# Underexpanded supersonic plume surface interactions: applications for spacecraft landings on planetary bodies


**Manish Mehta, Ph.D.**
Aerosciences Branch, EV33
NASA Marshall Space Flight Center
**Anita Sengupta, Ph.D.**
NASA Jet Propulsion Laboratory
**Nilton O. Renno, Ph.D.**
University of Michigan
**John W. Van Norman**
Analytical Mechanical Associates, Inc.
**Peter G. Huseman and Douglas S. Gulick**
Lockheed Martin Space Systems



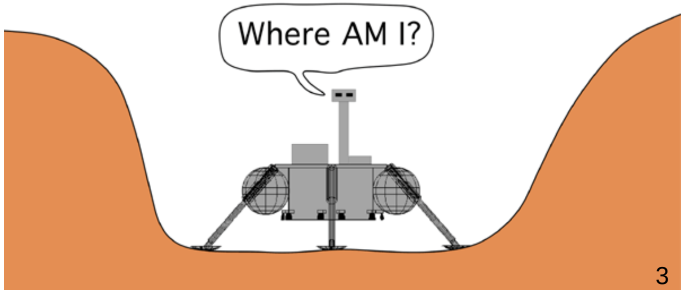

April 18,2011

# Outline

- **Introduction**
  - Motivation
  - Near-field and far-field plume flow fields
  - Scaling Theory
- **Phoenix Mars spacecraft**
  - Experimental
  - Numerical
  - Data comparison/Flow Physics
- **Mars Science Lab (MSL) Descent Stage spacecraft**
  - Experimental
  - Numerical
  - Data comparison/Flow Physics
- **Conclusion**

# Motivation

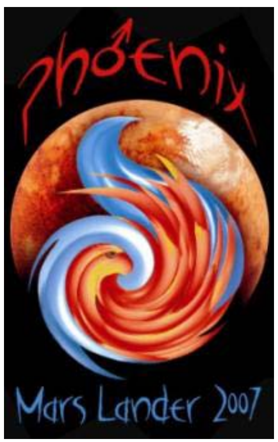
- **Plume-surface interactions due to spacecraft landings**
  - Spacecraft stability and survival
    - Moments/Torques
    - Updraft plumes
    - Plume induced heating
  - Cratering & dust lifting
  - Implications for manned and large payload landings to Mars, moon, asteroids and other planetary bodies
- **Theory, test data and numerical simulations were used to characterize the complex plume impingement physics and identify the environments observed due to spacecraft landings**



# Motivation

## 1998 Mars Polar Lander Failure Report
## *(Whetsel et al, 2000)*

- MPL Project failed to conduct studies on plume-surface interactions
- Recommended these investigations for future powered descent landing missions to Mars




2007


2011

These NASA spaceflight projects deemed it necessary to conduct these investigations thru University research partnership.

Phoenix: Pulsed-modulated descent system (Rocket Engine Module – REM)

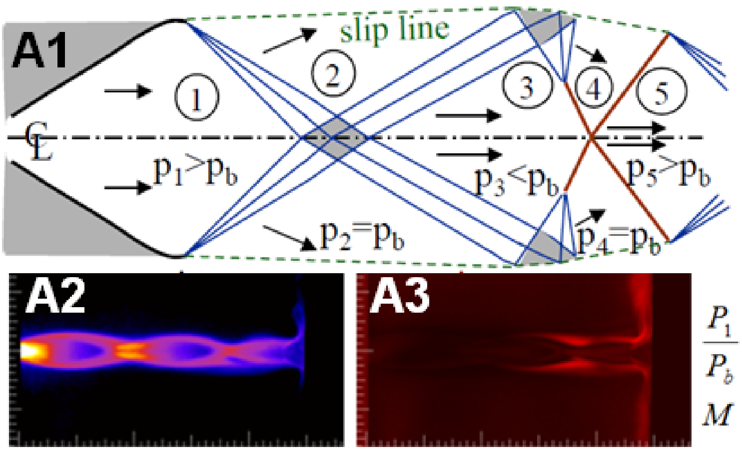
Mars Science Lab: Sky-crane throttled landing system (Mars Landing Engine – MLE)

Last detailed study was completed in 1973 for Viking 1 and 2.

# Near-field flow – TEST DATA

# Far-field flow/ Impingement zone – TEST DATA

## Underexpanded Supersonic Jet

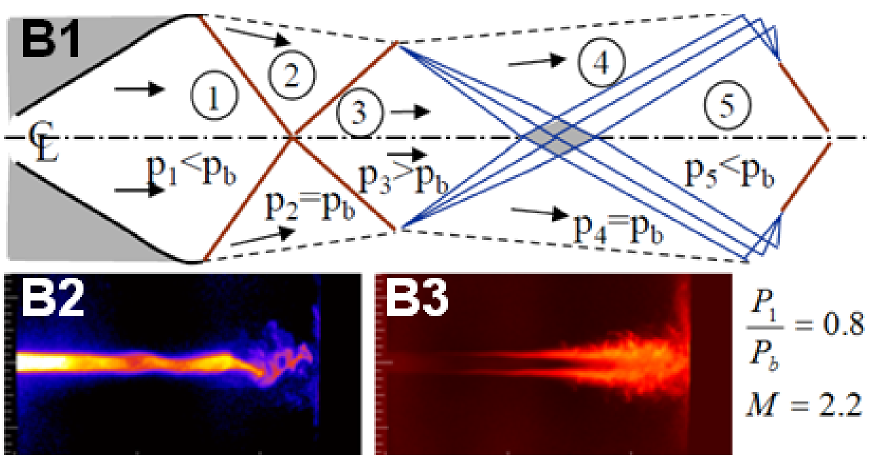



$\frac{P_1}{P_b} = 3.4$

$M = 2.2$

Planar Laser Induced Fluorescence Imaging

## Overexpanded Supersonic Jet

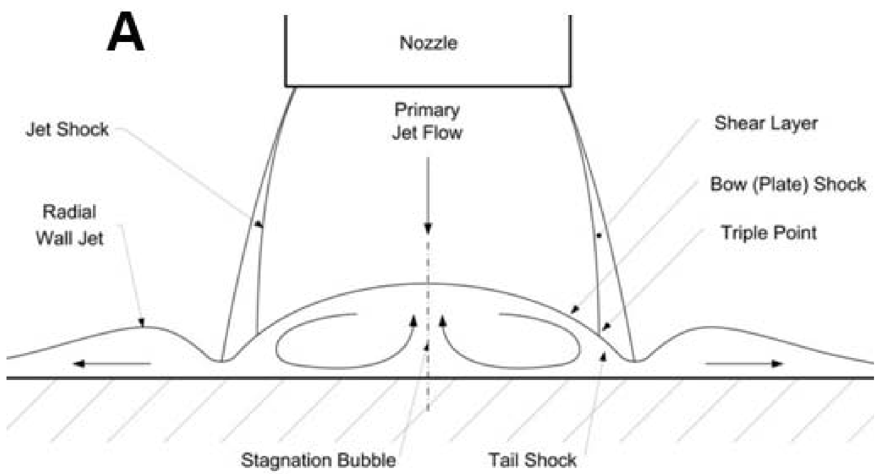


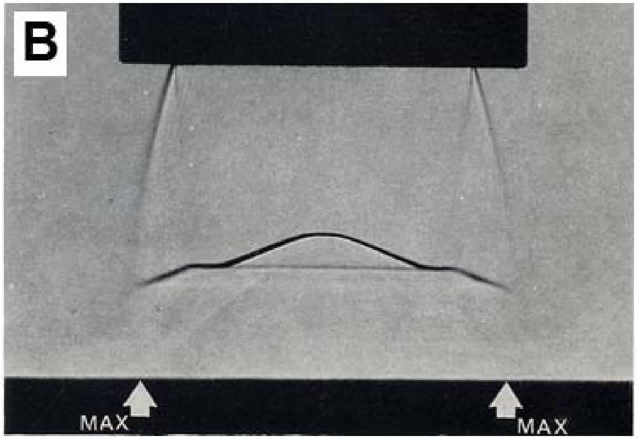

$\frac{P_1}{P_b} = 0.8$

$M = 2.2$

*Inmann et al., 2009*

**Important flow structures with implications to cratering, acoustics and spacecraft dynamics during descent**




*Lamont and Hunt, 1976*

# Scaling theory for plume-surface interactions

$$\frac{D\rho}{Dt} = -\rho\,\nabla\cdot\vec{U}$$ **Continuity**

$$\rho\frac{D\vec{U}}{Dt} = \vec{f} - \nabla p + \nabla\cdot[\vec{\tau}]$$ **Conservation of Momentum**

$$\rho c_p \frac{DT}{Dt} = \nabla\cdot(\lambda\nabla T) + \beta T\frac{Dp}{Dt} + \phi$$ **Conservation of Energy**

**Nondimensional Navier-Stokes Equations**

$$\frac{D\rho'}{Dt'} = -\rho'\,\nabla'\cdot\vec{v}'$$

$$\rho'\frac{D\vec{v}'}{Dt'} = \frac{1}{\mathrm{Fr}^2}\rho'\vec{g} - \nabla'p' + \frac{1}{\mathrm{Re}}\nabla'\cdot[\vec{\tau}']$$

$$\rho' c_p' \frac{DT'}{Dt'} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\nabla'\cdot(\lambda'\nabla'T') + \frac{U^2}{c_{pe}T_e}\beta' T'\frac{Dp'}{Dt'} + \frac{U^2}{c_{pe}T_e\,\mathrm{Re}}\phi'$$

$$\frac{U^2}{c_{pe}T_e} = \mathrm{Ma}^2\frac{c_e^2}{c_{pe}T_e} = \mathrm{Ma}^2(\gamma-1)$$

$$\rho' c_p' \frac{DT'}{Dt'} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\nabla'\cdot(\lambda'\nabla'T') + \mathrm{Ma}^2(\gamma-1)\beta' T'\frac{Dp'}{Dt'} + \frac{\mathrm{Ma}^2(\gamma-1)}{\mathrm{Re}}\phi'$$

$$x' = x/D,\quad t' = tU_e/D,\quad \vec{v}' = \vec{u}/U_e,\quad p' = (p-p_e)/\rho_e U_e^2,\quad T' = T/T_e,\quad \rho' = \rho/\rho_e,$$

$$c_p' = c_p/c_{pe},\quad \lambda' = \lambda/\lambda_e,\quad \beta' = \beta/\beta_e,\quad \nabla' = D\nabla,\quad \phi' = \phi D^2/\mu_e U_e^2,\quad \mu' = \mu/\mu_e$$

