>	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		
<b>Bridle Cut</b>						
Time from Entry	sec	348.2 <sup>d</sup>	319.7 <sup>d</sup> -376.3 <sup>d</sup>	349.7	320.6-378.7	
<b>Height</b>	<b>m</b>	<b>12.4<sup>d</sup></b>	<b>4.2<sup>d</sup> -20.1<sup>d</sup></b>	<b>13.6</b>	<b>11.1-16.1</b>	<b>8.5</b>
Wind-Relative Velocity	m/s	9.8 <sup>d</sup>	0.2 <sup>d</sup> -25.3 <sup>d</sup>	9.3 <sup>c</sup>	0.3 <sup>c</sup> -20.4 <sup>c</sup>	11.8
<b>Landing</b>						
Time from Entry	sec	350.5 <sup>d</sup>	321.0 <sup>d</sup> -379.5 <sup>d</sup>	352.3	322.9-381.5	
Wind-Relative Velocity	m/s	13.9 <sup>d</sup>	7.2 <sup>d</sup> -25.0 <sup>d</sup>	13.9 <sup>c</sup>	6.7 <sup>c</sup> -21.2 <sup>c</sup>	14.0

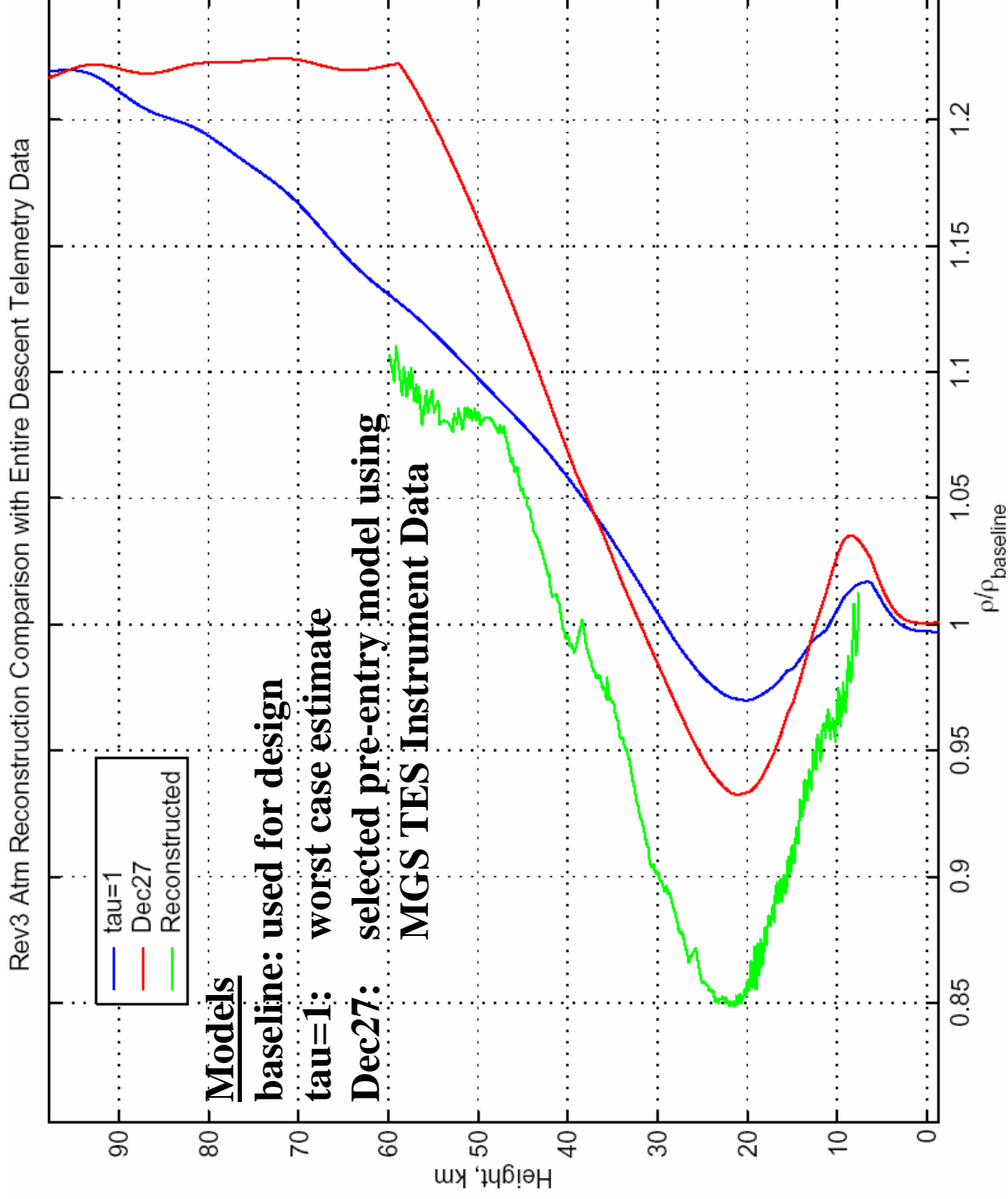
<sup>a</sup>Computed in 6DOF only, <sup>b</sup>Different calculation method used, <sup>c</sup>Planet-relative velocity listed,

<sup>d</sup>Results obtained from 24DOF multi-body POST simulation.

