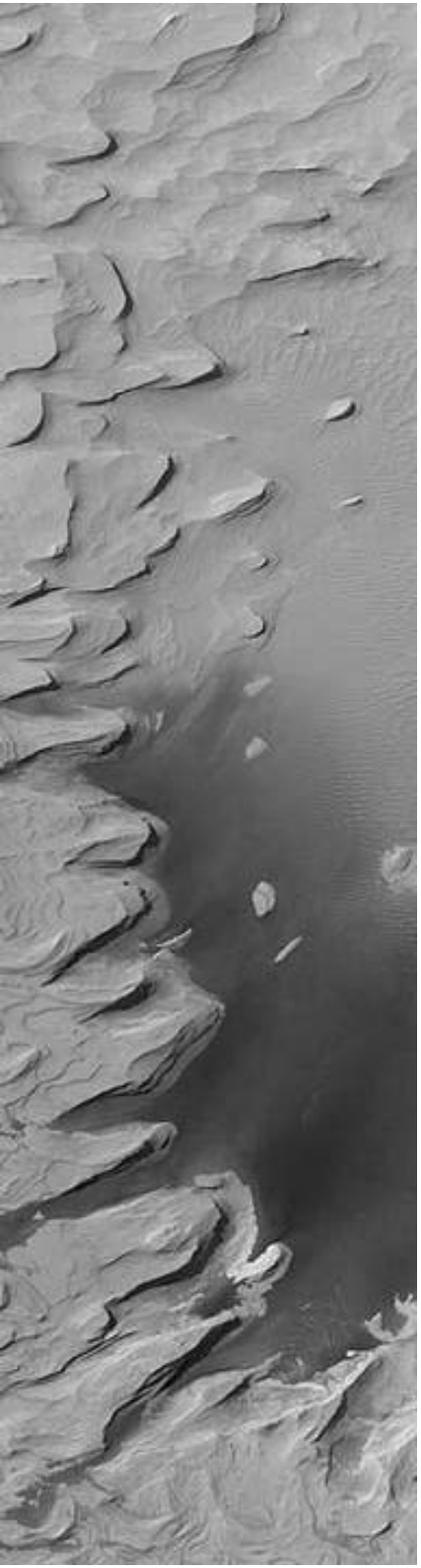


Lessons Learned and Flight Experience from Planetary Parachute Development

Douglas S. Adams

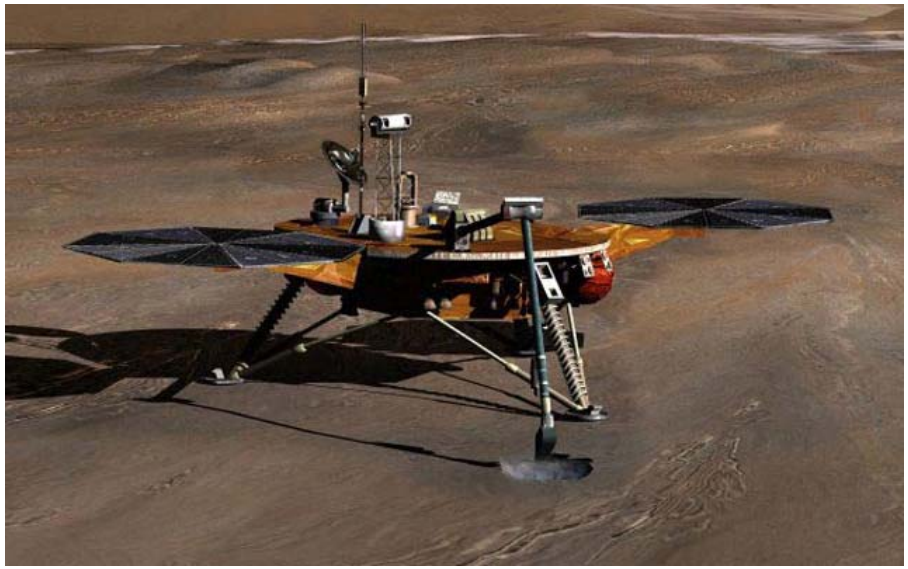
Jet Propulsion Laboratory

California Institute of Technology

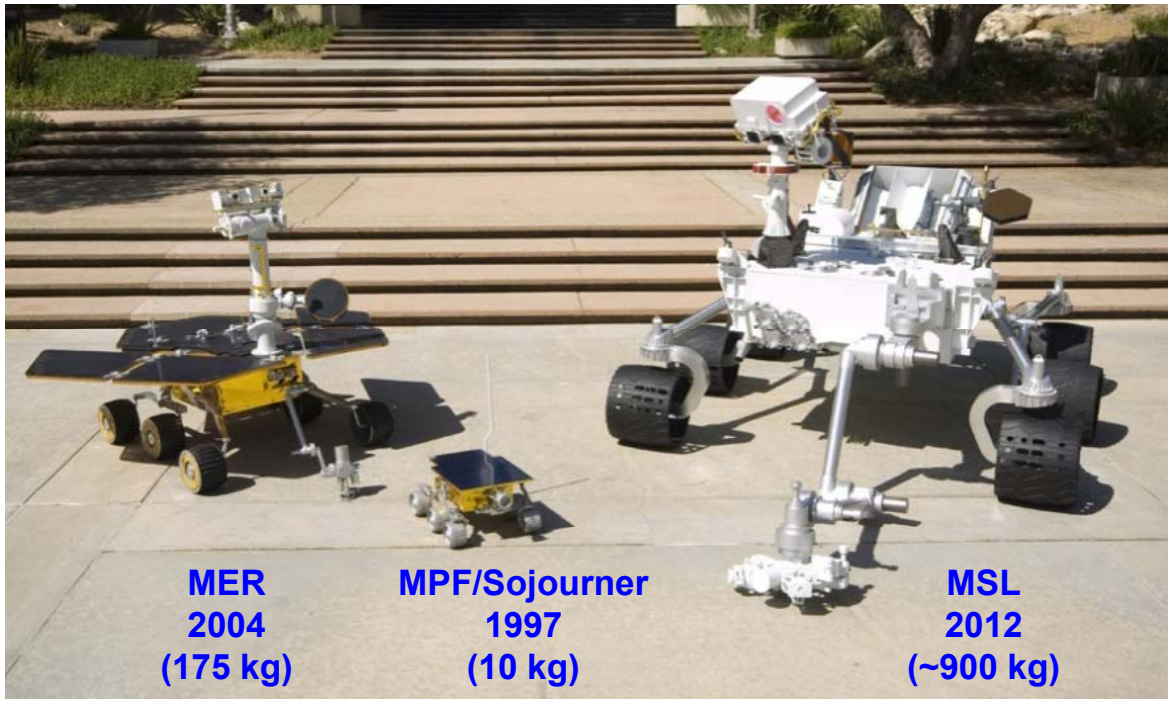
7th International Planetary Probe Workshop (IPPW7)
Barcelona, ES
14-18 June, 2010

Overview

- Testing methods and challenges for structural qualification
- Historical perspective of the importance of the parachute supersonic dynamics & opening loads
- Phoenix supersonic parachute performance and wrist mode excitation
- Other challenges to parachute growth
- Speculation on parachutes beyond MSL



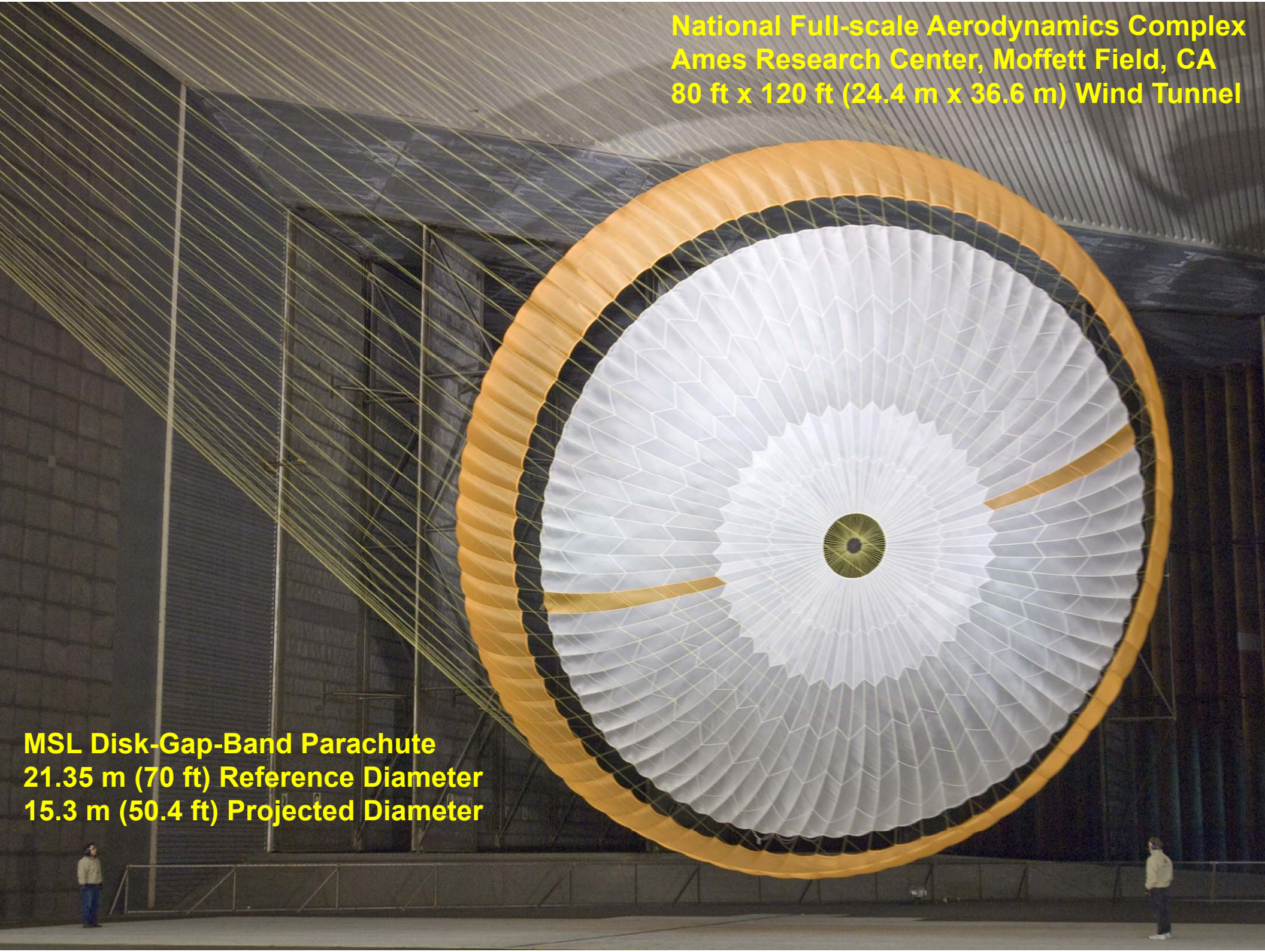
Phoenix
2008
(345 kg)