**Normalized parameters**

***Schlichting and Gersten, 2001***

# Scaling theory for plume-surface interactions

$$p'_{fb} = \frac{P_\infty - P_e}{\rho_e U_e^{\,2}} = \frac{P_\infty\left[1-\left(\frac{P_e}{P_\infty}\right)\right]}{\rho_e U_e^{\,2}} = \frac{P_\infty(1-e)}{\rho_e U_e^{\,2}} \quad e = \text{jet expansion ratio}$$

**Free surface boundary condition**

**Nondimensional numbers that satisfy dynamic similarity**

$$\boxed{\mathrm{Re} = \frac{\rho_e U_e D}{\mu_e},} \quad \mathrm{Fr} = \frac{U_e}{\sqrt{gD}}, \quad \boxed{\mathrm{Ma} = \frac{U_e}{a_e},} \quad \mathrm{Pr} = \frac{\mu_e c_{pe}}{\lambda_e}, \quad \gamma = \frac{c_{pe}}{c_{ve}}, \quad \boxed{\mathrm{St} = \frac{fD}{U_e}} \quad \alpha = \frac{P_{C-\max}}{P_\infty} \quad \boxed{e = \frac{P_e}{P_\infty}} \quad \boxed{k = \gamma(\gamma-1)M^2}$$

| | | MSL MLE ¼ scale | MSL MLE full-scale | Phoenix REM ½ scale | Phoenix REM full-scale |
|---|---|---|---|---|---|
| Hypersonic similarity | *k* | 14.8 | 14.0 | 12.7 | 11.4 |
| Jet expansion ratio | *e* | 2.9 – 2.1 - exp<br>3.5 - num | 6.8 – 2.2 – flt<br>6.8 – 4.1 - num | ~4.4 - exp<br>4.5 – num | 3.8 - flt<br>4.7 – num |
| Reynolds Number | *Re* | 24.5 – 14.7 x $10^5$ -exp<br>23.3 x $10^5$ - num | 8.4 – 5.0 x $10^5$ - flt | 12.7 x $10^5$ | 3.4 x $10^5$ |
| Mach Number | $M_e$ | 5.14 | 5.08 | 4.77 | 4.67 |
| Strouhal Number | *St* | 0 | 0 | 4.4 x $10^{-4}$ | 3.3 x $10^{-4}$ |

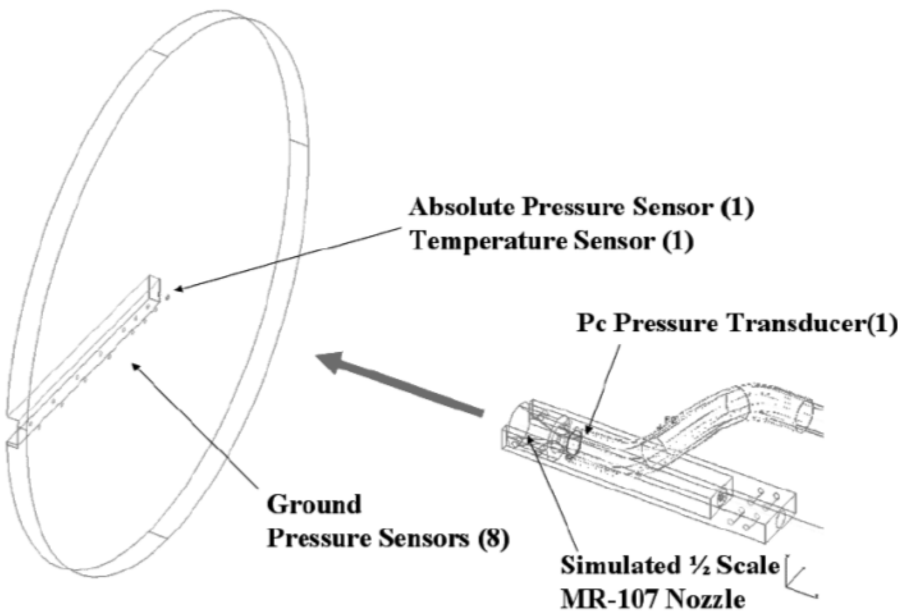
Table 1. Scaling parameters; exp-experiment; num-numerical simulation; flt-spaceflight conditions

# Phoenix Mars Spacecraft

***Courtesy of NASA/JPL/Lockheed Martin***

# Experimental and Numerical Methodology

## Experimental Methodology




-½ scale Phoenix nozzle (MR-107)
-$N_2$ test gas
-10 Hz pulsing
-Mars atmosphere

*University of Michigan Thermal Vacuum Chamber*

## Numerical Methodology

-Two Navier-Stokes computational solvers were used for modeling and analyses

-<u>ANSYS FLUENT</u>
-3-D & axisymmetric density based solver
-Transient RANS
-Time step – 1 us – explicit marching
-Turbulent (RNG) model
-Adaptive meshing for resolving shocks
-Grid independence
-2nd order upwind discretization scheme
-2 million unstructured grid cells

-<u>Aerosoft GASP</u>
-3-D density based solver
-Transient & steady-state RANS eqns solved
-Van Leer flux splitting
-Laminar
-Dual implicit time stepping
-Single species – frozen flow
-Grid independence
-4 million unstructured grid cells

*Plemmons, Mehta et al, 2008*

# Ground pressure profiles – TEST DATA

MARS ATMOSPHERE ~ 700 Pa

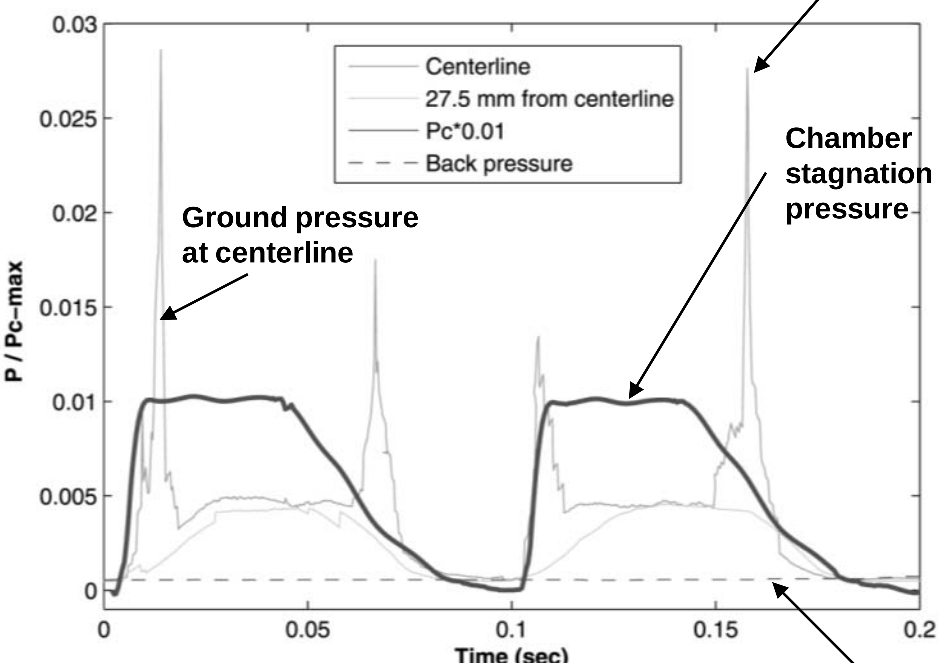
## Temporal Profile

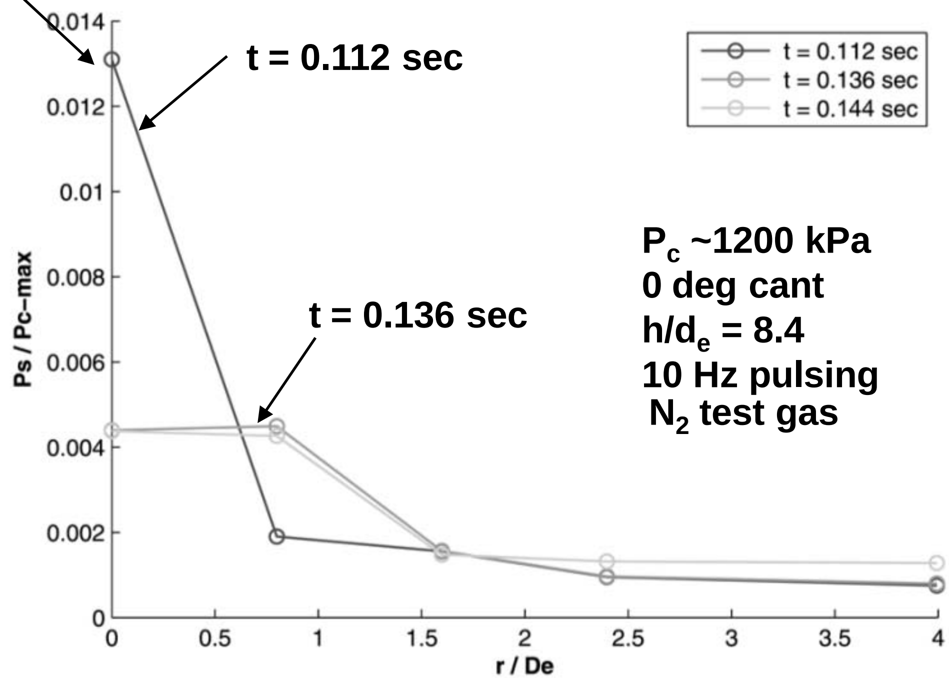
**Observed large transient overpressures during engine start-up and shut down**