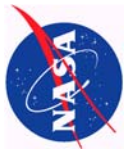


# Reconstructed ‘Spirit’ Entry Density Profile LaRC

Mars Exploration Rover



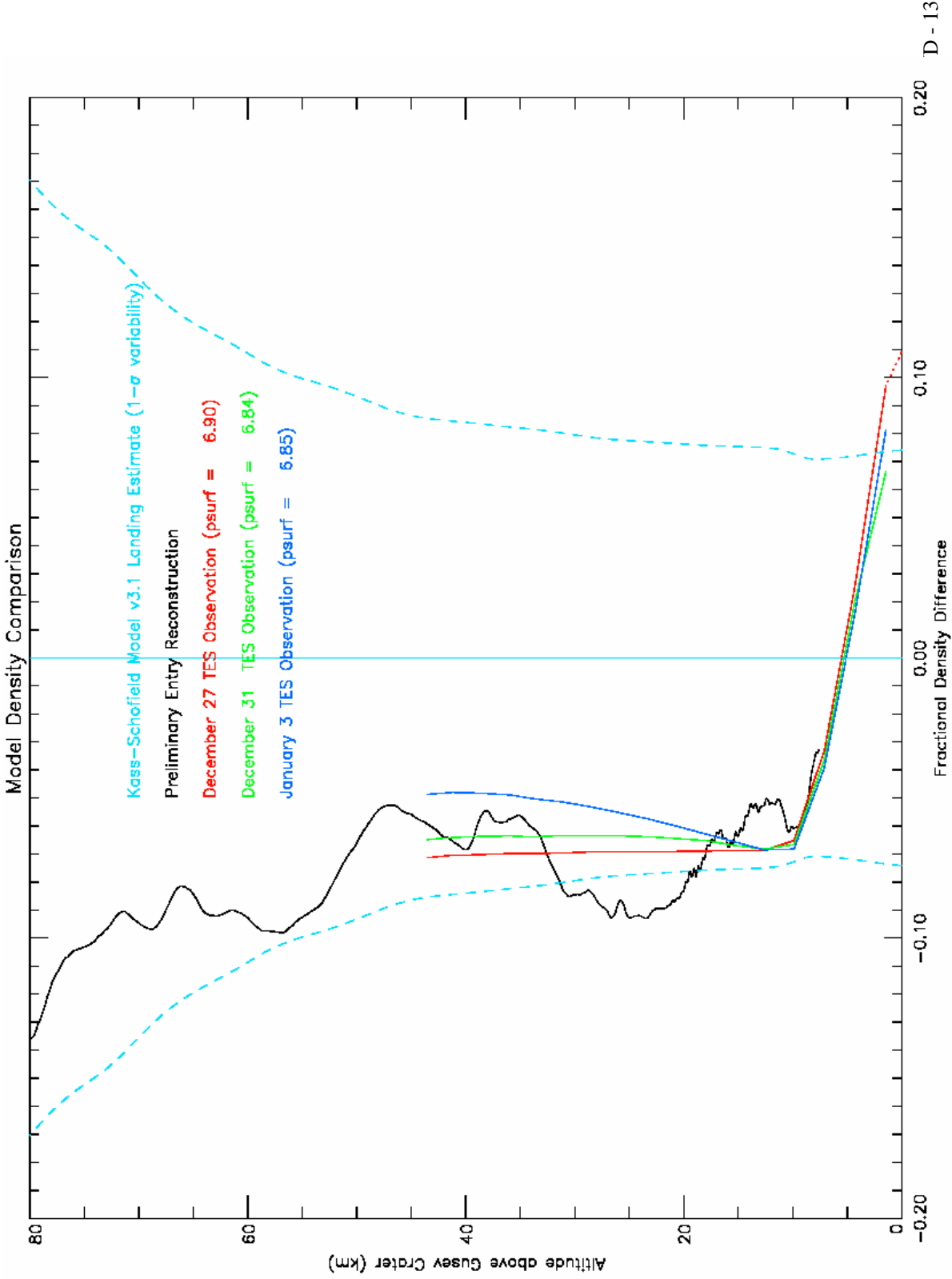


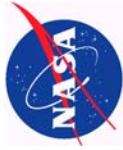


# Refined Reconstructed “Spirit” Entry Density Profile

LaRC

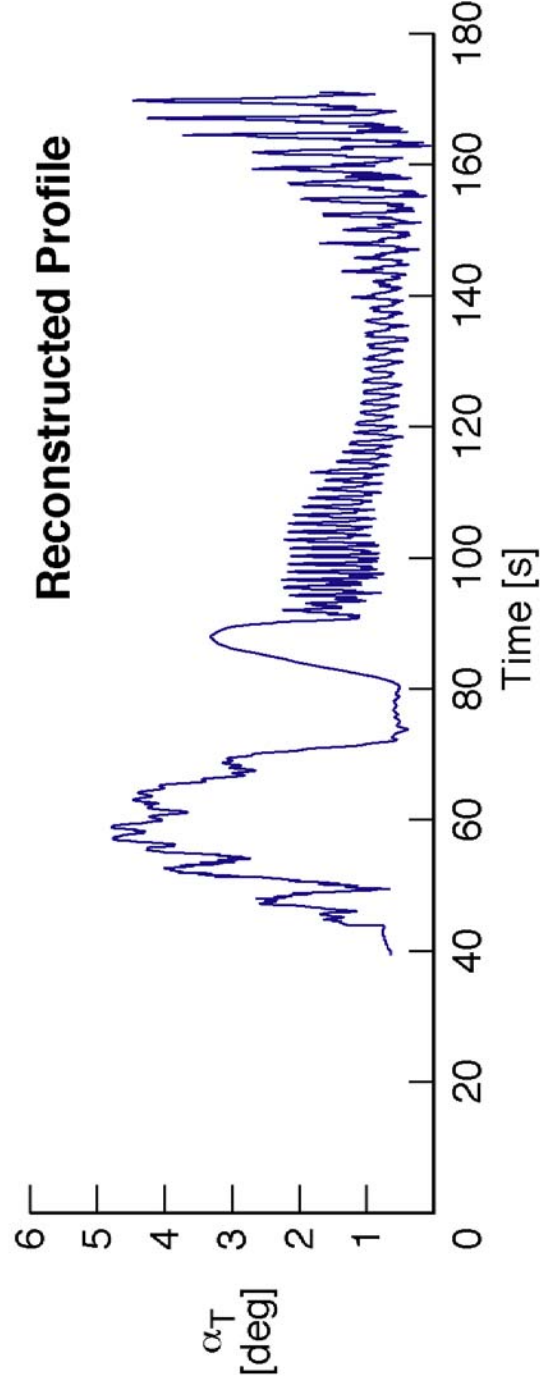
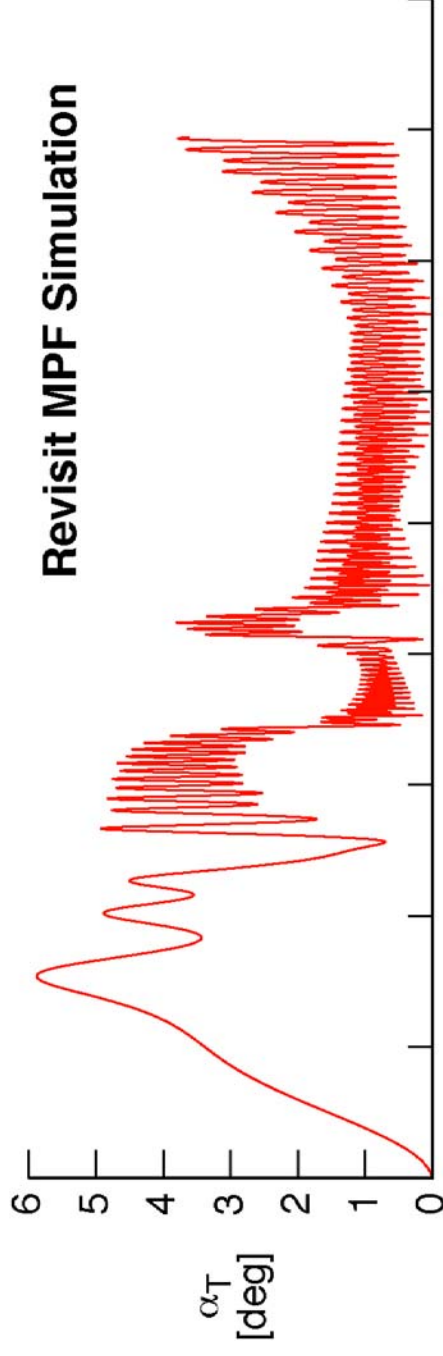
Mars Exploration Rover