MER & Phoenix Parachute in NFAC

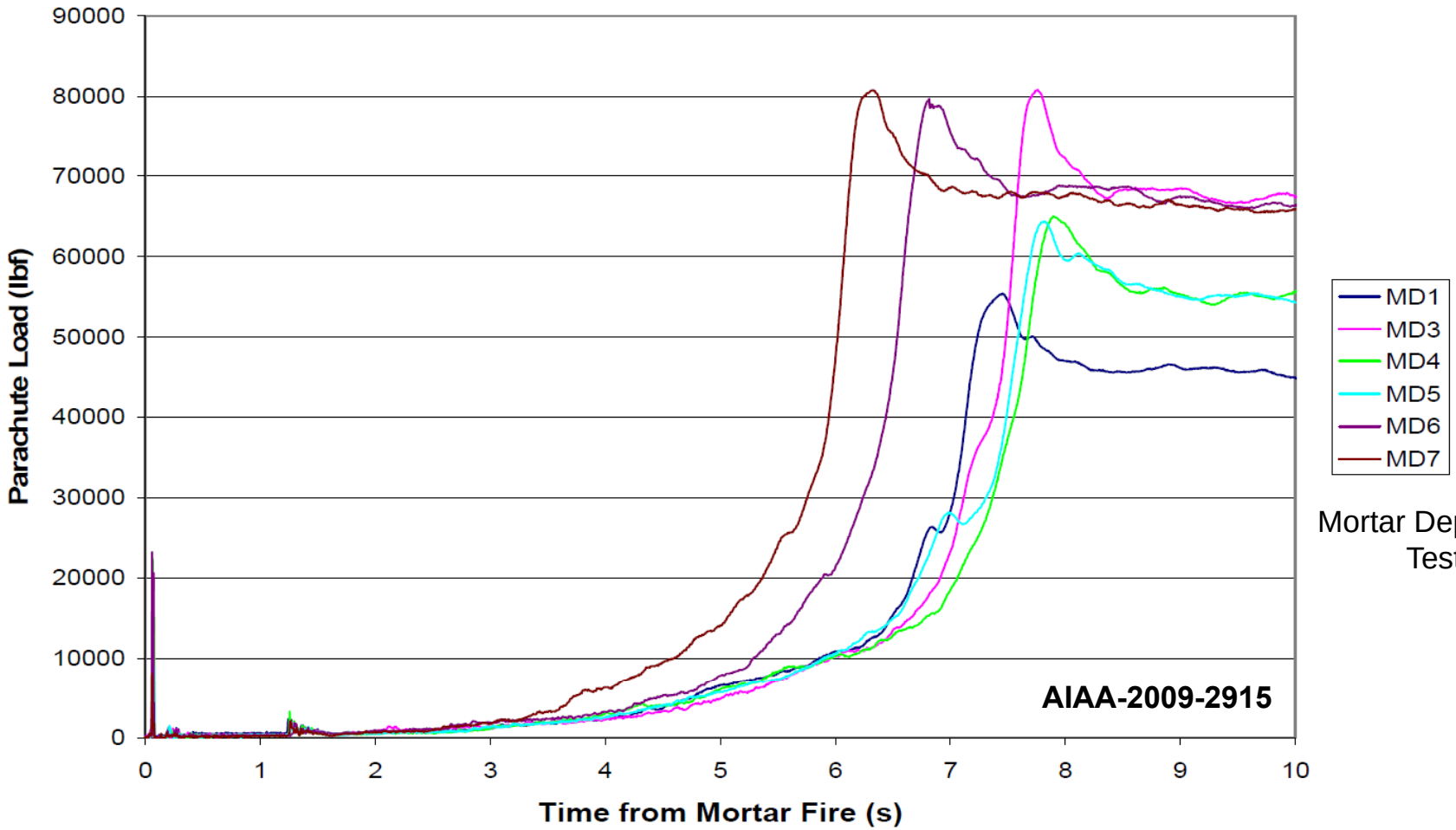
MER (14.1 m D_o)

Phoenix (11.8 m D_o)


National Full-scale Aerodynamics Complex
Ames Research Center, Moffett Field, CA
80 ft x 120 ft (24.4 m x 36.6 m) Wind Tunnel
MSL Disk-Gap-Band Parachute
21.35 m (70 ft) Reference Diameter
15.3 m (50.4 ft) Projected Diameter

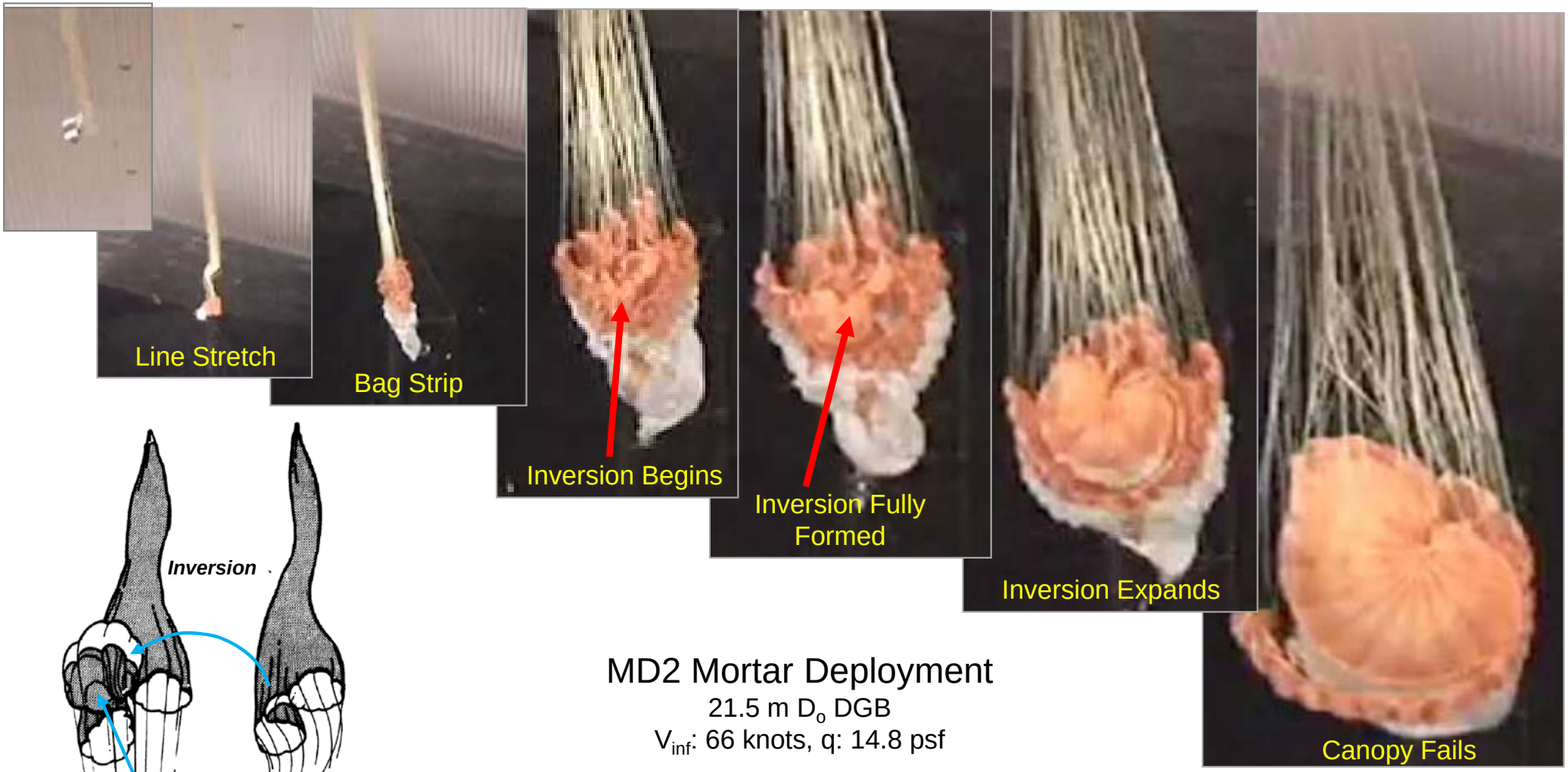
MSL Opening Time Uncertainty

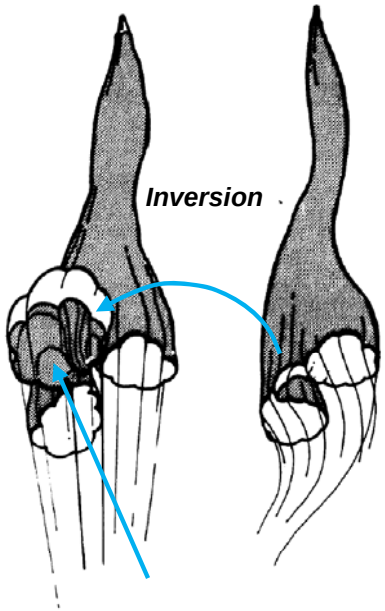
- Even under controlled velocity conditions in the NFAC wind tunnel the opening time variation was significant
  - A 2 second uncertainty corresponds to approximately 3 reference diameters
  - This results in about 20 m/s (66 ft/s) for a drop test which is huge!