## Spatial Profile

**Observe a monotonic rise in ground pressure followed by a drop in centerline pressure**

**Overpressure**

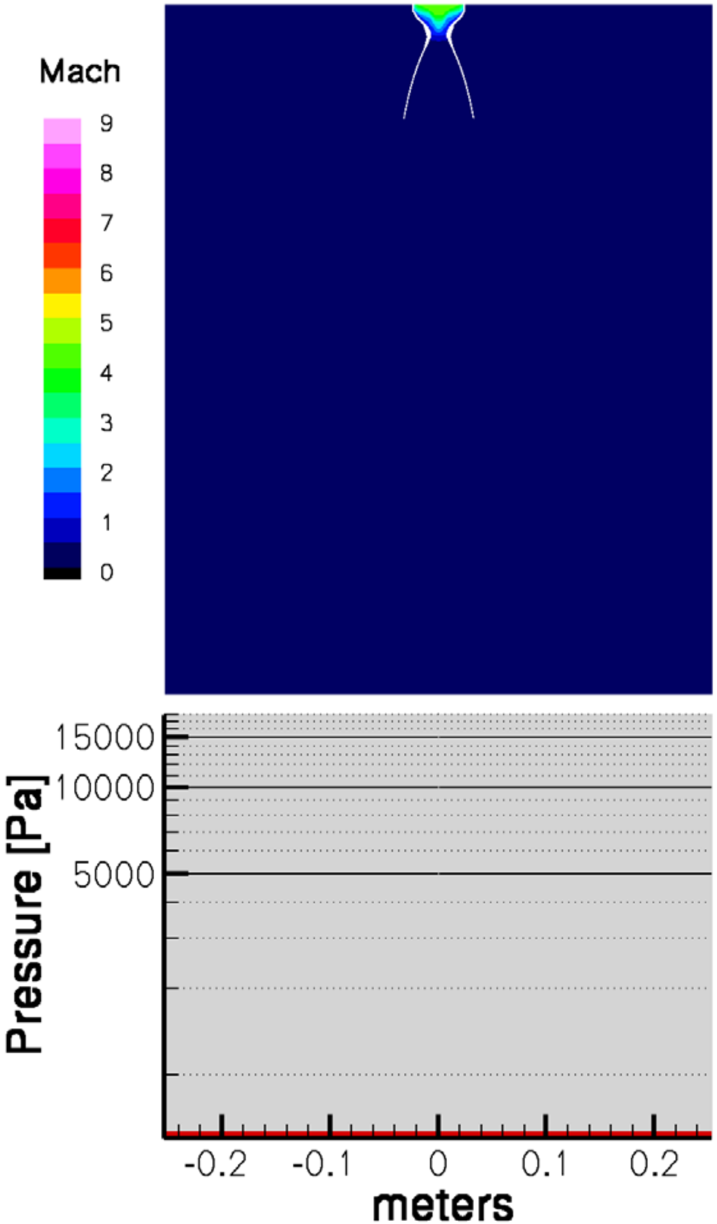



**Back pressure**

*Plemmons, Mehta et al, 2008*

# Plate shock dynamics - CFD




**Mechanism deduced from experimental measurements, transient numerical simulations and theory.**

| MARS ATMOSPHERE ~ 700 Pa |
|---|

**Plate (recovery) shock formation**

**$P_c$ ~ 1200 kPa**
**0 deg cant**
**$h/d_e$ = 8.4**
**$N_2$ test gas**
**Axisymmetric transient simulation**

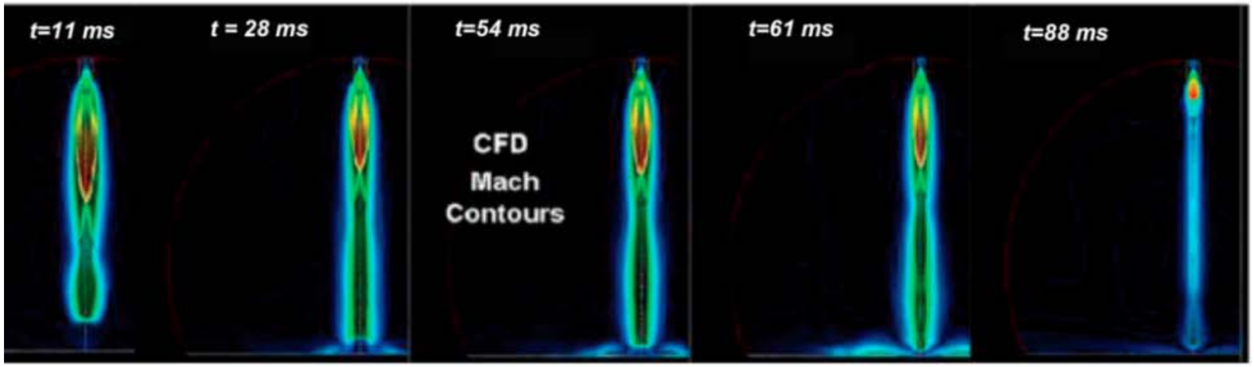
**GASP**

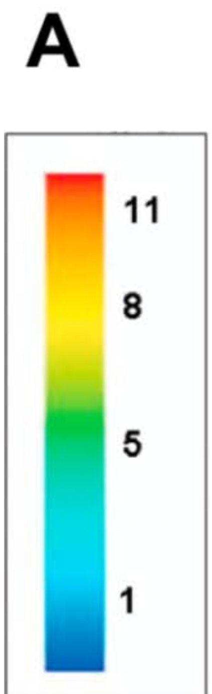
***Gulick et al., 2006***

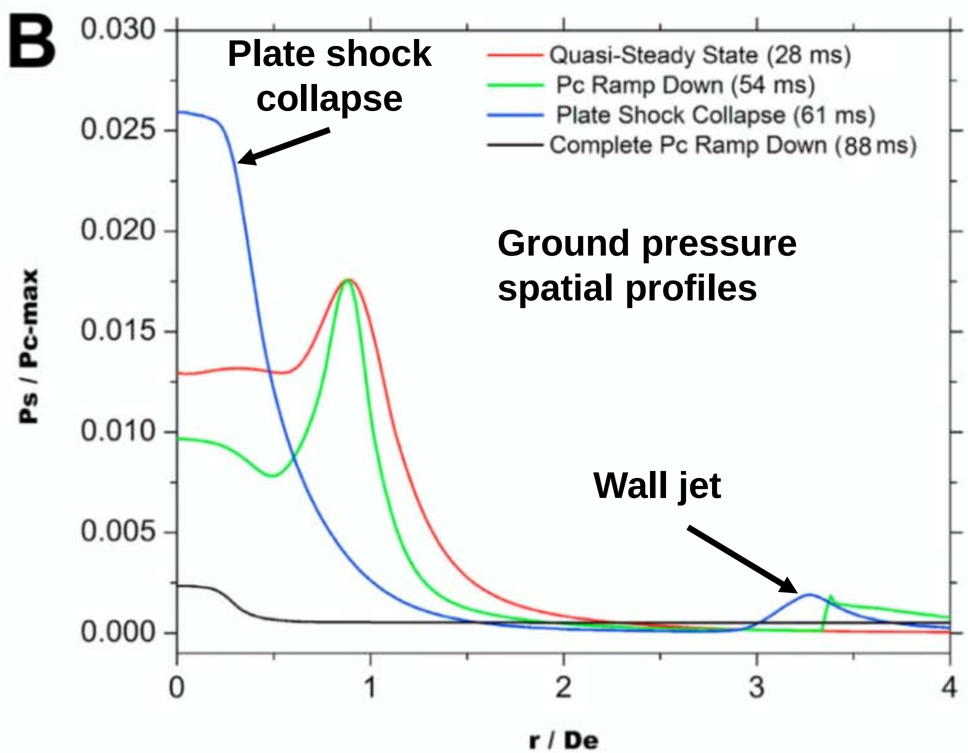
# Plate shock dynamics - CFD

**Plate shock formation and collapse**

**MARS ATMOSPHERE ~ 700 Pa**




**$P_c$ ~1200 kPa**
**0 deg cant**
**$h/d_e$ = 25**

- **$N_2$ test gas**
- **Axisymmetric**
- **Transient**
- **10 Hz pulsing**

# FLUENT

***Plemmons, Mehta et al, 2008***

# Plate shock dynamics - CFD

[redacted]

**Plate shock formation and collapse**

**FLUENT**

***Plemmons, Mehta et al, 2008***

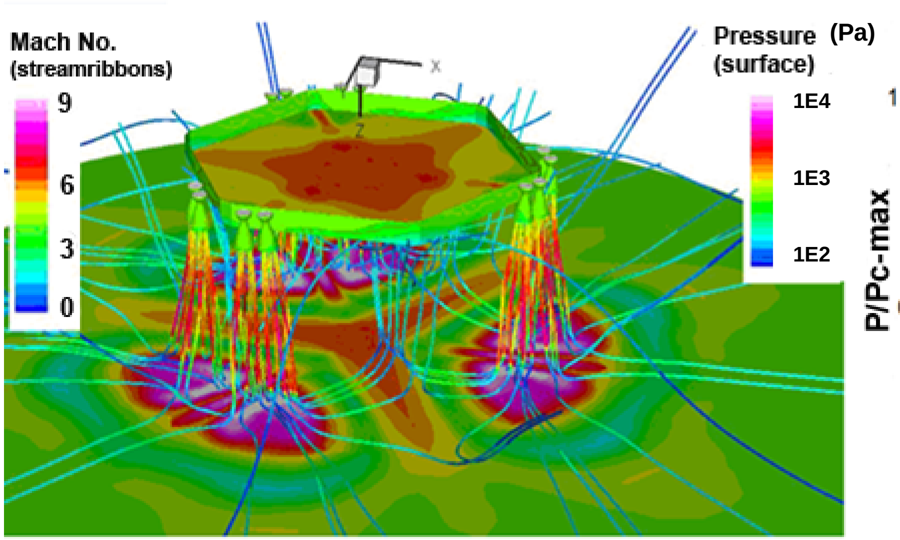
# 3-D full-scale flow field and ground pressure profiles - CFD

MARS ATMOSPHERE ~ 700 Pa

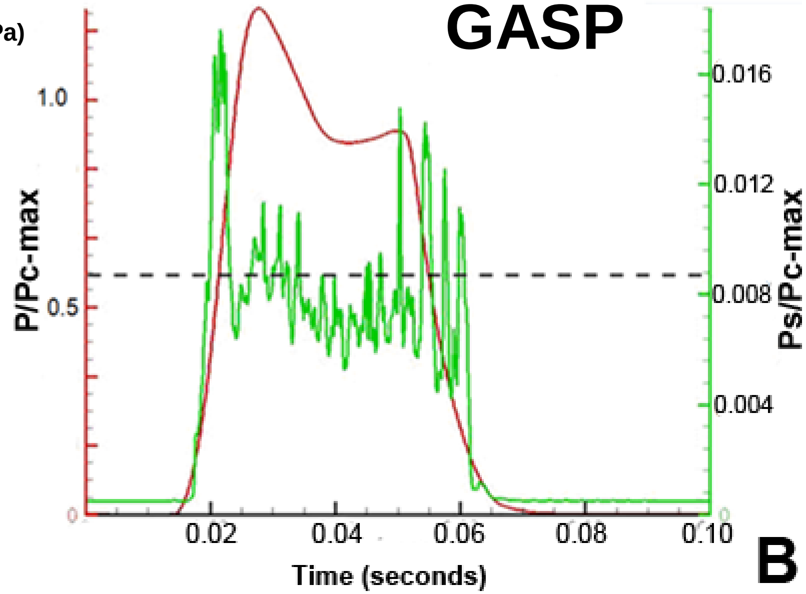
Modeled as a 60 degree wedge to reduce computational resources