# Mars Pathfinder Attitude Reconstruction LaRC

Mars Exploration Rover



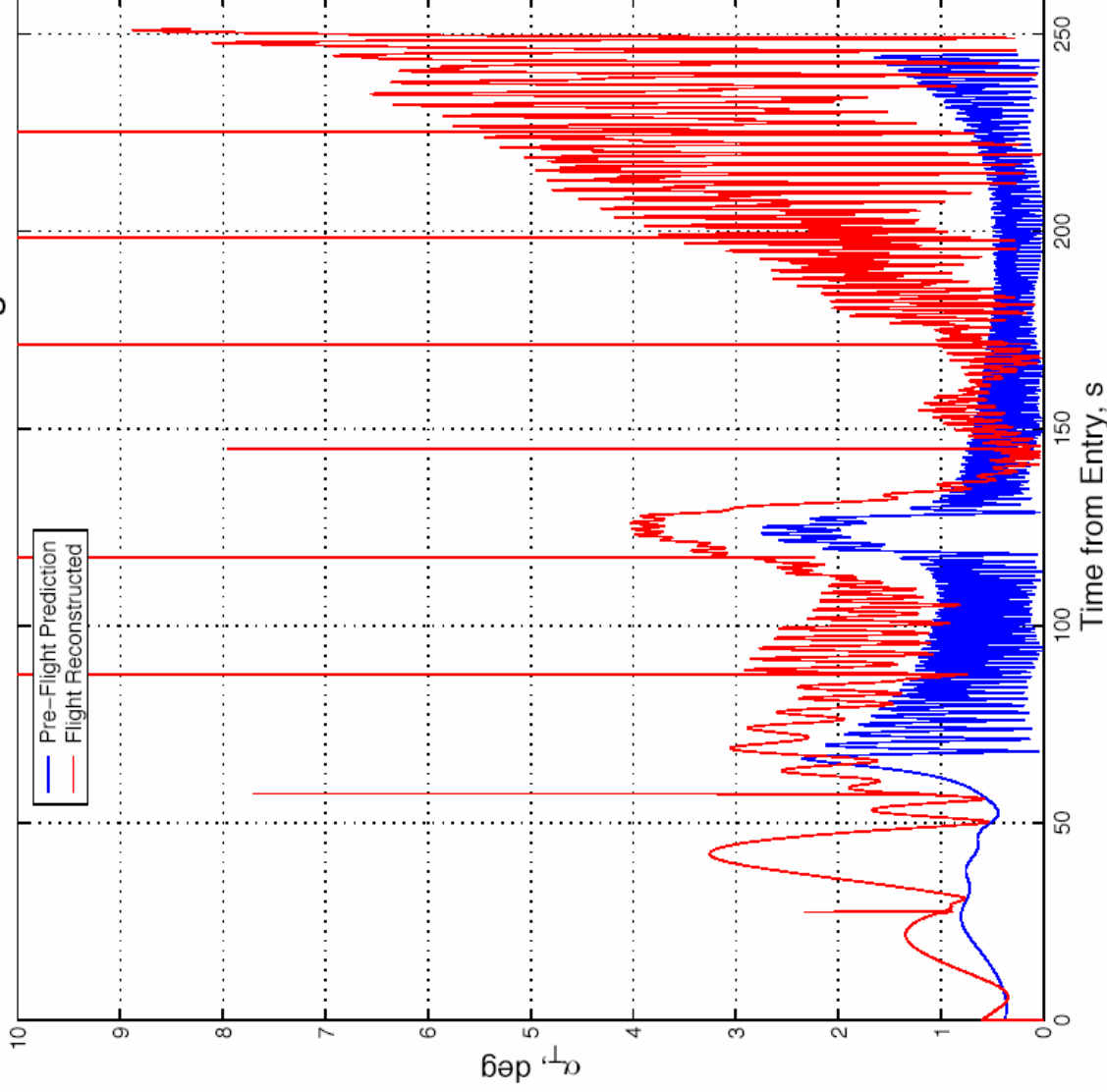


# “Spirit” Attitude Reconstruction

## LaRC

Mars Exploration Rover

MER-A Reconstructed Attitude using Quaternions



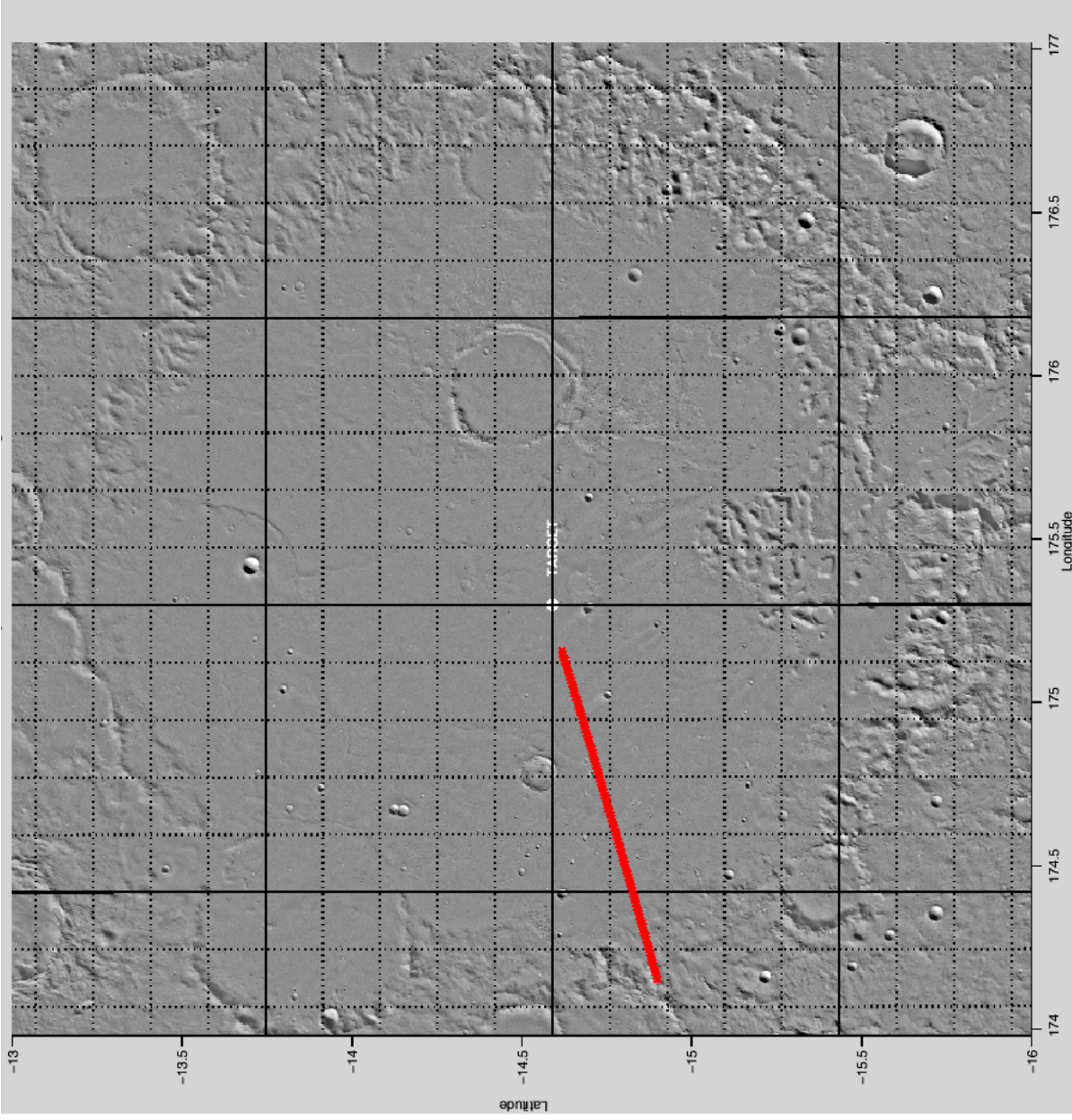
Attitude Growth at ~170s (Mach 6) theorized due to atmosphere turbulence arising from Spirit flying over western rim of Gusev Crater (next slide)



# “Spirit” Entry Ground Track

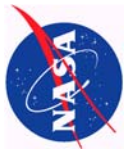
## LaRC

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)