Mortar Deployment (MD) Tests 1, 3-7

MD2 Parachute Inversion Summary



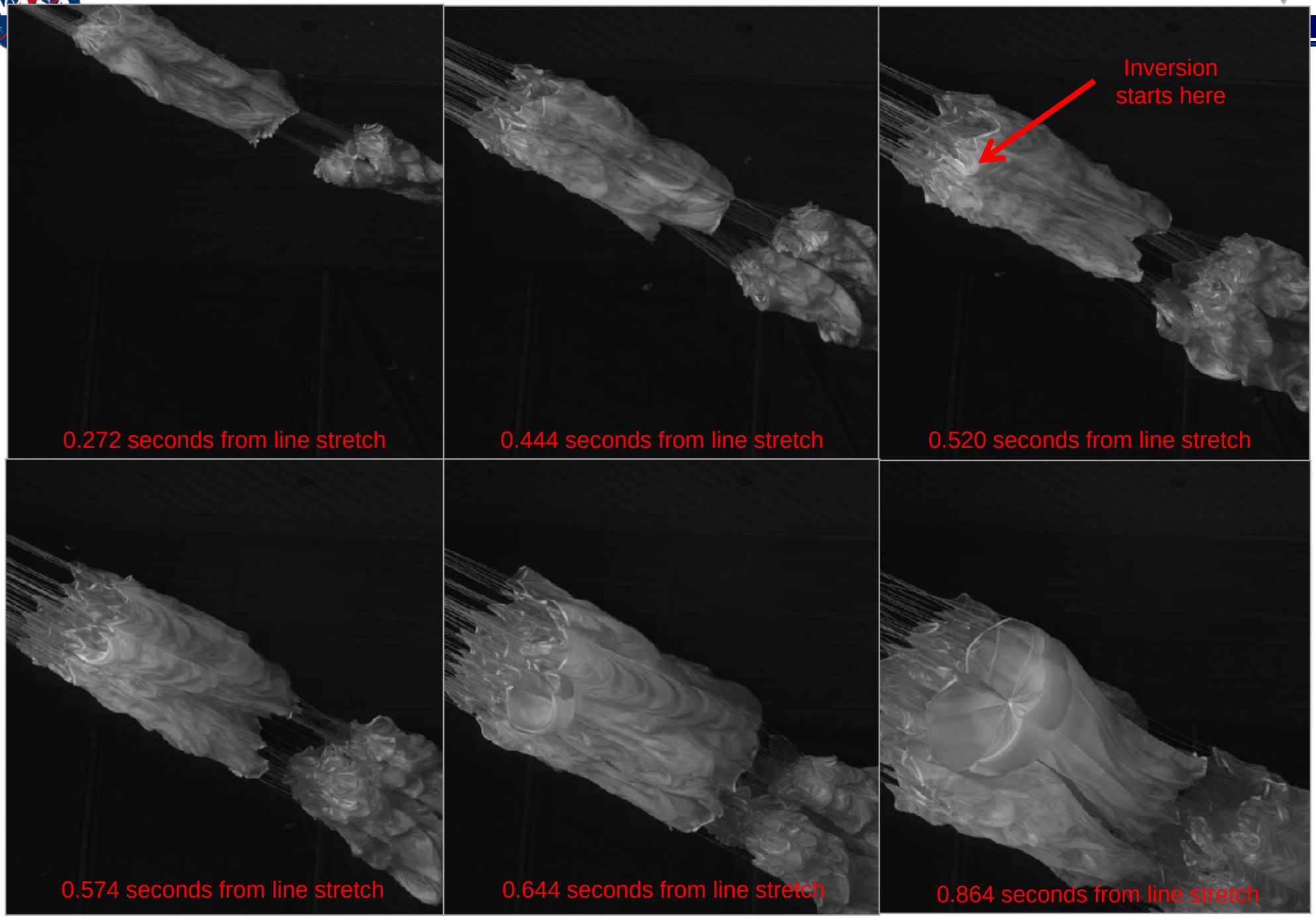


Portion of canopy is "inside-out"
J. D. Reuter, COMMERCIAL PARXCHUTES, AIAA 1979-0458

MD2 Mortar Deployment
21.5 m D_o DGB
V_{inf}: 66 knots, q: 14.8 psf

Canopy inversion begins during initial deployment phase. Expansion of the inversion led to catastrophic failure of the canopy. Standard videographic footage (as shown) was inadequate to clearly identify the root cause of the inversion.

MD8 Inversion Sequence

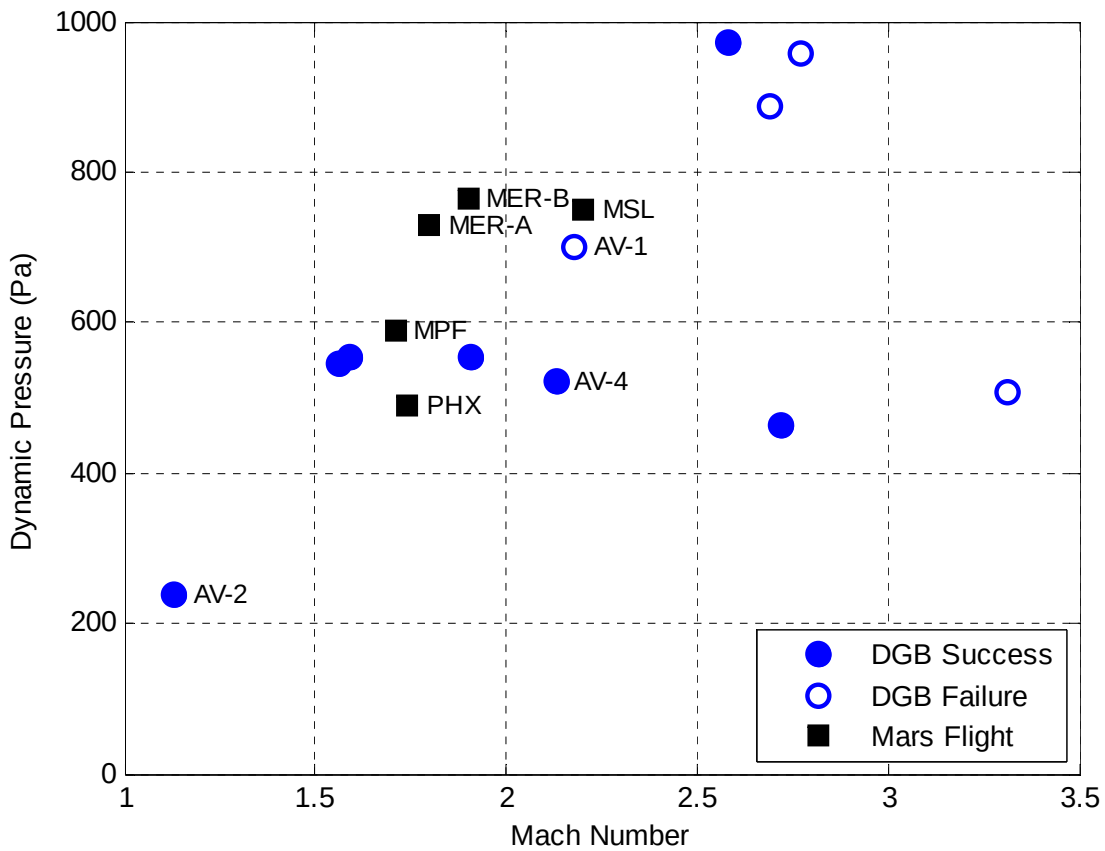


MSL Inversion Risk Assessment

- The physics of testing at NFAC are very different than flight
- It appears from all available data that Mars flight will not involve any of the behaviors witnessed in the NFAC
  - Initial inflation occurs during bag strip - the canopy is never flagging
  - The inflation process, both initial and final, happen before an inversion can develop
  - MSL period of vulnerability is low (<0.2 sec) and in all 10 sec of exposure to these conditions (supersonic data) no inversions have occurred
- There are no inversion countermeasures for which efficacy and hypocracy can be established without high altitude test
  - Deviating from flight heritage without additional testing is not recommended
- All available data suggests that MSL flight risk will be commensurate with other observed supersonic inflations (Viking, MPF, MER, PHX)
  - More than a dozen deployments and no inversions
  - Inversion risk appears very low
  - MSL flight risk is acceptable

