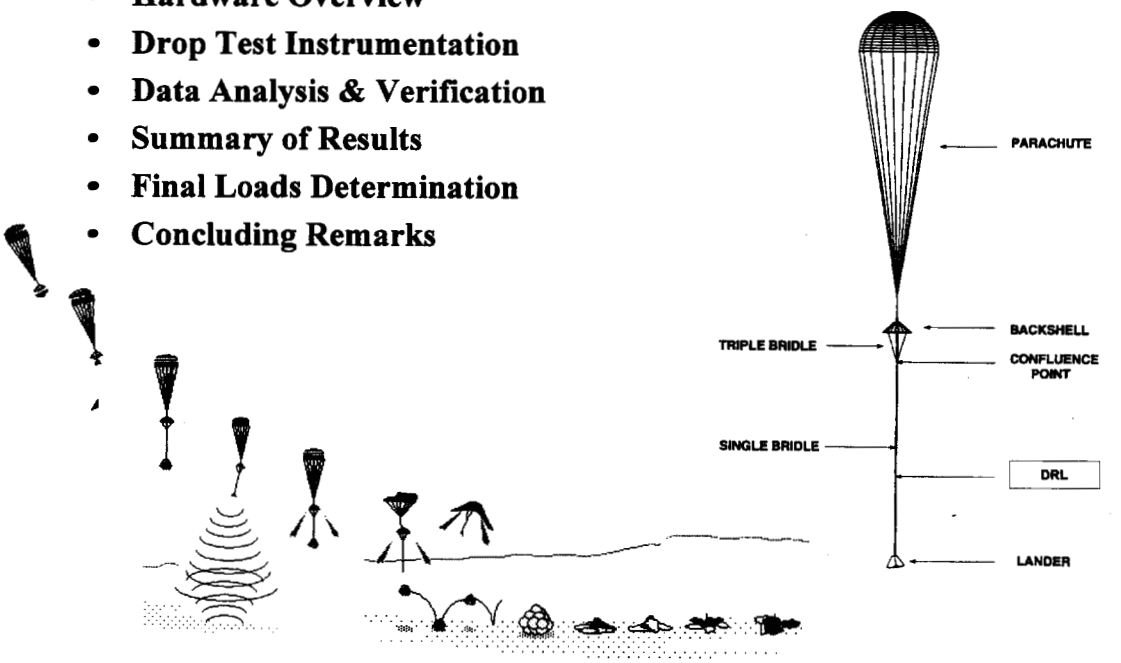
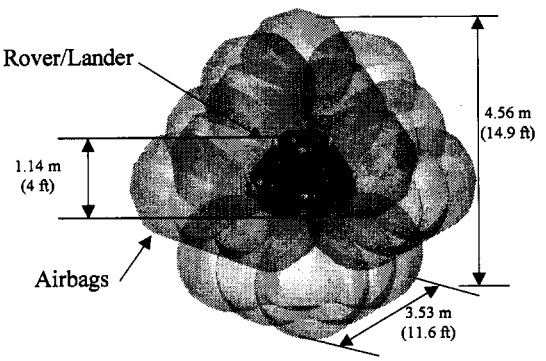
Outline

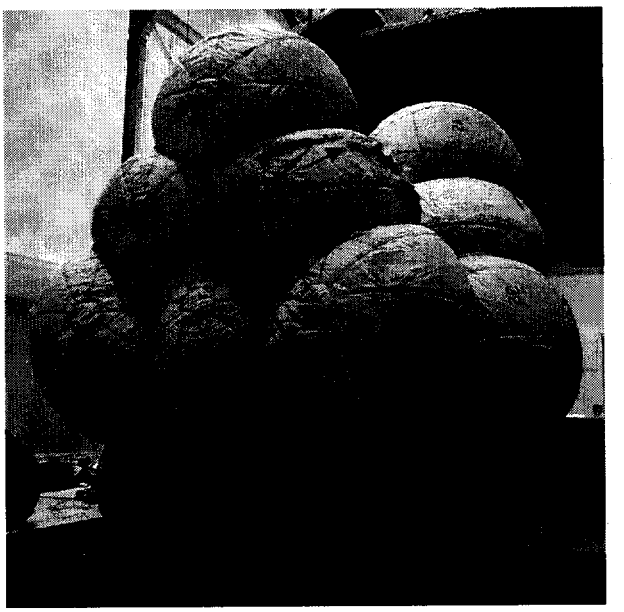
- Hardware Overview
- Drop Test Instrumentation
- Data Analysis & Verification
- Summary of Results
- Final Loads Determination
- Concluding Remarks