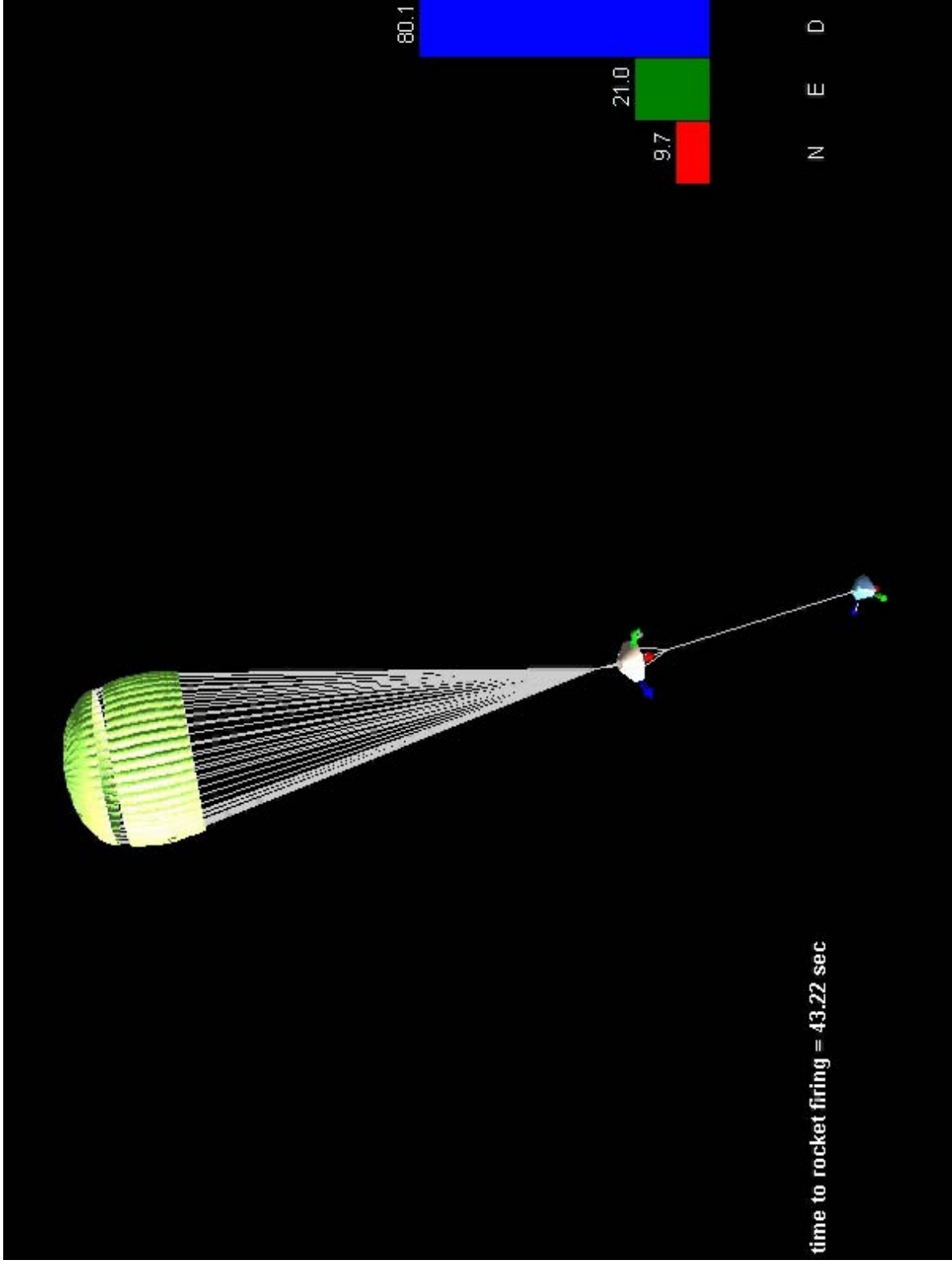


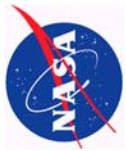


# Reconstructed “Spirit” Terminal Descent Dynamics (Side View)

LaRC

Mars Exploration Rover

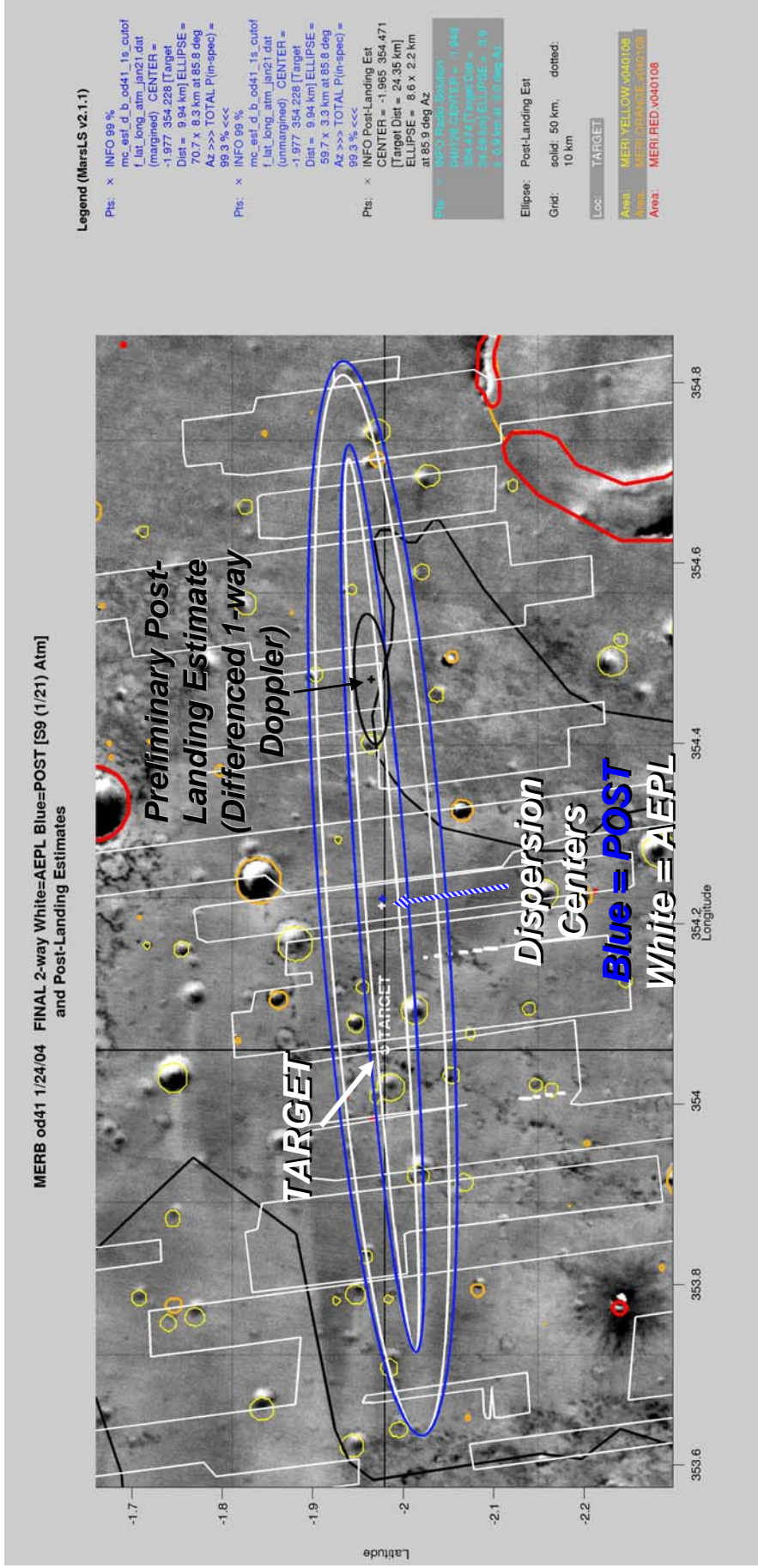




# “Opportunity” Landing Ellipse at Final OD, & Updated Estimate Differenced 1-way Doppler

## LaRC

Mars Exploration Rover

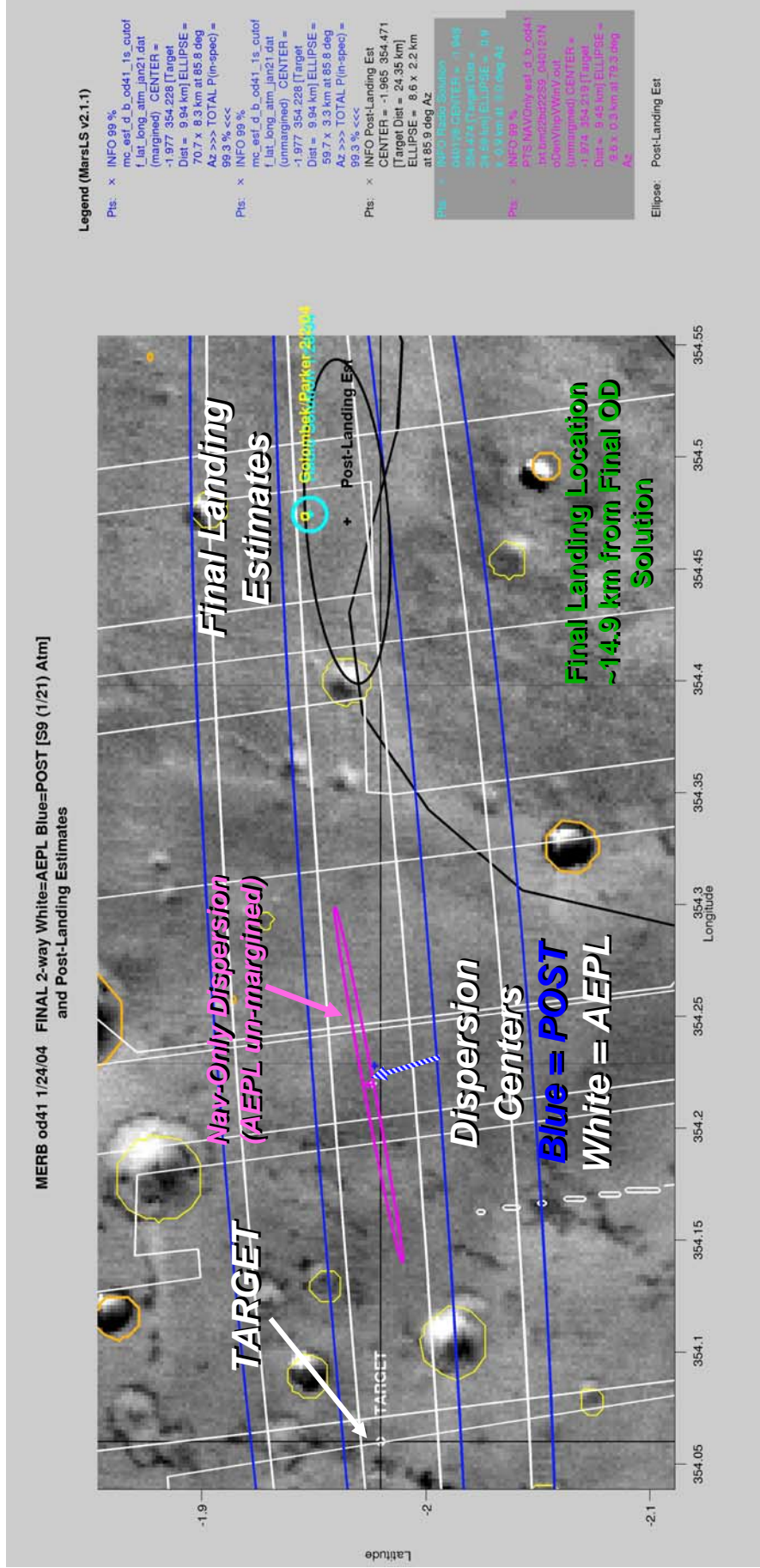




# “Spirit” Landing Ellipse at Final OD and Final Location Estimates

## LaRC

Mars Exploration Rover





# Monte Carlo Results for “Opportunity” LaRC

## Mars Exploration Rover

Parameter	Units	6DOF		3DOF		Reconstructed
		Mean	3- $\sigma$ Range	Mean	3- $\sigma$ Range	
<b>Hypersonic Flight</b>						
Peak Heating Rate	W/cm <sup>2</sup>	42.2	39.3-45.2	47.9 <sup>b</sup>	44.6 <sup>b</sup> -51.1 <sup>b</sup>	
Attitude @ Peak HeatRate	deg	0.6	0-2.1	$\check{S}$ <sup>a</sup>	$\check{S}$ <sup>a</sup>	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 <sup>2</sup>	10835	9868-11803	10812	9863-11760	