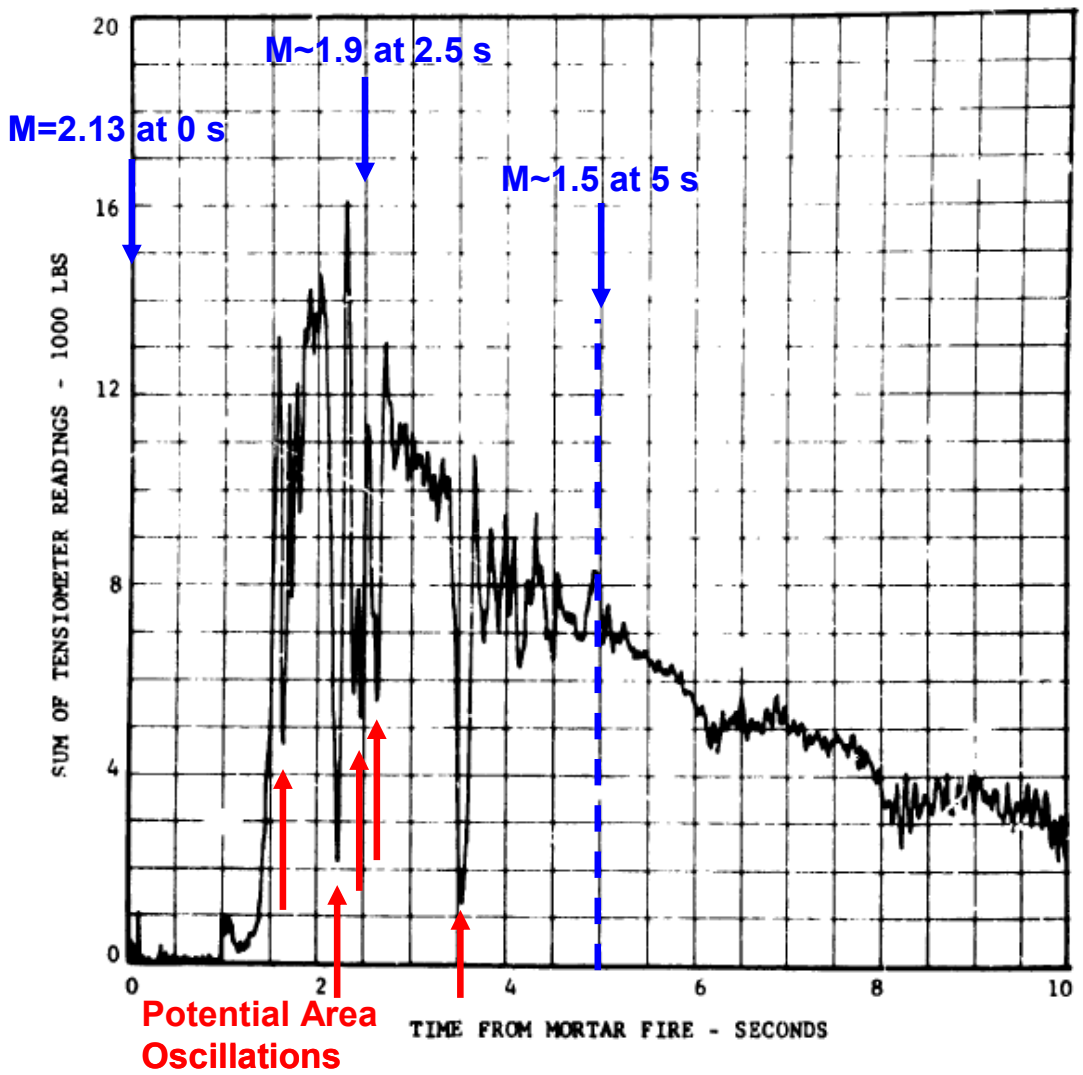
Historic Flight Data

- Historic flight data was leveraged extensively in the qualification of both the Phoenix and MSL parachutes
- The Phoenix flight conditions were much more benign than those expected for MSL



“Area Oscillations” Phenomenon

- Large load drop-outs in BLDT AV-4 (Balloon Launched Decelerator Test) at speeds above Mach 1.5 that are termed “area oscillations”

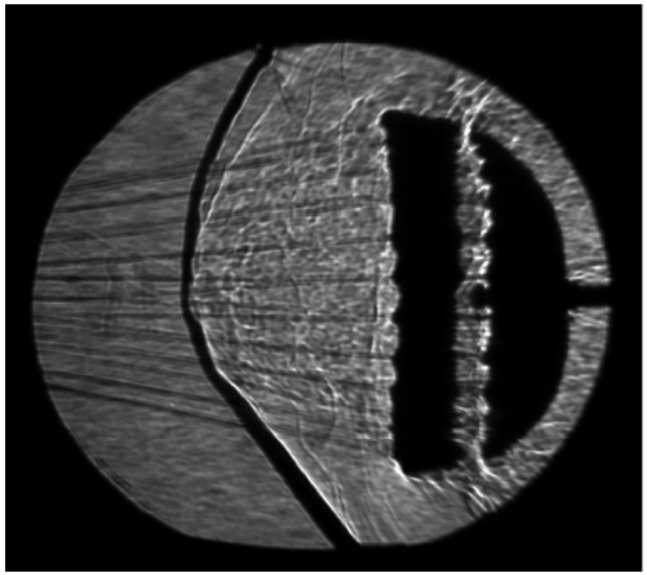


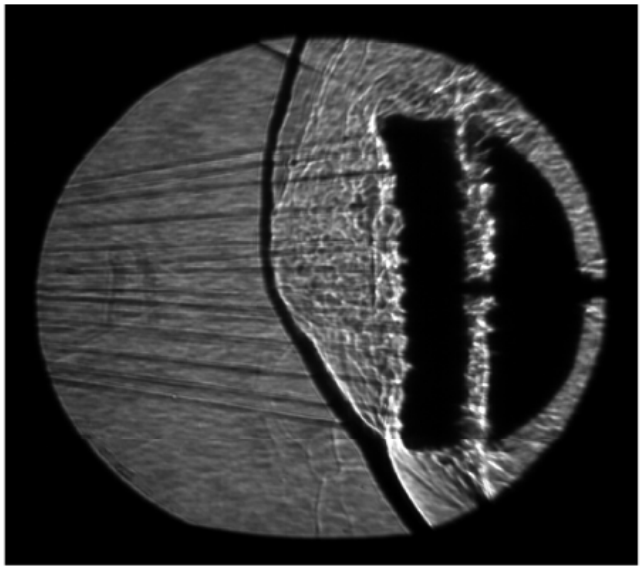
Viking BLDT AV-4
NASA-CR-112179
October 20, 1972