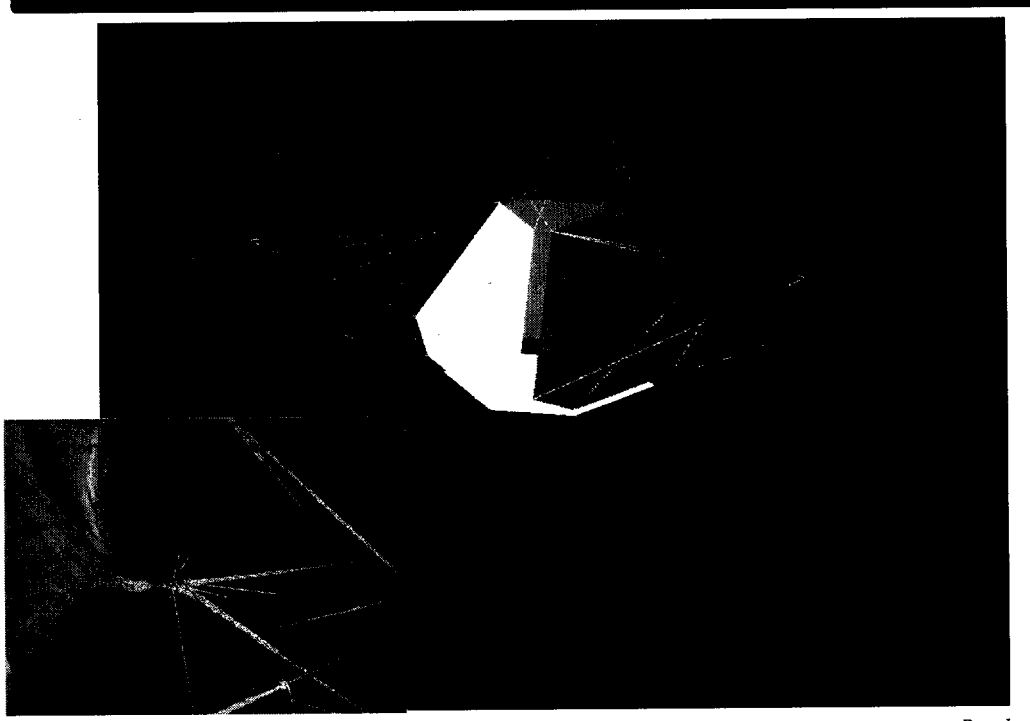
Airbags in Inflated Configuration

- Total of 4 airbags
  - Six 1.8 m dia. lobes/airbag
- Nominal 1.0 psi inflation
  - Varied in some tests
- Total mass ~ 565 kg