Total Heat Load	J/cm <sup>2</sup>	2711	2595-2826	3190 <sup>b</sup>	3064 <sup>b</sup> -3317 <sup>b</sup>	
<b>Parachute Deployment</b>						
<b>Time from Entry</b>	<b>sec</b>	<b>242.1</b>	<b>234.5-249.7</b>	<b>242.1</b>	<b>235.2-249.0</b>	<b>250.3</b>
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 <sup>c</sup>	395.4 <sup>c</sup> -455.2 <sup>c</sup>	434
Mach Number		1.86	1.78-1.94	1.86	1.79-1.94	
Dynamic Pressure	N/m <sup>2</sup>	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	
<b>Attitude</b>	<b>deg</b>	<b>1.0</b>	<b>0-4.4</b>	$\check{S}$ <sup>a</sup>	$\check{S}$ <sup>a</sup>	<b>8</b>
<b>Heatshield Jettison</b>						
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 <sup>c</sup>	94.1 <sup>c</sup> -132.1 <sup>c</sup>	
Planet-Relative FPA	deg	-47.6	-53.0- -42.2	-47.6	-53.3- -42.0	
Dynamic Pressure	N/m <sup>2</sup>	63.5	47.1-80.0	$\check{S}$ <sup>a</sup>	$\check{S}$ <sup>a</sup>	