Constrained 4% Subscale Testing

Fully Inflated Condition | **Area Oscillation**

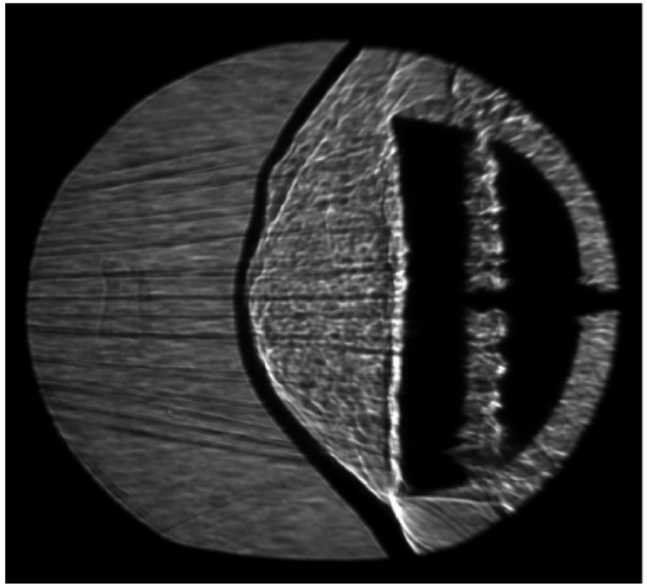
M=2.0

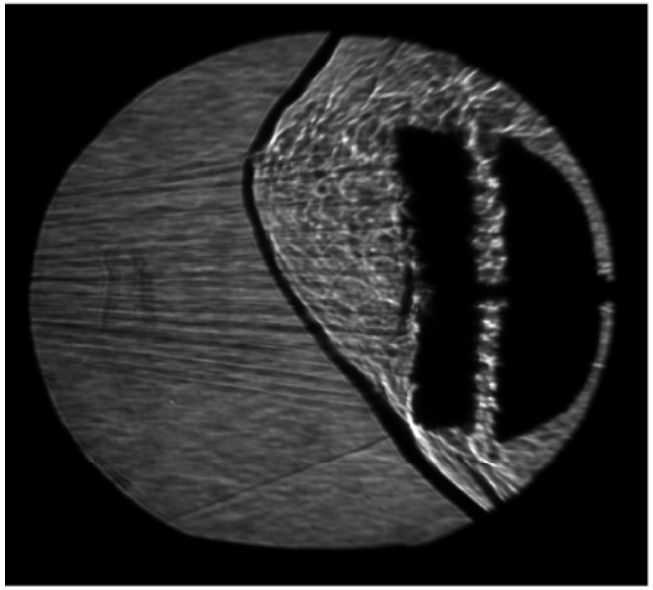




M=2.0

M=2.5

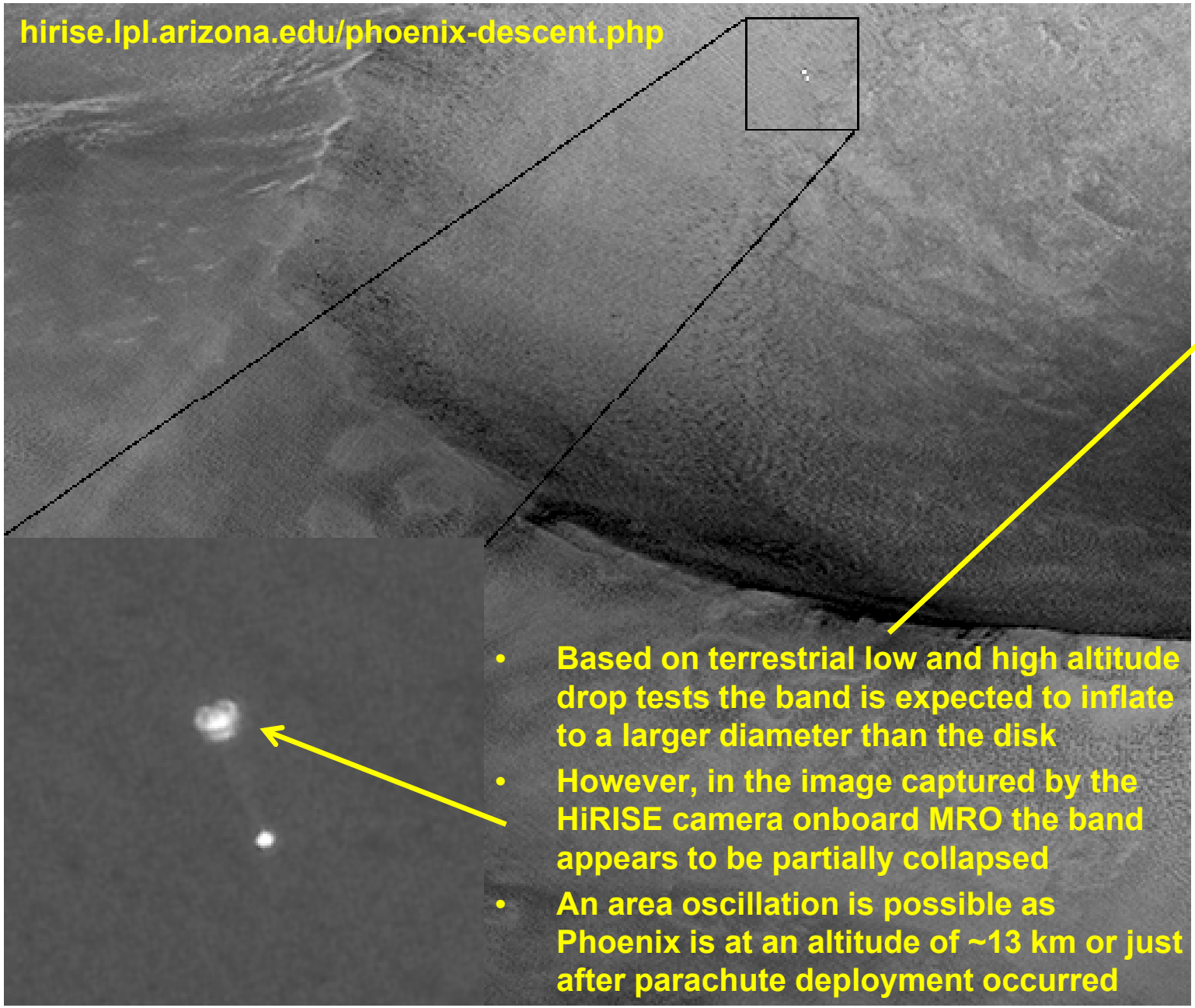




M=2.5

Sengupta, et al., AIAA JSR, Vol. 46, No. 6

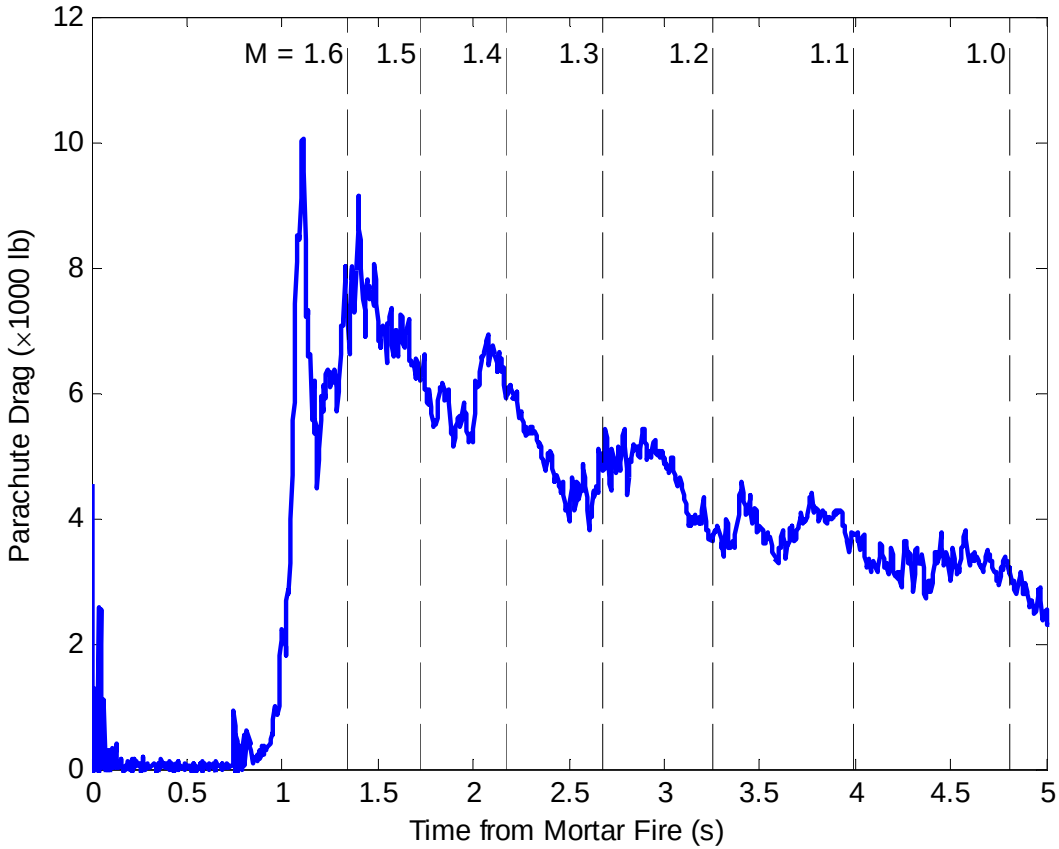
Phoenix Test and Flight Geometry



- Based on terrestrial low and high altitude drop tests the band is expected to inflate to a larger diameter than the disk
- However, in the image captured by the HiRISE camera onboard MRO the band appears to be partially collapsed
- An area oscillation is possible as Phoenix is at an altitude of ~13 km or just after parachute deployment occurred

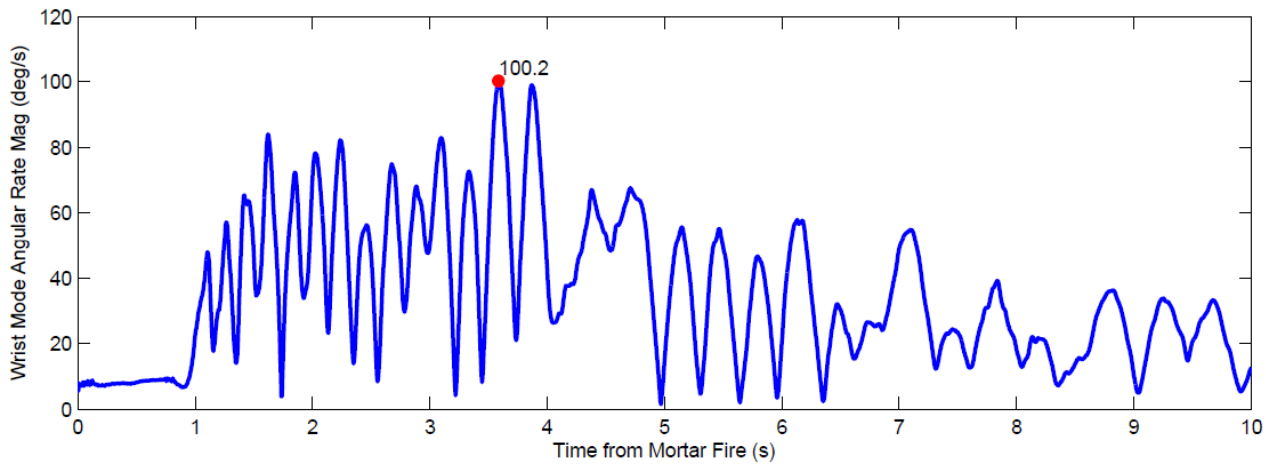
Phoenix Supersonic Parachute Drag Force

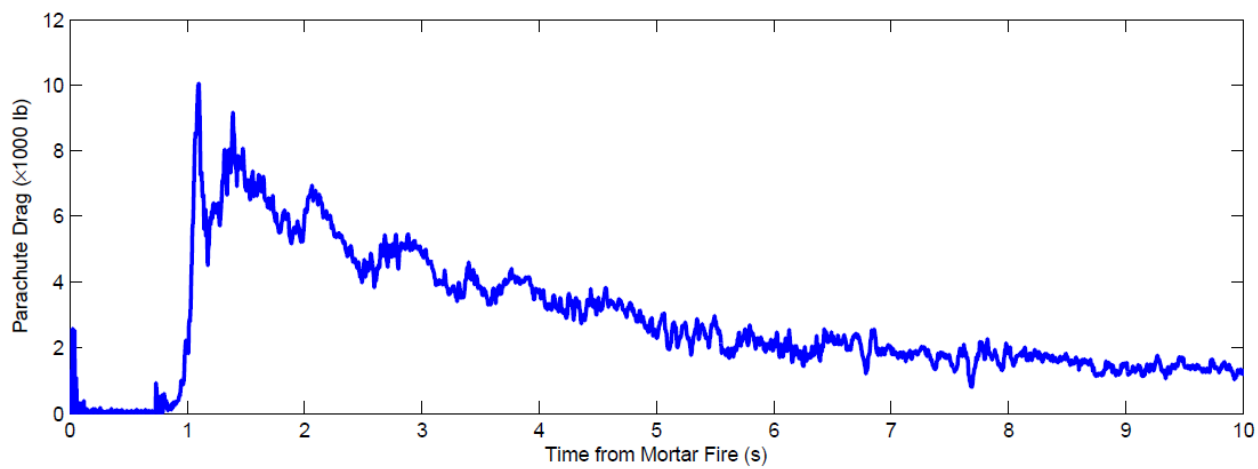
- The Phoenix 11.8 m D_o parachute opened faster than any any DGB deployed on Mars or at high Earth altitudes (0.365 seconds)
- There was only one significant area oscillation (drag reduction) above Mach 1.5
- Drag stability below Mach 1.5 was consistent with the BLDT data