$P_c$ ~ 1200 kPa
0 deg cant
$h/d_e$ = 25
10 Hz pulsing
Equivalent plume gas

3-D transient simulations of full-scale Phoenix plumes interacting at surface




A




B

3-D numerical simulations show that ground pressure loads are asymmetric and develop overpressures during rapid engine startup and shutdown

*Gulick et al, 2006*

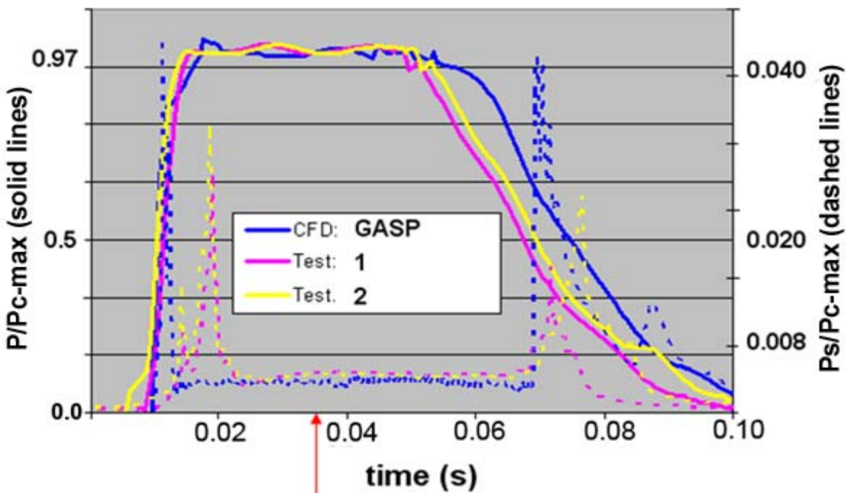
# Experimental and numerical data

**Good agreement between experimental results and numerical simulations (CFD)**

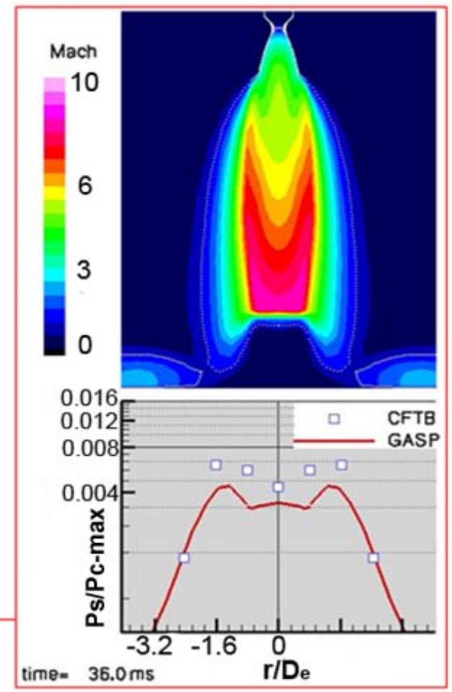
**Comparing spatial and temporal ground pressure profiles**

**MARS ATMOSPHERE ~ 700 Pa**

**TEMPORAL**




**SPATIAL**

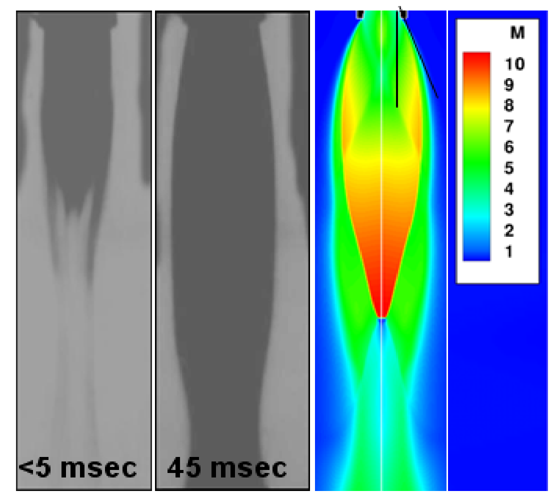



**Dashed lines – surface pressure**

**Solid lines – thruster inlet stagnation pressure (chamber pressure)**

**Red line – CFD**
**Dots – Test Data**

**Comparing plume shock structure**




*(a)* *(b)* *(c)*

**Shadowgraph** **FLUENT**

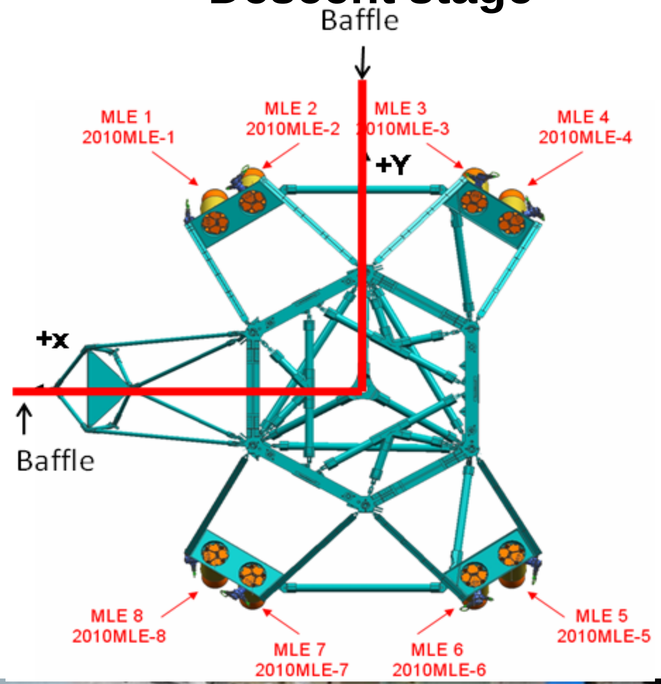
**$P_c$ ~ 1200 kPa**
**0 deg cant**
**$h/d_e$ = 8.4**
**10 Hz pulsing**
**$N_2$ test gas**