Mach number	0.49	0.42-0.56	0.49	0.42-0.56		

<sup>a</sup>Computed in 6DOF only, <sup>b</sup>Different calculation method used, <sup>c</sup>Planet-relative velocity listed,

<sup>d</sup>Results obtained from 24DOF multi-body POST simulation.





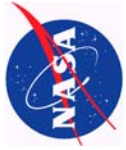
# Monte Carlo Results for “Opportunity” (cont’d) LaRC

## Mars Exploration Rover

Parameter	Units	6DOF		3DOF		Reconstructed
		Mean	3- $\sigma$ Range	Mean	3- $\sigma$ Range	
<b>Lander Descent Initiation</b>						
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 <sup>c</sup>	78.6 <sup>c</sup> -113.9 <sup>c</sup>	
Planet-Relative FPA	deg	-60.6	-67.5- -53.8	-60.7	-67.8- -53.6	
Dynamic Pressure	N/m <sup>2</sup>	43.6	33.0-54.3	$\xi^a$	$\xi^a$	
Sensed Acceleration	Earth g	0.44	0.40-0.49	0.44	0.40-0.48	
<b>RAD Initiation</b>						
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 <sup>c</sup>	61.1 <sup>c</sup> -84.4 <sup>c</sup>	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	
<b>Bridle Cut</b>						
Time from Entry	sec	347.9 <sup>d</sup>	318.6 <sup>d</sup> -377.2 <sup>d</sup>	347.6	320.4-374.8	
Height	m	<b>13.1<sup>d</sup></b>	<b>4.5<sup>d</sup> -21.7<sup>d</sup></b>	<b>13.4</b>	<b>11.4-15.4</b>	<b>6.9</b>
Wind-Relative Velocity	m/s	9.6 <sup>d</sup>	0.7 <sup>d</sup> -23.6 <sup>d</sup>	7.1 <sup>c</sup>	0.6 <sup>c</sup> -18.5 <sup>c</sup>	9.3
<b>Landing</b>						
Time from Entry	sec	348.6 <sup>d</sup>	320.3 <sup>d</sup> -376.9 <sup>d</sup>	350.1	322.8-383.3	
Wind-Relative Velocity	m/s	13.8 <sup>d</sup>	6.9 <sup>d</sup> -23.5 <sup>d</sup>	12.6 <sup>c</sup>	5.7 <sup>c</sup> -19.5 <sup>c</sup>	

<sup>a</sup>Computed in 6DOF only, <sup>b</sup>Different calculation method used, <sup>c</sup>Planet-relative velocity listed,

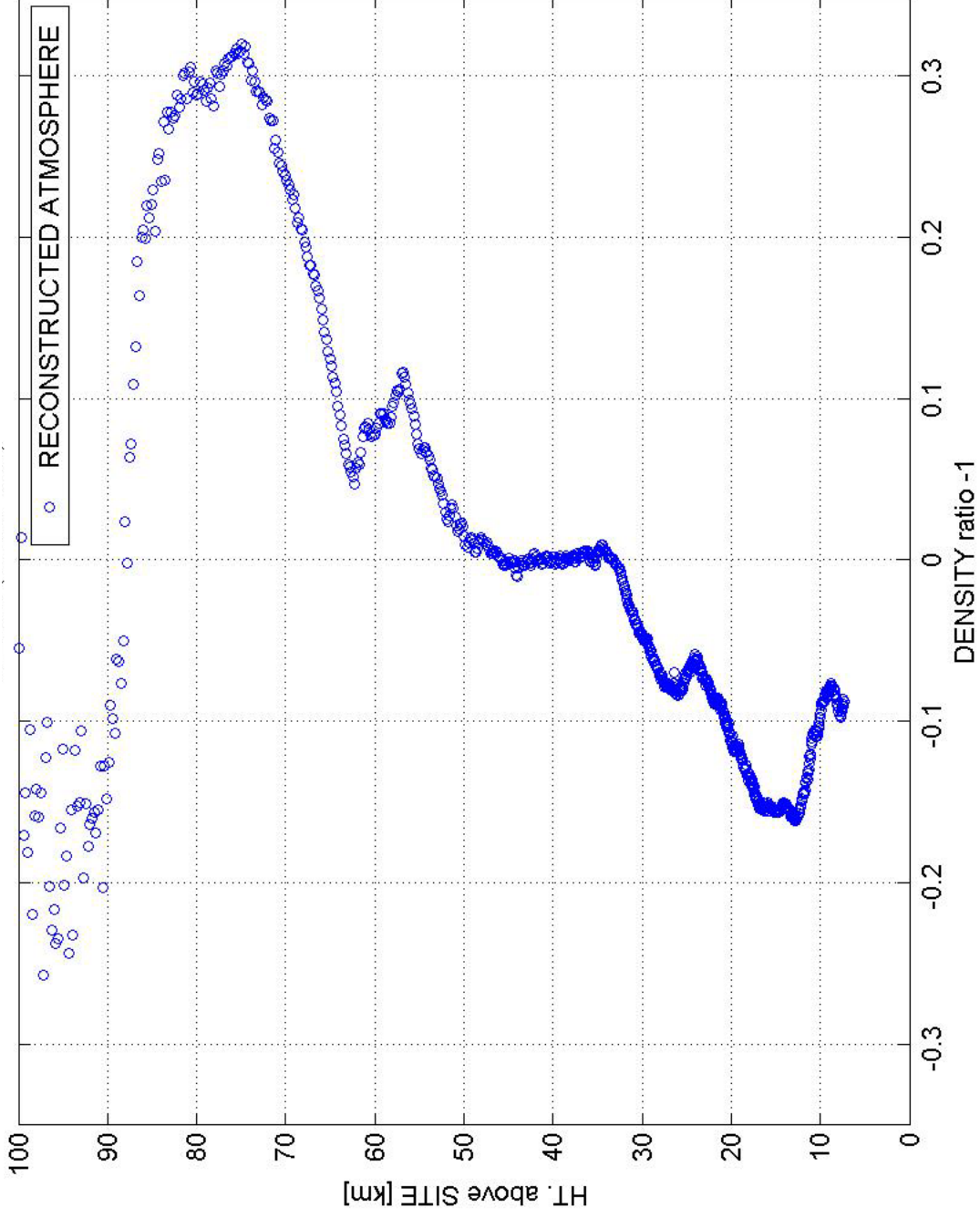
<sup>d</sup>Results obtained from 24DOF multi-body POST simulation.