Phoenix Wrist-mode Stability

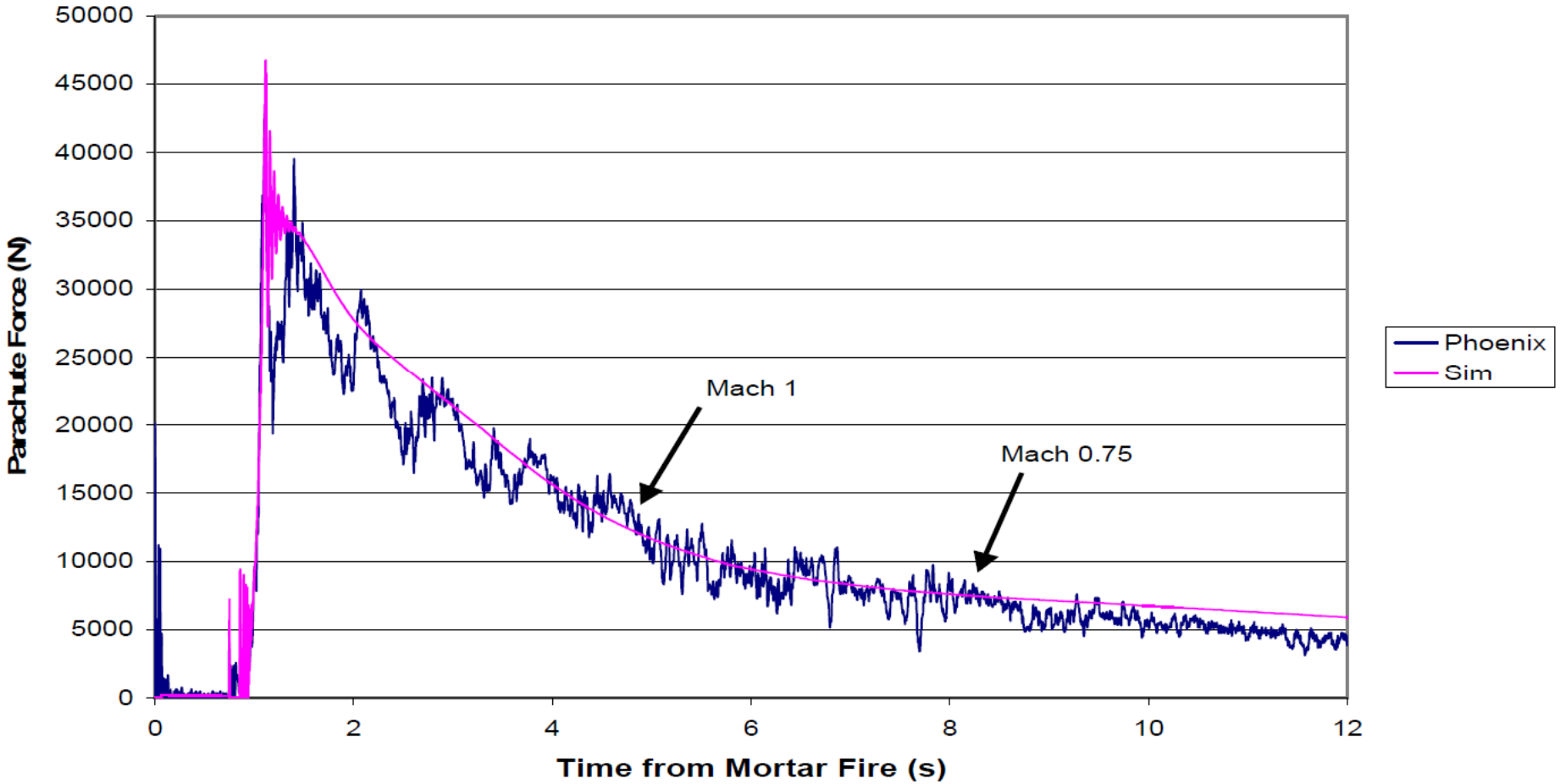
- The wrist-mode was excited by the initial opening, drag force variability, & instability
- The amplitude grew from an initial rate of ~50 deg/s to just over 100 deg/s in the first 4 s before decaying due to hysteretic mechanisms
  - Both of these behaviors were expected





Phoenix Flight Drag vs. Model Comparison

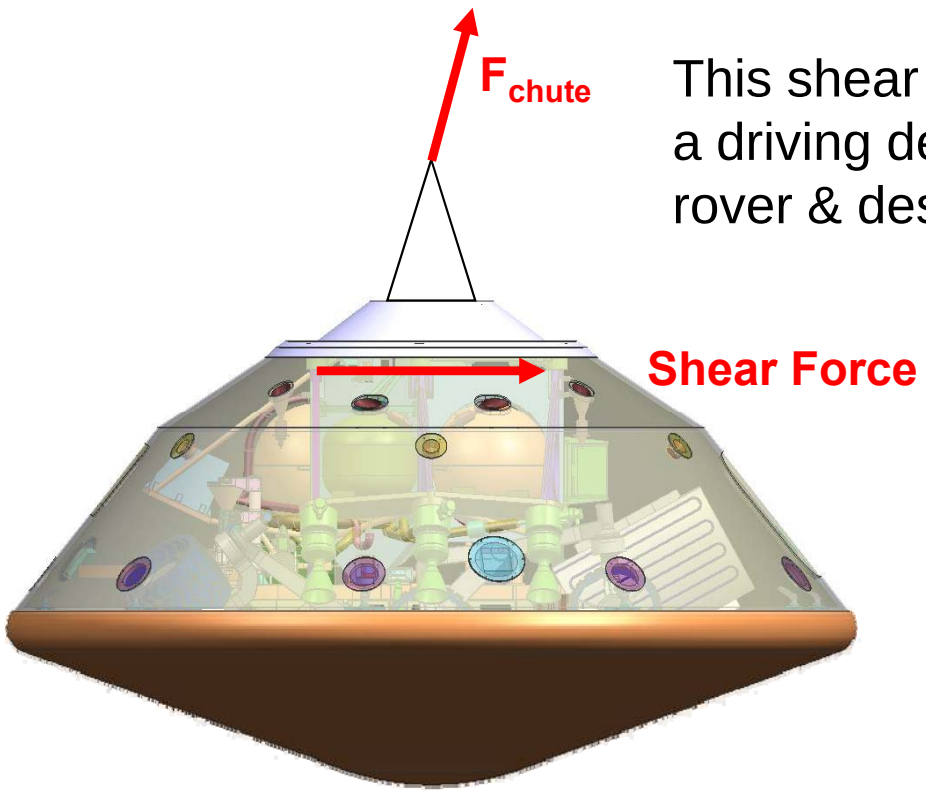
- A comparison of the flight drag was made with a post-flight simulated parachute opening with excellent agreement
  - A number of parameters were updated to better reflect flight conditions



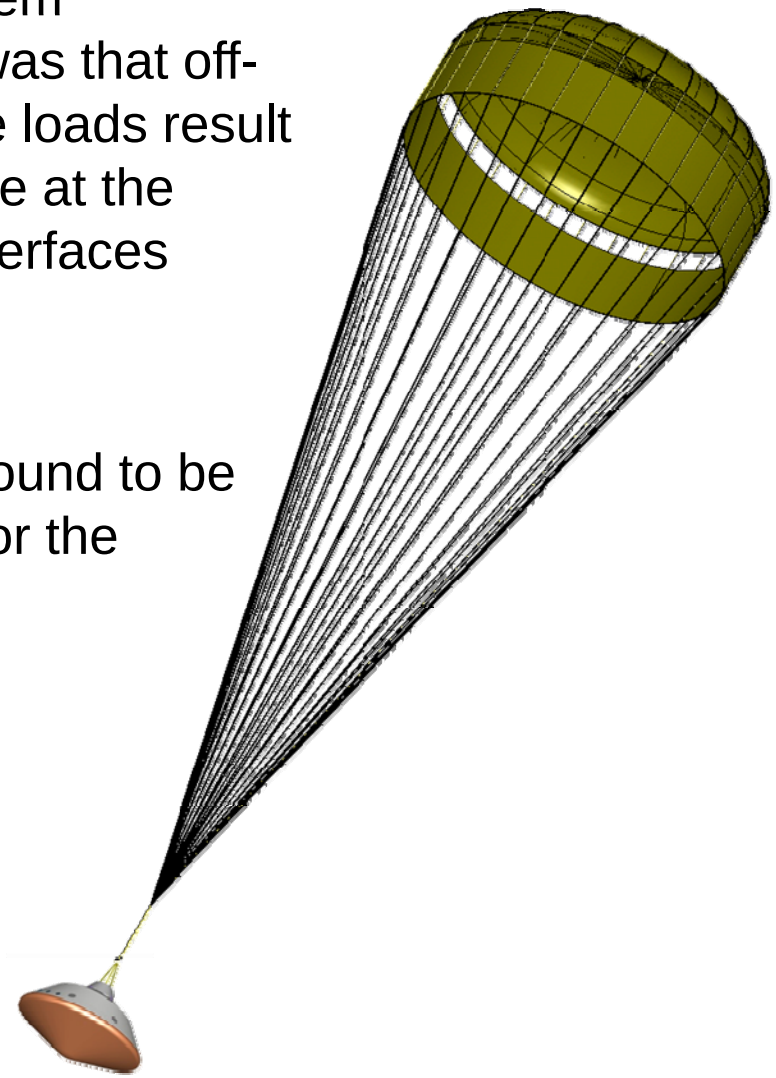
Witkowski, Kandis, & Adams, AIAA-2009-2907