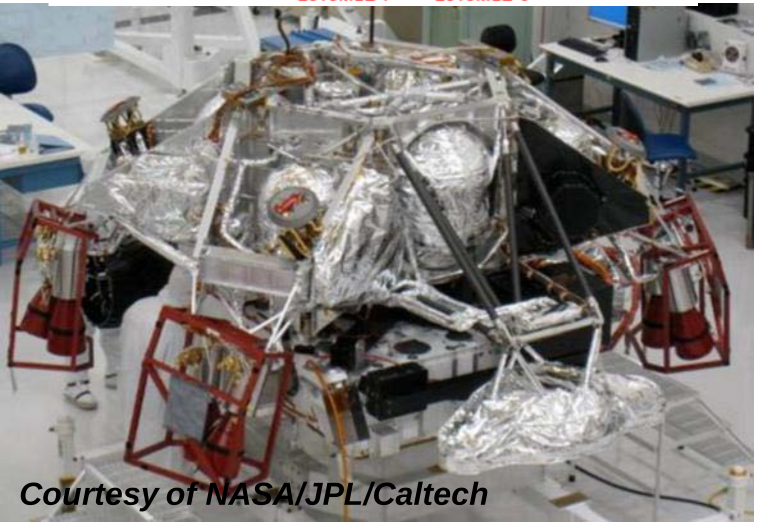
**GASP**

***Gulick et al, 2006***

# MSL Descent Stage Spacecraft & Testbed

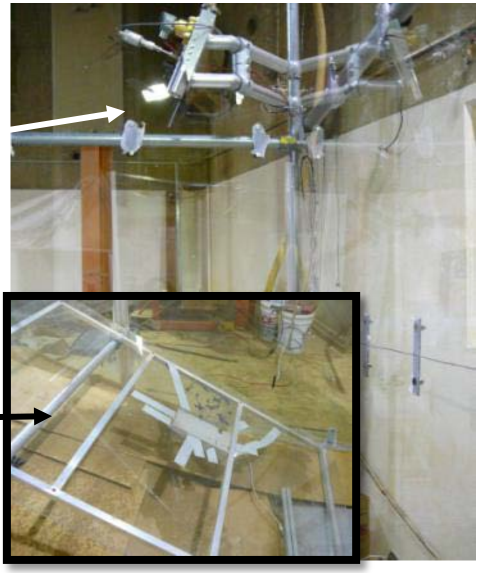
## Descent stage

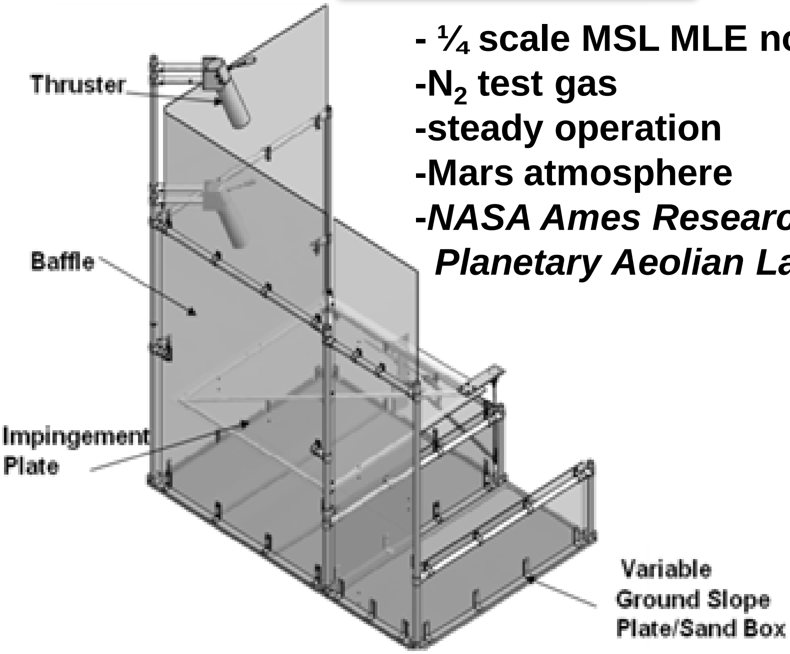


*Courtesy of NASA/JPL/Caltech*

## Testbed



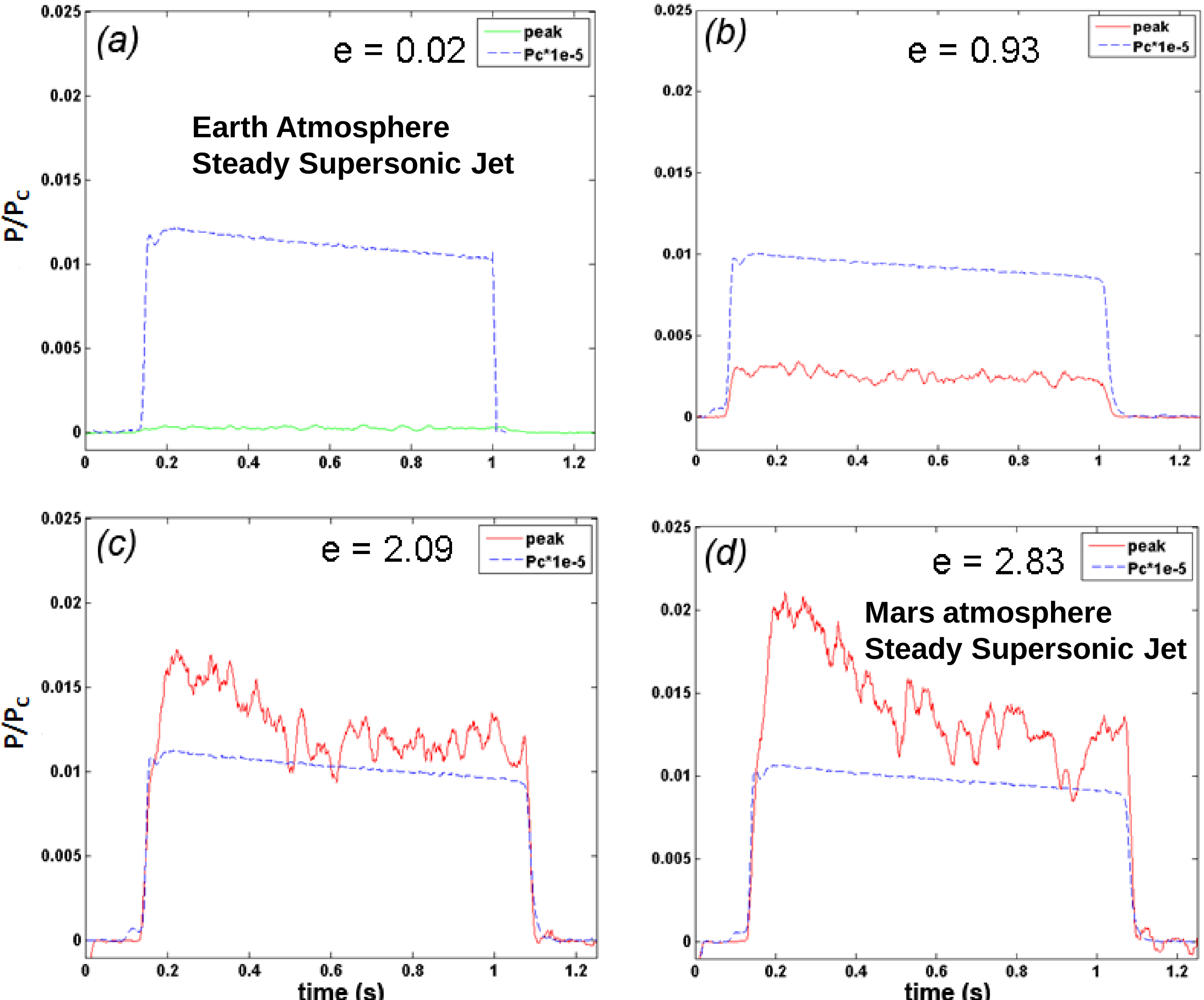




- ¼ scale MSL MLE nozzle
- $N_2$ test gas
- steady operation
- Mars atmosphere
- *NASA Ames Research Center Planetary Aeolian Laboratory*

# Numerical methodology

- <u>NASA OVERFLOW 2.1</u>
- 3-D time-marching implicit code
- structured overset grid
- Navier-Stokes eqns solved over full domain and internal nozzle
- SST turbulence model
- compressibility correction
- steady-state
- frozen flow used for modeling rocket plume gases
- 12 million cells

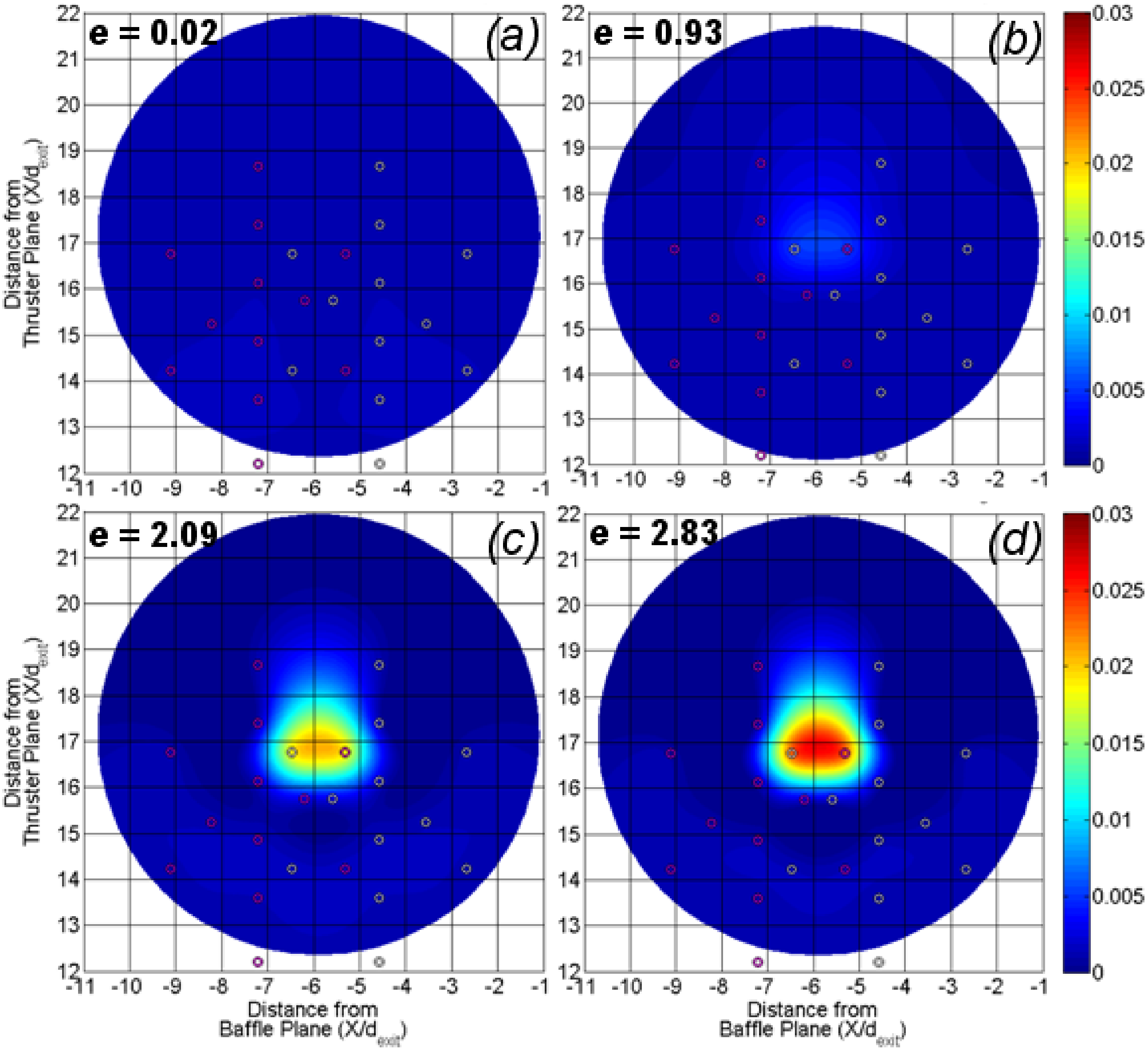
# Temporal ground pressure profiles – TEST DATA