# Reconstructed “Opportunity”’ Entry Density Profile

LaRC

Mars Exploration Rover

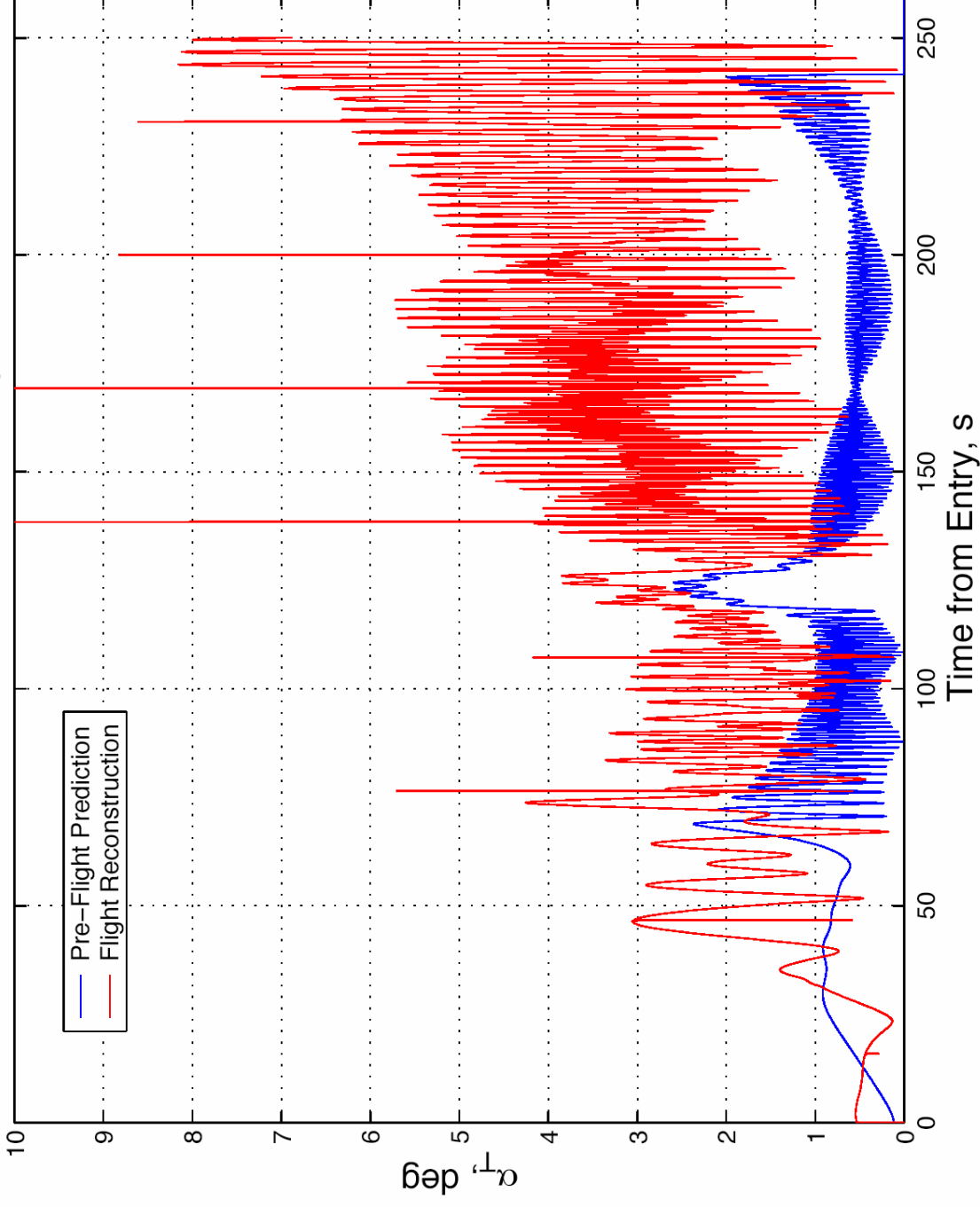




# “Opportunity” Attitude Reconstruction LaRC

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

## LaRC

### 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