MSL Off-axis Parachute Shear Loads

An early problem encountered was that off-axis parachute loads result in a shear force at the component interfaces



This shear force was found to be a driving design load for the rover & descent stage

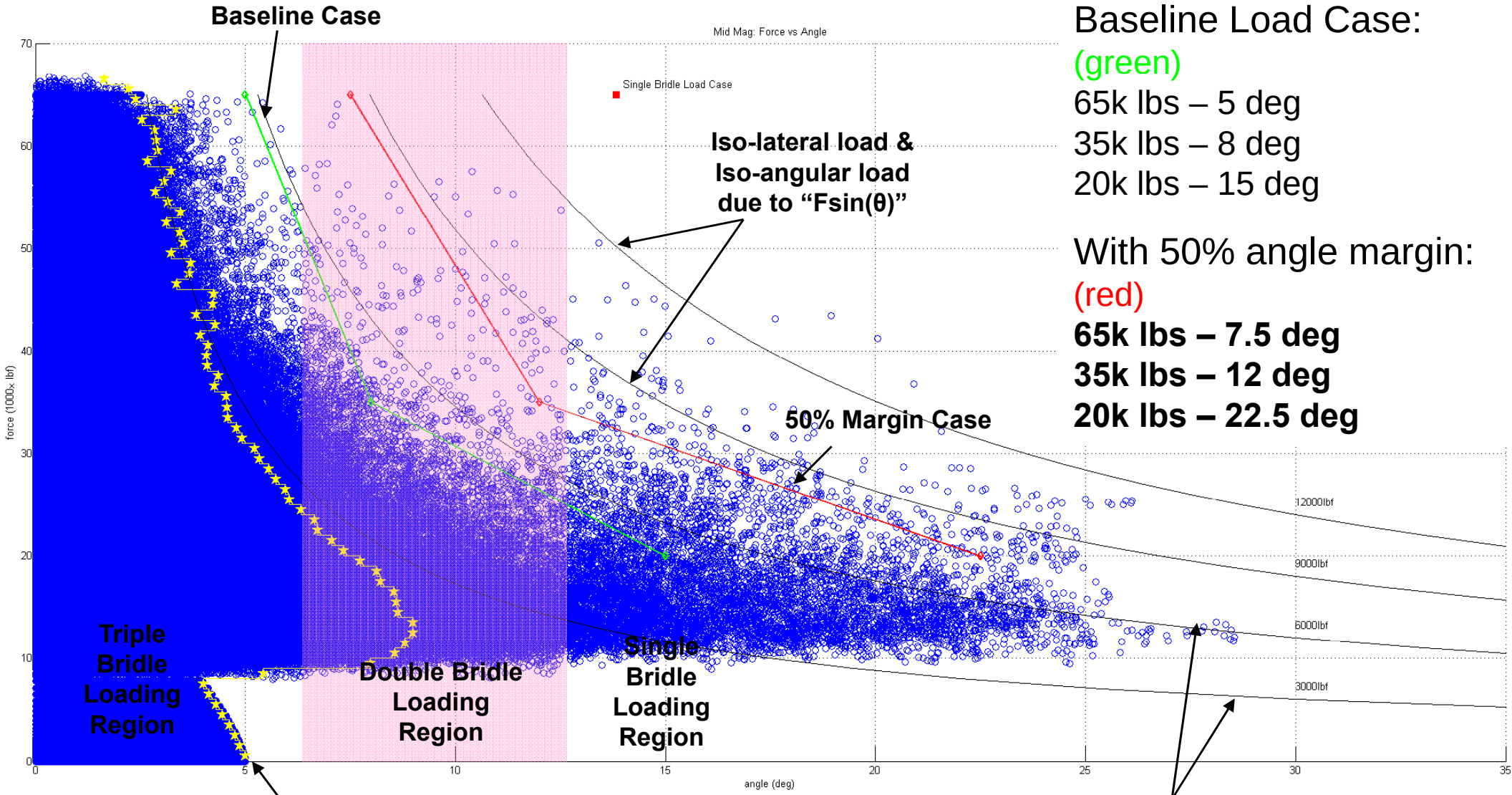


Area Oscillation Modeling

- Use Pflanz inflation profile with re-loading events superimposed
- Randomize the re-loading events under rules based on:
  - Number of Events
  - Magnitude
  - Frequency
  - Mach number
- Create profiles whose characteristics are in family with BLDT AV-4 and AV-1 data for use in a Monte Carlo analysis
- Events occur between Mach 2.2 (after first inflation) through around Mach 1.5
  - The ending Mach number is also varied as a parameter in the simulation

Mid Magnitude Monte Carlo Results

(5,000 Cases)



Baseline Load Case:
(green)
65k lbs – 5 deg
35k lbs – 8 deg
20k lbs – 15 deg

With 50% angle margin:
(red)
65k lbs – 7.5 deg
35k lbs – 12 deg
20k lbs – 22.5 deg

Growing Pains

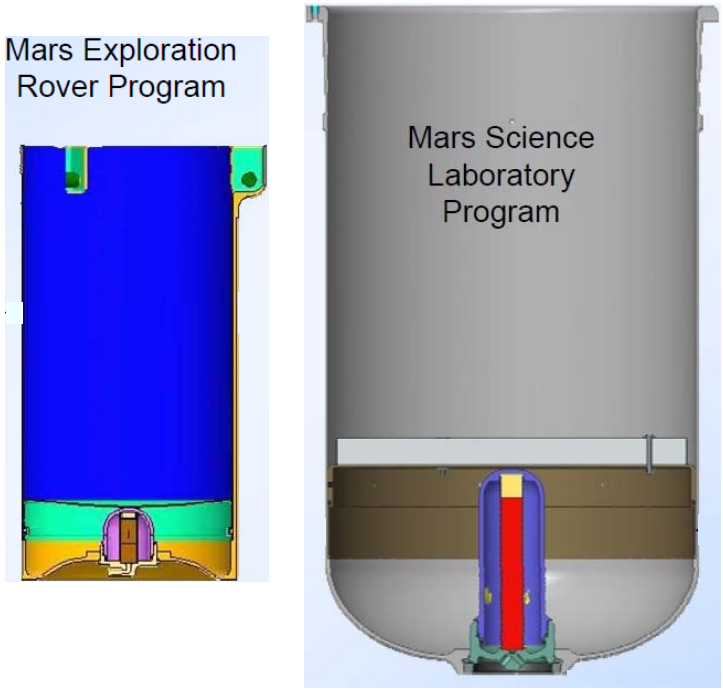
- Parachute pack stiffness / density
- Mortar gas generator performance
- Deployment bag mass
- Triple bridle confluence fitting

This is an actuator!

MER & Phoenix – Link was 0.38 kg
MSL – Confluence Fitting is 3.8 kg or 10x the mass
Testing required 162,500 lbf (73,700 kgf) equipment and 3-D restraints

Mortar Deployment System Growth

- Parachute mass growth resulted in significant design changes from the MER/PHX mortar paradigm to the MSL mortar
- The Parachute Close-out Cone (PCC) lid also grew to the point that it became a threat to the parachute during EDL