**$P_c$ ~1700 kPa**
**22.5 deg cant**
**$h/d_e$ = 35**
**$N_2$ test gas**
**steady operation**

**Repetitive overpressures not observed**

# Spatial ground pressure profiles – TEST DATA




$P_g/P_c$

$P_c$ ~1700 kPa
22.5 deg cant
$h/d_e = 35$
$N_2$ test gas
steady operation

$P_g/P_c$

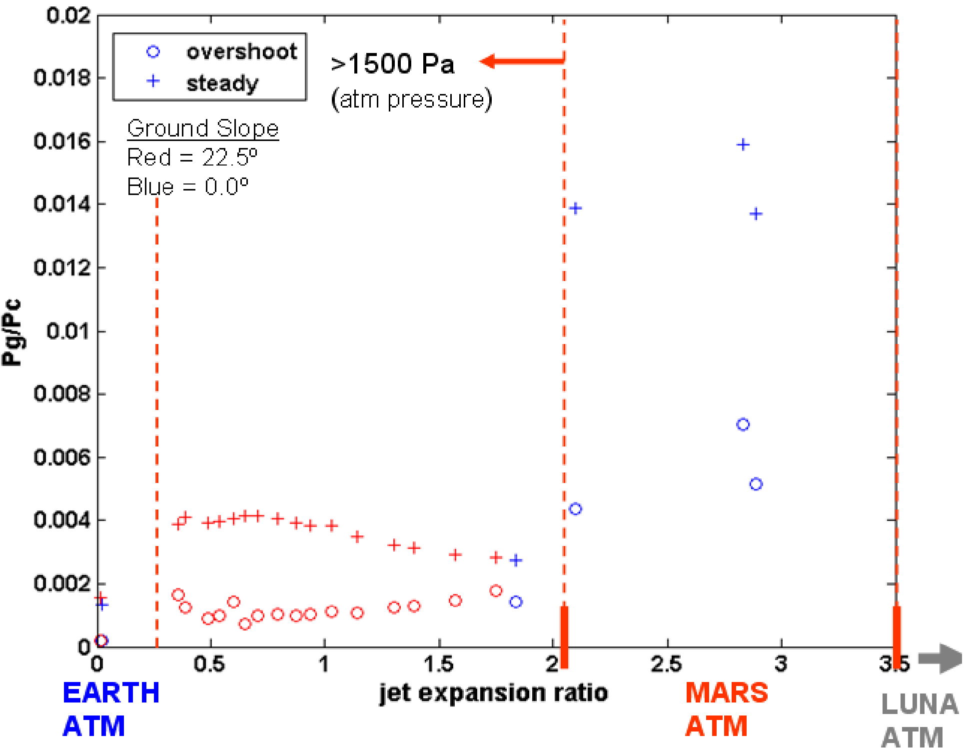
$P_s = P_g$

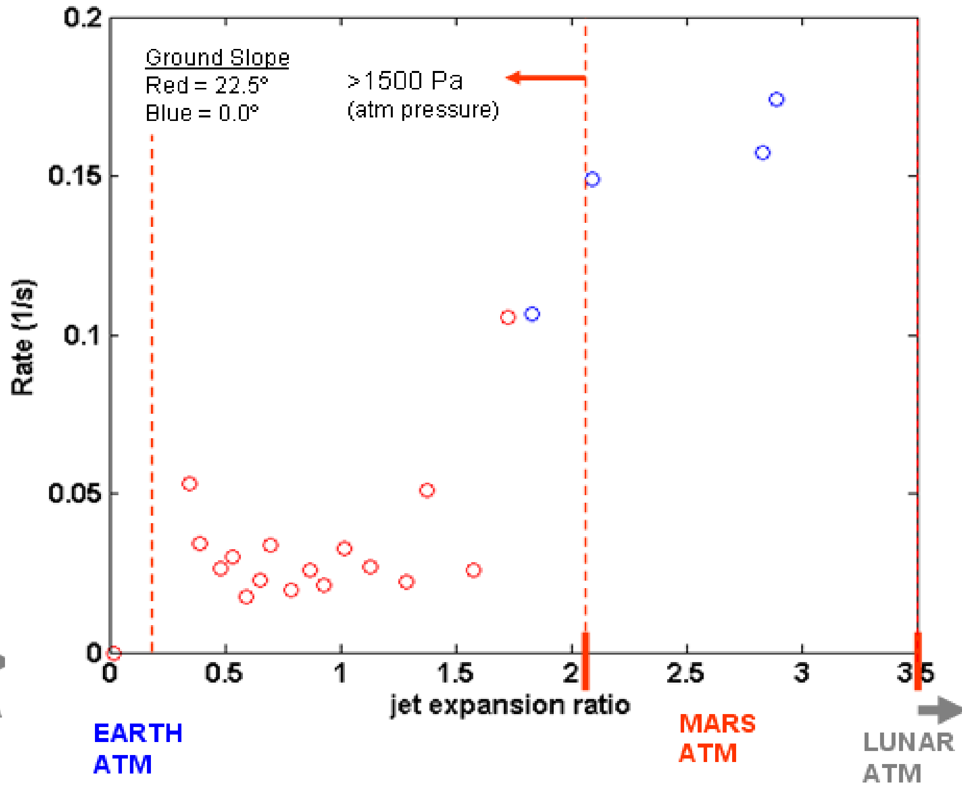
**Shows that the plume is collimated and leads to large pressure gradients at Mars atmospheric pressure**

# Ground pressure and rise rate vs. jet expansion ratio – TEST DATA

$$\text{jet expansion ratio} = e = \frac{P_e A_e}{P_{amb} A_e} = \frac{P_e}{P_{amb}}$$

$$\text{rise rate} = \left(\frac{\Delta P_g}{P_c}\right)\left(\frac{1}{\Delta t}\right) = \left(\frac{P_{g\max} - P_{g\min}}{P_c}\right)\left(\frac{1}{t_{g\max} - t_{g\min}}\right)$$

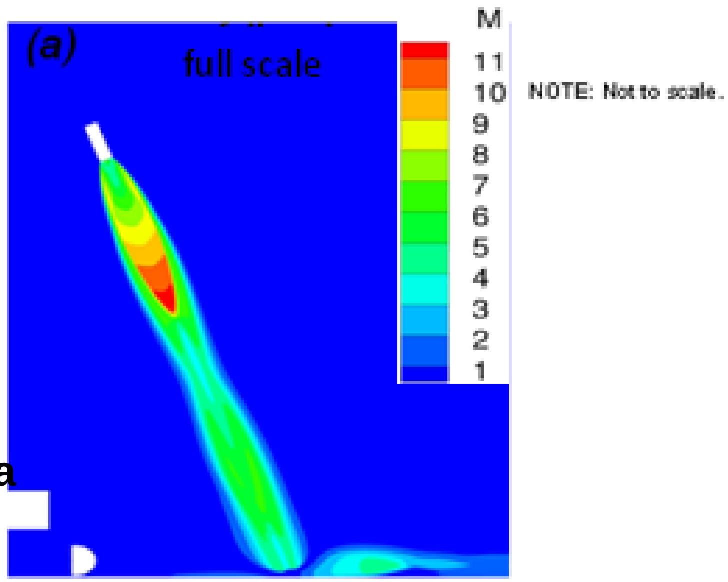


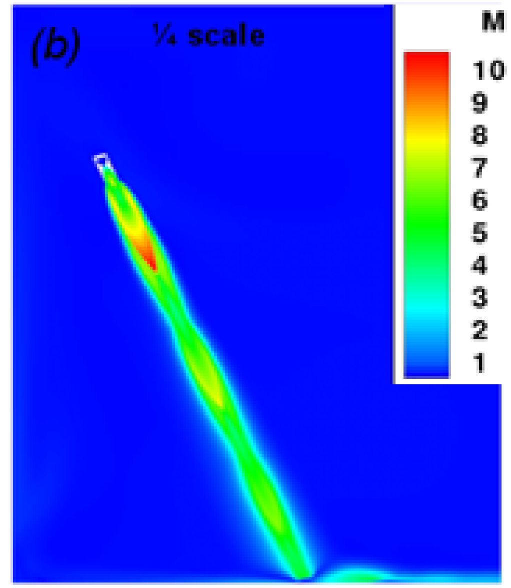




**Overshoot = Max ground pressure – quasi-steady ground pressure**

# Plume flowfield and spatial pressure profiles - CFD

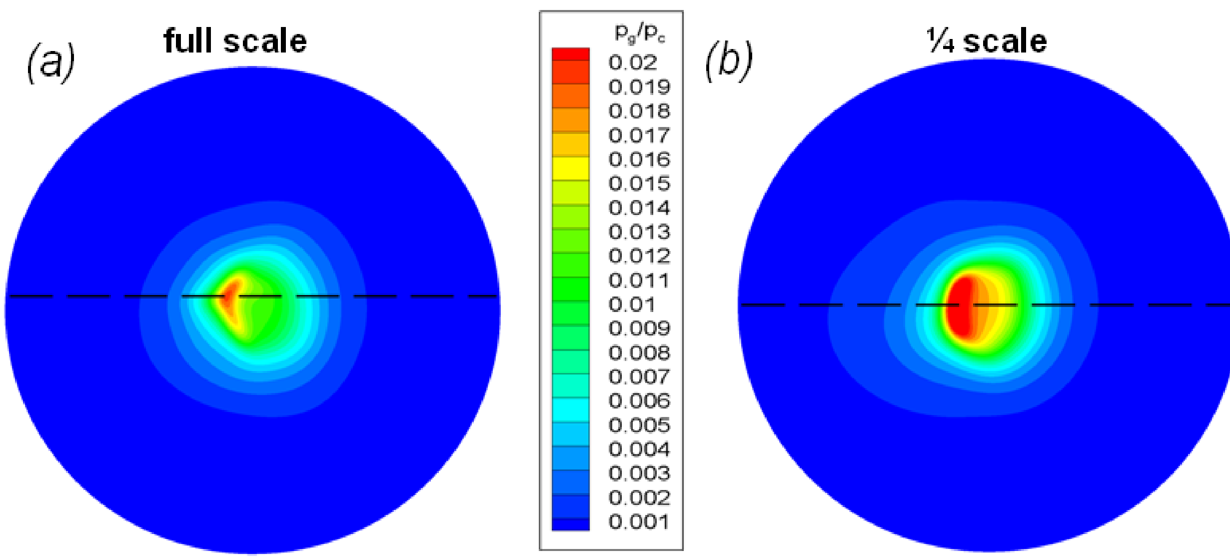
MARS ATMOSPHERE ~ 700 Pa




Plume is collimated and does not dissipate at large axial distances – in agreement with test data

**$P_c$ ~ 1.7e3 kPa**
**22.5 deg cant**
**$h/d_e$ ~35**
**Equivalent Plume gas steady-state**

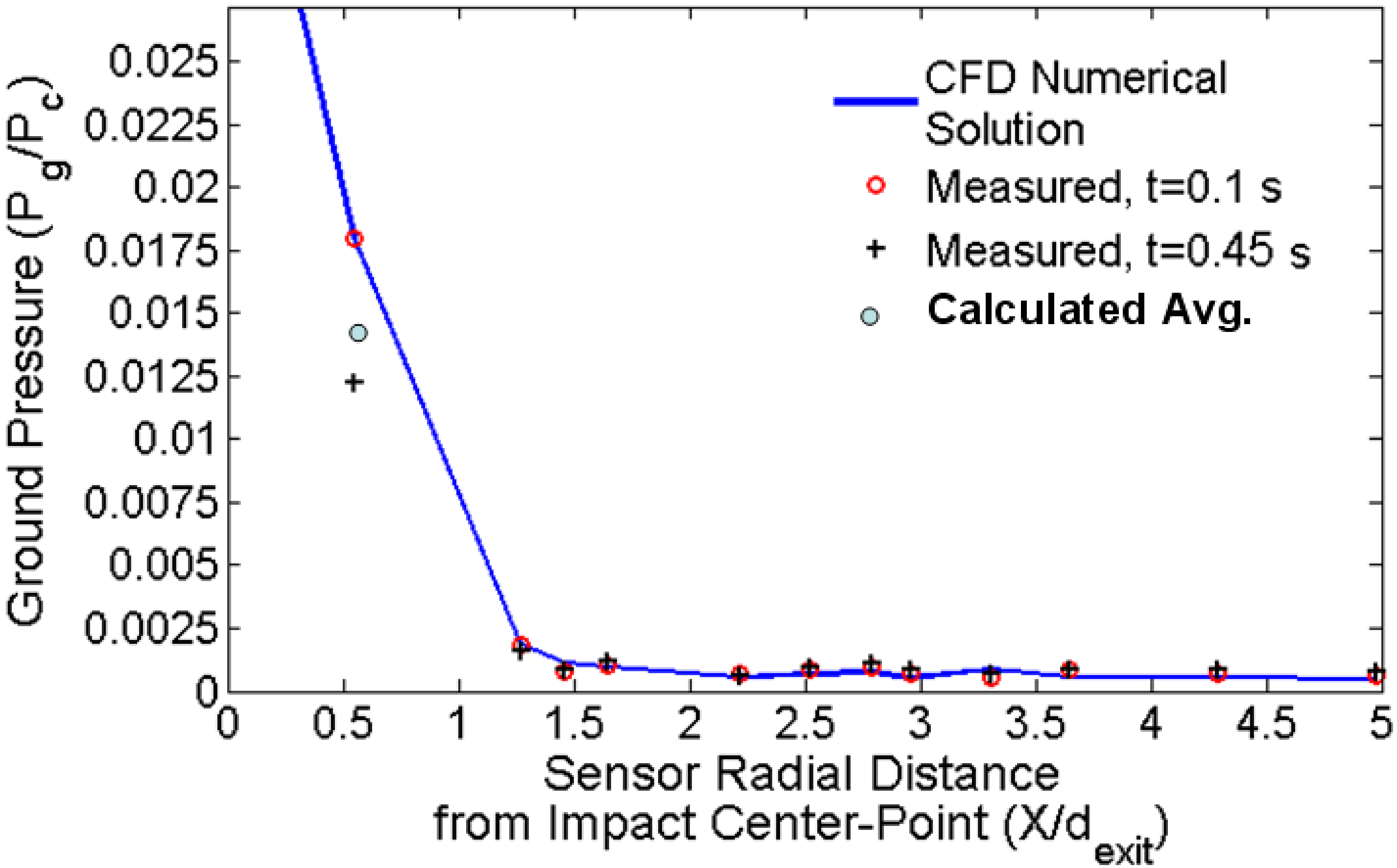



**$P_c$ ~ 1.7e3 kPa**
**22.5 deg cant**
**$h/d_e$ ~35**
**$N_2$ test gas steady-state**

**OVERFLOW**

# Experimental and numerical data

MARS ATMOSPHERE ~ 700 Pa

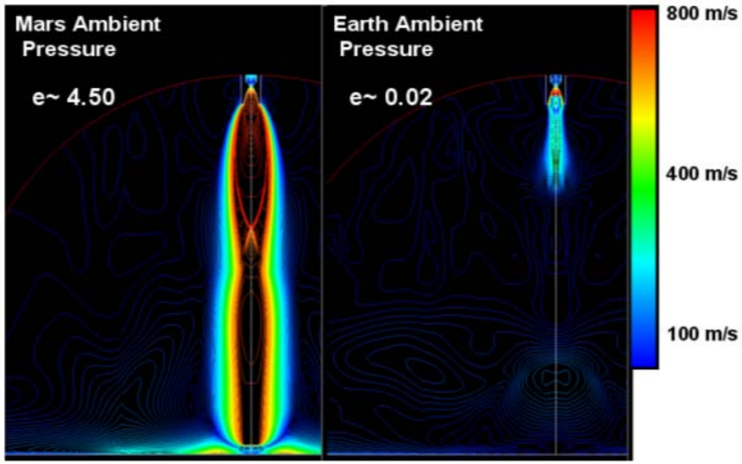



**$P_c$ ~ 1.7e3 kPa**
**22.5 deg cant**
**$h/d_e$ ~35**
**$N_2$ test gas**

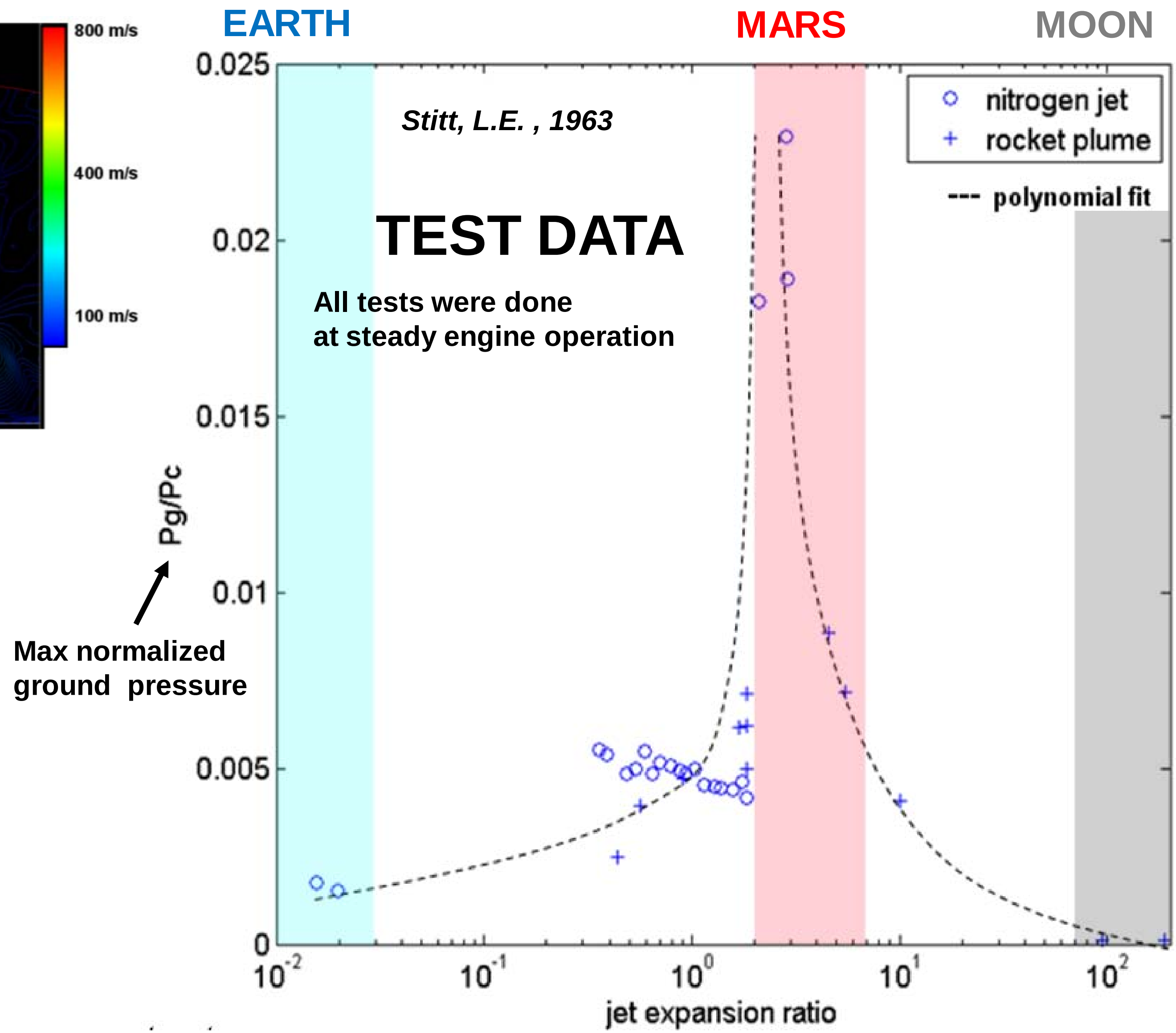
**OVERFLOW**

# Jet expansion ratio

## CFD – Mach Contours




**e = 4.50** **e = 0.02**




**Mars – moderately underexpanded plumes lead to max ground pressure loads due to collimated plume structure and development of a small areal plate shock**

**Earth – highly overexpanded plumes dissipate/no plate shock formation**

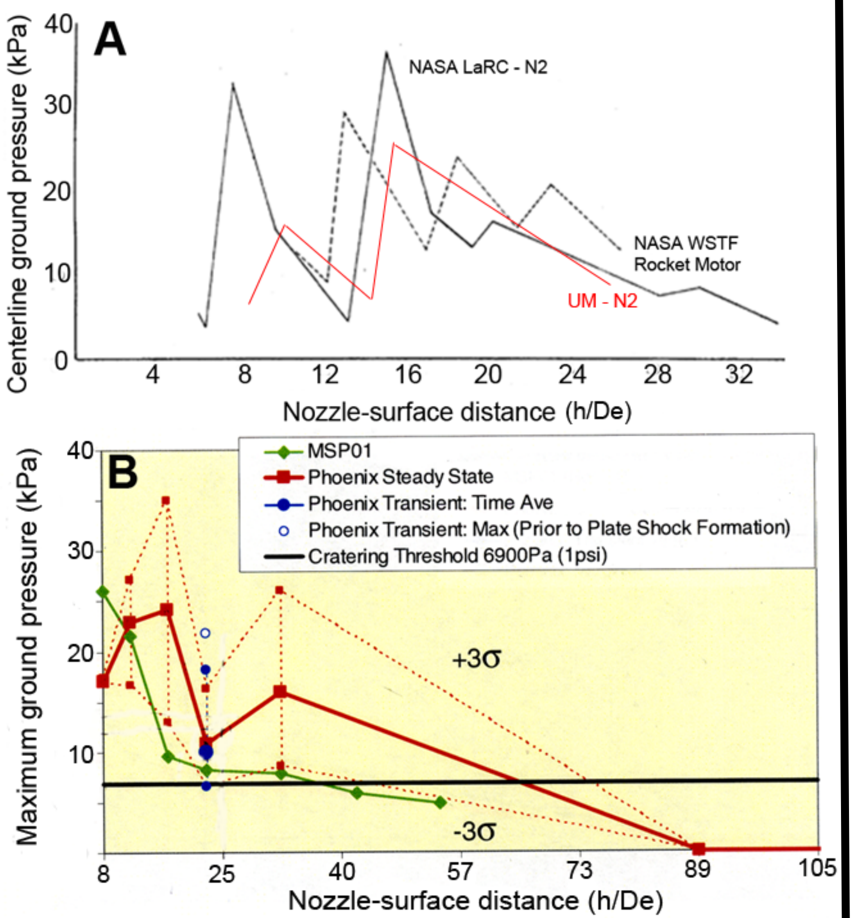
**Moon – highly underexpanded plumes leads to a large areal plate shock – decreases ground pressure**