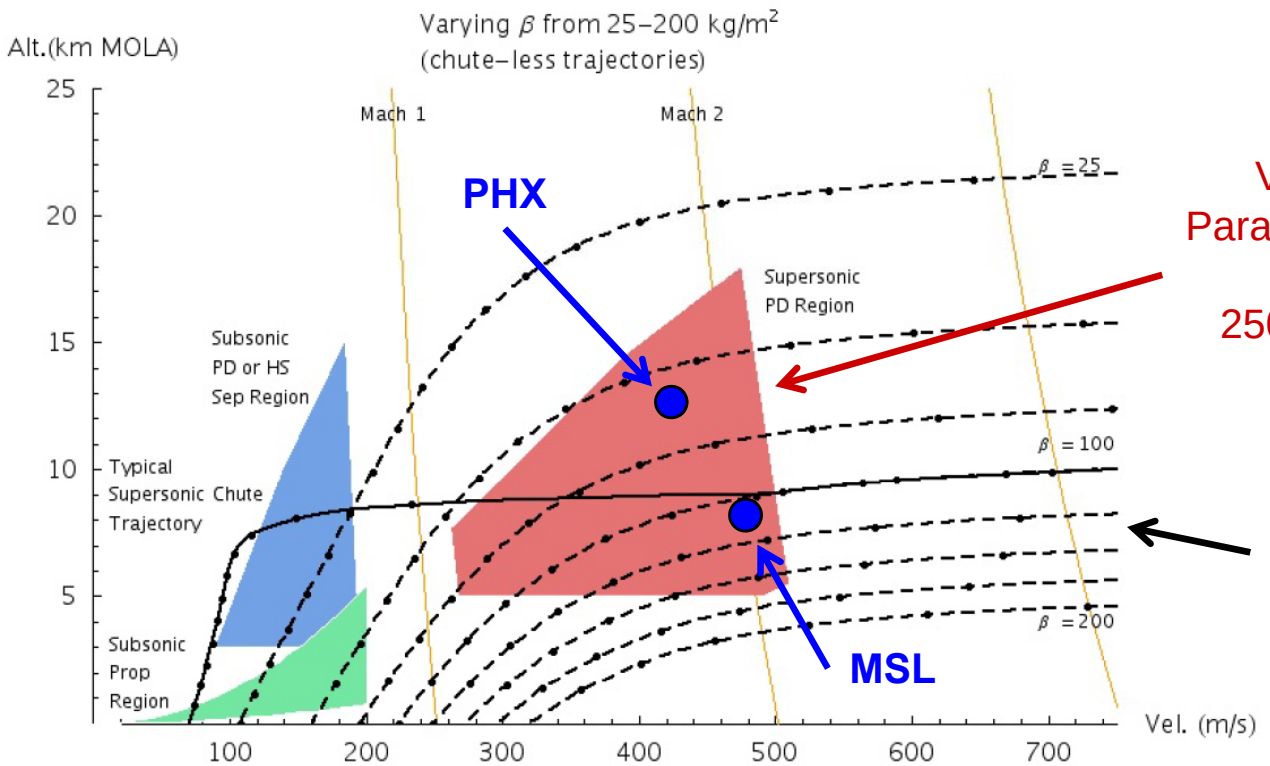
Scale Comparison of MER/MSL

MSL Mortar Test Stand

MSL PCC Lid

The Supersonic Problem

- Viking heritage supersonic parachute technology has a restricted Mach-dynamic pressure deployment region without further testing
- Straight scaling of MSL from an Atlas V 531 to an Atlas V 551 results in a ballistic coefficient on the order of ~170 kg/m2
- This is approaching the limit of a single stage supersonic parachute



Viking Supersonic
Parachute Deploy Region
1.1 < M < 2.1
250 Pa < q < 1200 Pa
h > 5 km

Lines shown for
L/D = 0.18

Braun & Manning, AIAA JSR Vol. 42, No. 2, and IEEEAC-0076

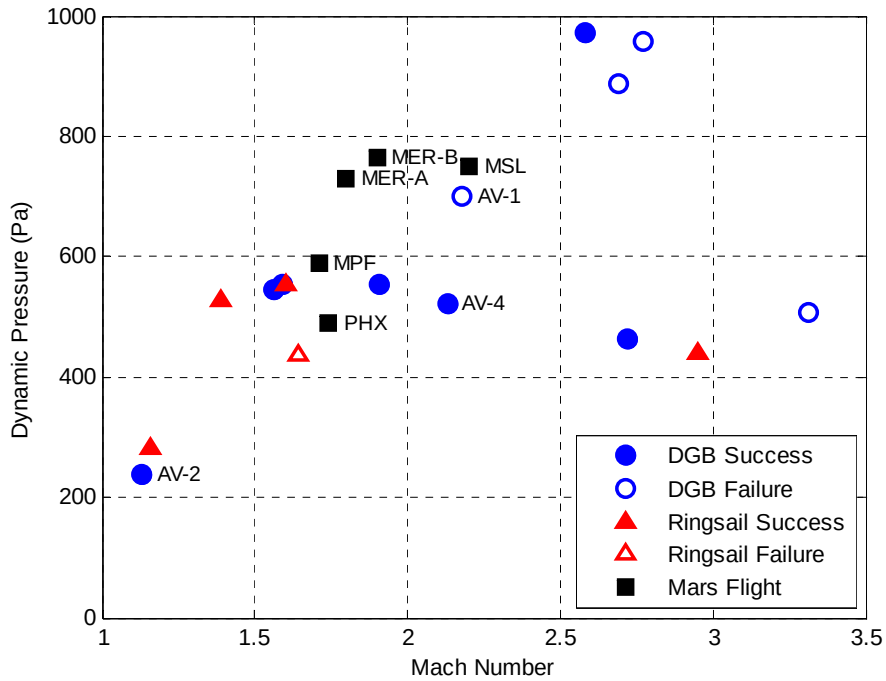
Viking DGBs Beyond MSL?

- It is dangerous to embark upon such endeavors but …
- If we use the MSL ballistic coefficient to estimate the terminal descent requirements for powered landing …
- And we assume a similar launch/entry body mass ratio …
- Then it *may be* possible to exhaust the Atlas V launch capability using a single stage supersonic DGB?

	Launch Vehicle	Launch Mass (kg)	Terminal Descent Mass (kg)	Parachute Ref. Dia. Do (m)	Parachute Subsonic Cd	Ballistic Coefficient β = m/CdA (kg/m^2)
PHX (flight)	Delta II	664	510	11.8	0.6	7.8
MSL (allocated)	Atlas 531	4050	2561	21.35	0.6	11.9
2018 and Beyond?	Atlas 541	4700	2972	23	0.6	11.9
	Atlas 551	5118	3236	24	0.6	11.9
	Heavy	5553	3512	25	0.6	11.9

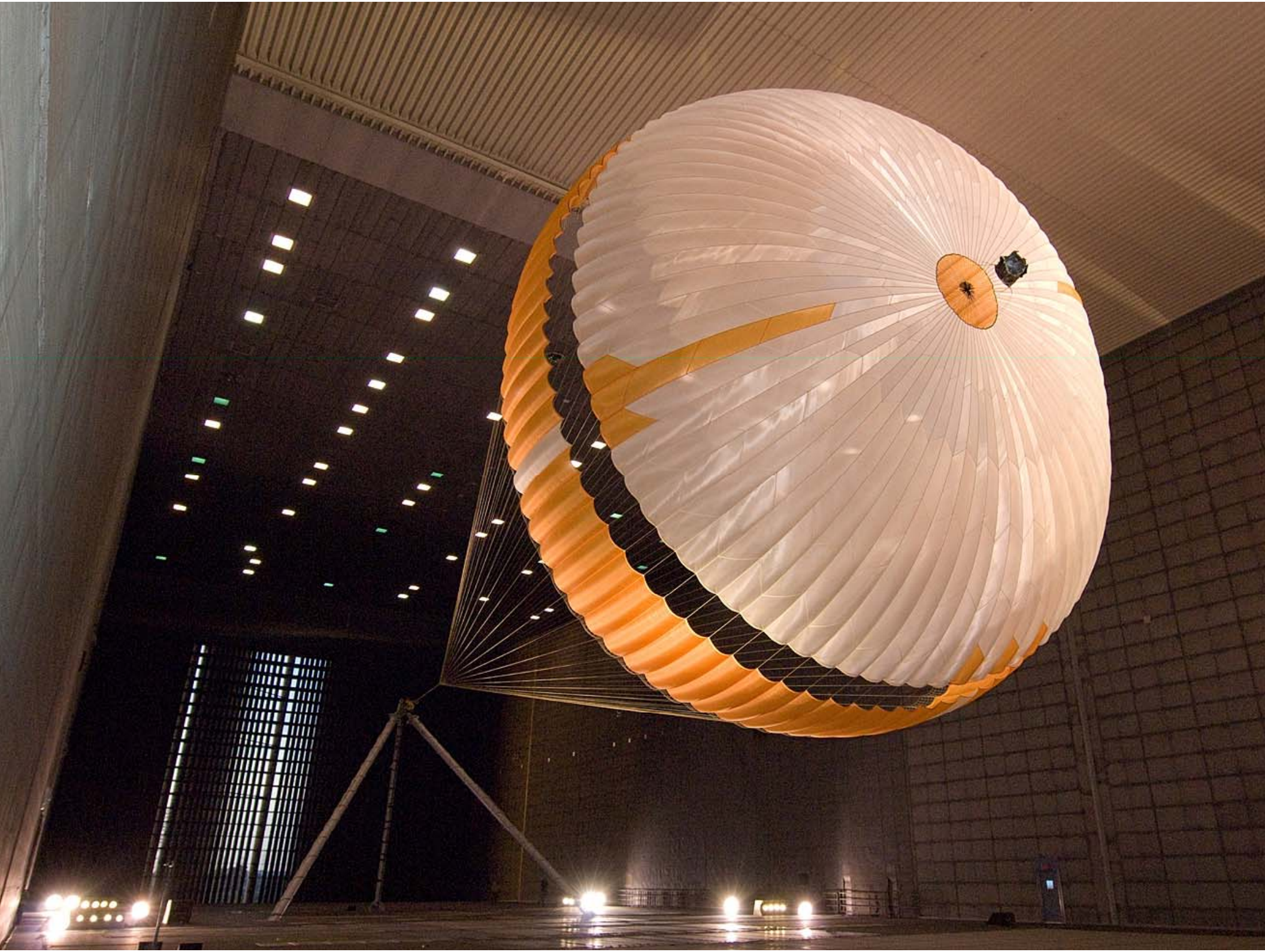
What About Ringsails?

- Ringsails offer more mass efficient drag generation but data under Mars conditions is limited at both supersonic and subsonic speeds
  - May require 2-stage DGB or IAD deployment to enable their use



Parachute Type	Nominal Diameter D_0 (m)	Deployment Mach Number M	Deployment Dynamic Pressure q (Pa)	Deployment Altitude h (m)	Test Vehicle Mass m_v (kg)	Successful?
Ringsail	12.2	1.64	436	26.5	108	No
Ringsail	26.0	1.16	282	40.4	125	Yes
Ringsail	9.5	1.39	527	37.3	100	Yes
Ringsail	16.6	1.60	555	40.2	244	Yes
Ringsail	12.2	2.95	440	52.3	127	Yes

Cruz & Lingard, AIAA-2006-6792

35.5 m Ringsail High Altitude Deployment Test

Witkowski, Machalick, & Taeger, AIAA-2005-1657