# Other shock interaction effects during spacecraft landings

## Altitude Effects

MARS ATMOSPHERE ~ 700 Pa

**Ground pressure vs normalized altitude**



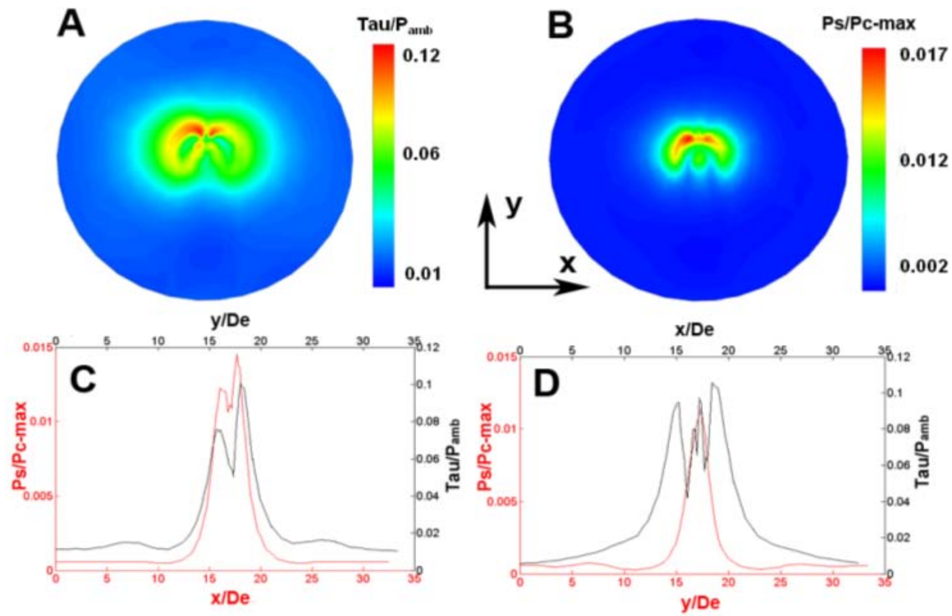

**GASP**

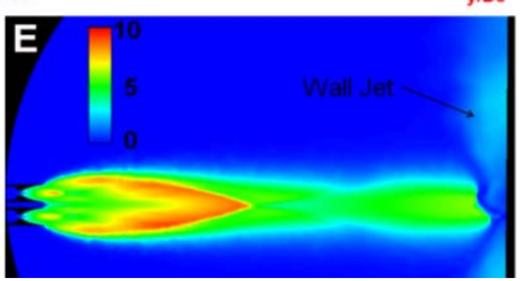
*Gulick et al, 2006*

## Spatial Asymmetry

MARS ATMOSPHERE ~ 700 Pa

**SURFACE SHEAR STRESS** **SURFACE PRESSURE**




$P_c$ ~ 1200 kPa
0 deg cant
$h/d_e$ = 25
Steady-state
$N_2$ test gas

**MACH CONTOUR**

**FLUENT**

# Conclusions

- <u>Moderately</u> **underexpanded jets demonstrate:**
  - collimated shock structures
  - large supersonic core lengths
  - plate shock dynamics
  - max pressure loads
- **Plate shock dynamics leads to:**
  - large pressure gradients
  - asymmetry
  - overpressure
- **Ground pressure loads are highly sensitive to**
  - jet expansion ratio
  - strouhal number
  - spacecraft altitude
- **Scaling laws show that cold plume gases can simulate ground pressure loads and interaction physics due to rocket plumes provided dynamic similarity is satisfied**
- **How does this effect spacecraft landing?**
  - Transient ground pressure loads translate to load perturbations at the spacecraft base which may lead to destabilizing moments (observed to a minor degree on the Phoenix spacecraft, *Gulick et al*, 2006)
  - Pressure loads can lead to extensive cratering and dust lifting which can destabilize the spacecraft upon touching down on the surface (observed at the Phoenix Landing Site, *Mehta et al, 2011*)
  - Dust lifting can erode important spacecraft sensors and science instrumentation (a concern for the MSL mission, *Mehta et al, 2011*)
  - Propulsion systems of small scale landers show maximum ground pressure loads at Mars atmosphere at relatively high altitudes ($h/d_e$ ~35) (a concern for the MSL mission)
- **Provided JPL with landing environments which they incorporated into their risk analysis models**

**MISSION SUGGESTION: Due to highly complex plume impingement physics, accurate landing environments are needed for future planetary manned and robotic spaceflight missions**

# Acknowledgement


- I would like to thank my supervisor Mark G. D’Agostino and my colleagues within the home organization – Aerosciences Branch (EV33) at NASA Marshall Space Flight Center for their support.

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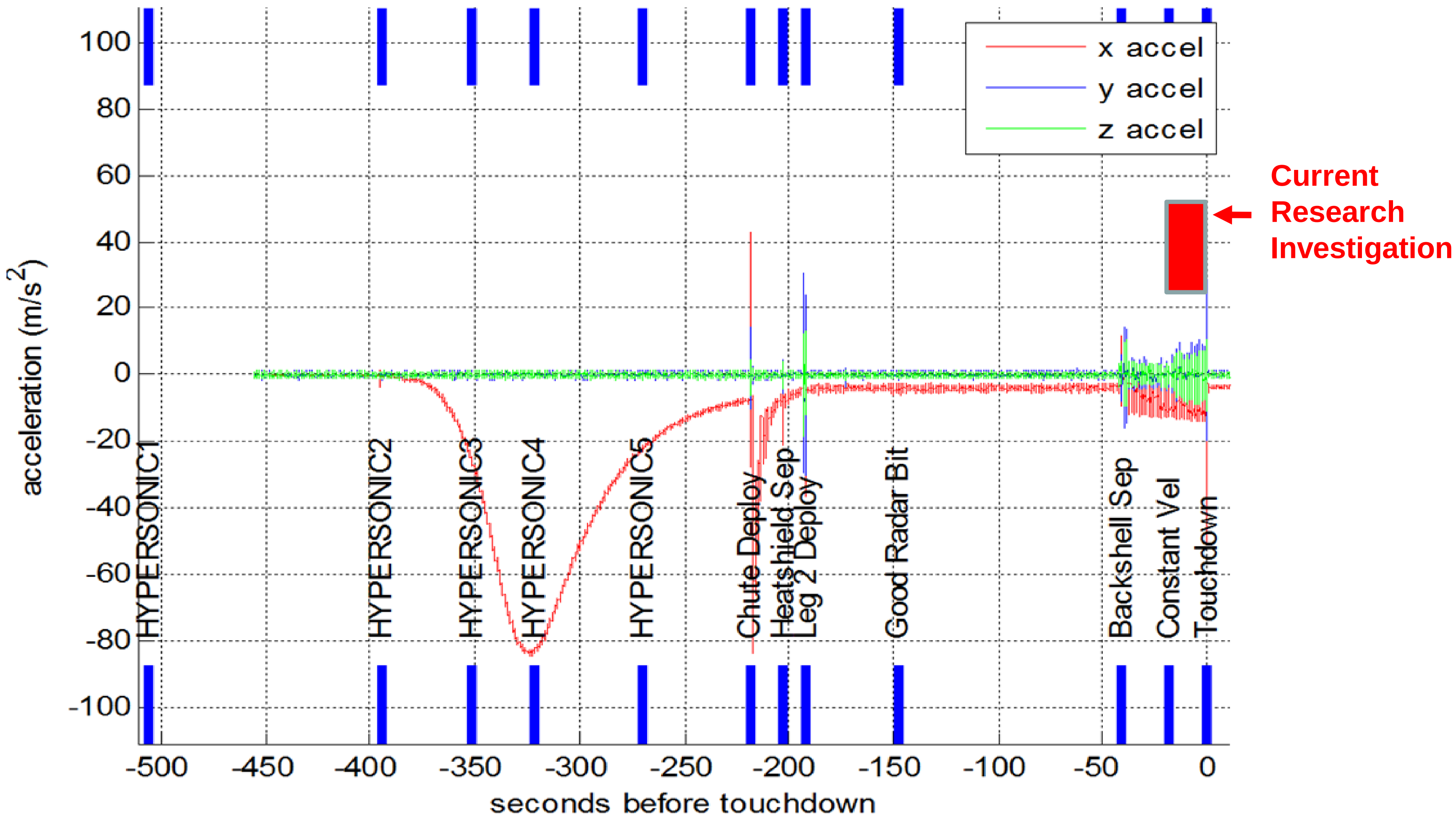
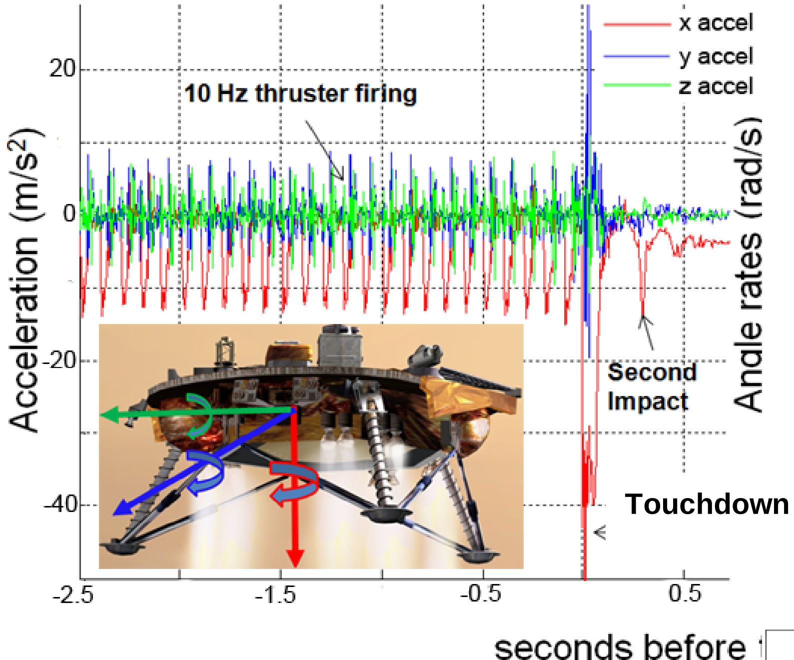
# Back-up Slide: Phoenix Entry, Descent and Landing Sequence

-200 Hz (Inertial Measureiment Unit) IMU data and 10 Hz Radar data



# Back-up Slide: Terminal descent




**Plumes interacted with the surface for less than 2 seconds (even less than predicted by landing simulations)**

**Lift loss occurred at ~4.5 m and ground effect started around ~3.5 m**

**Noticed a second bounce – could be the result of plume-surface interactions after Initial contact.**