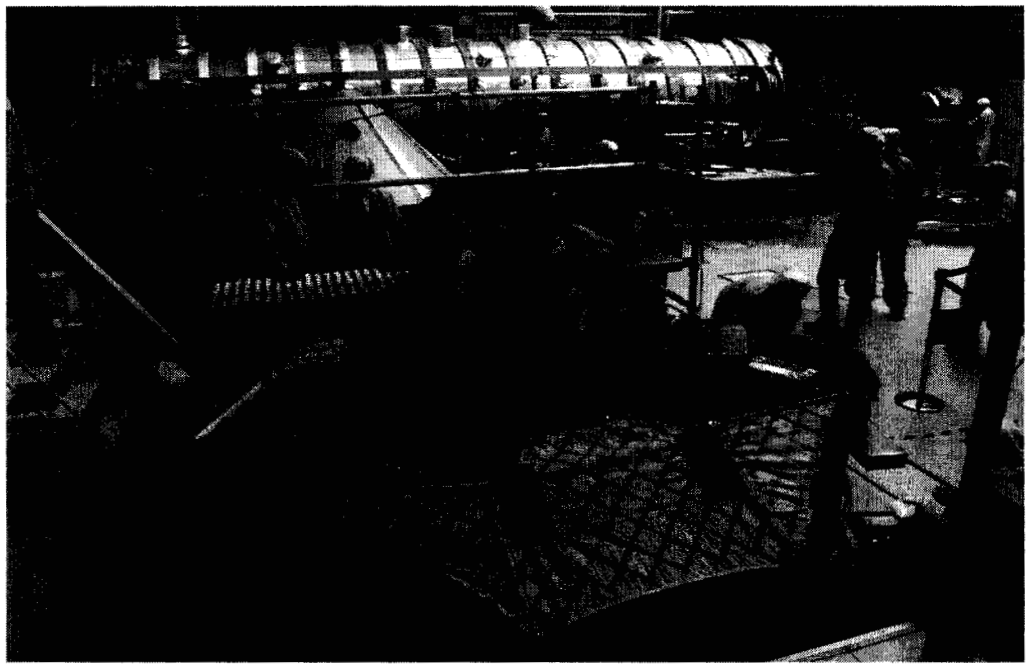




ADAMS Airbag Tendon Definitions

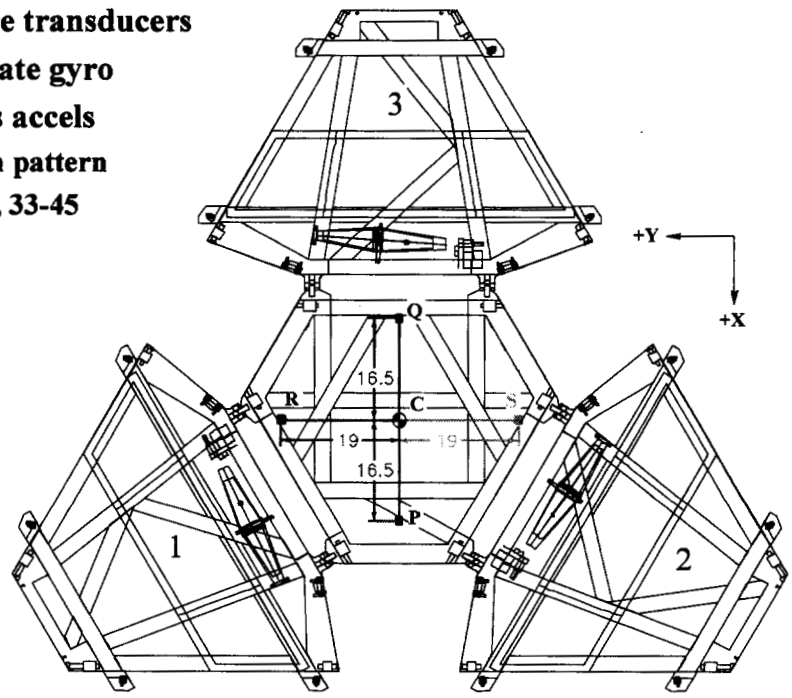


MER Rover & Lander with Petals Deployed



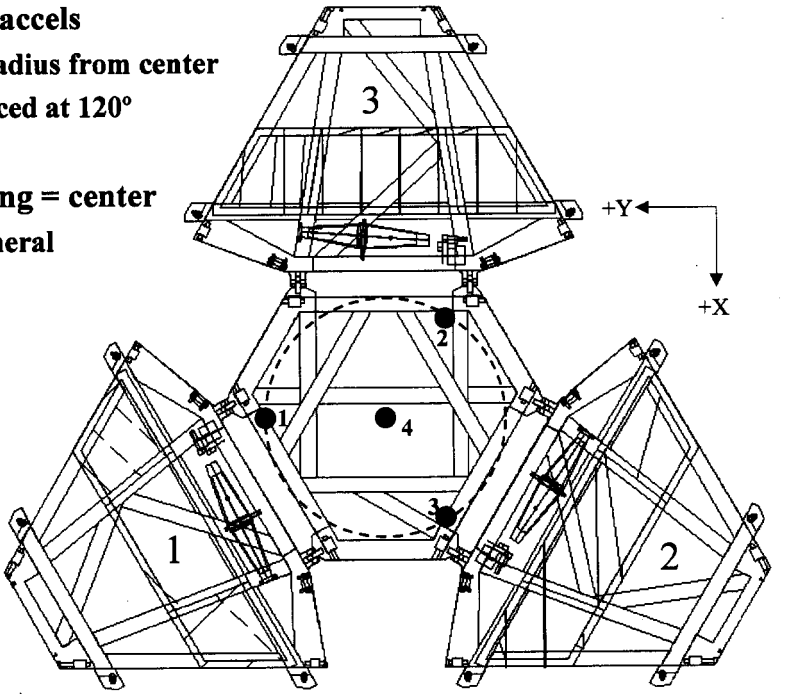
Cruciform Accelerometer Pattern

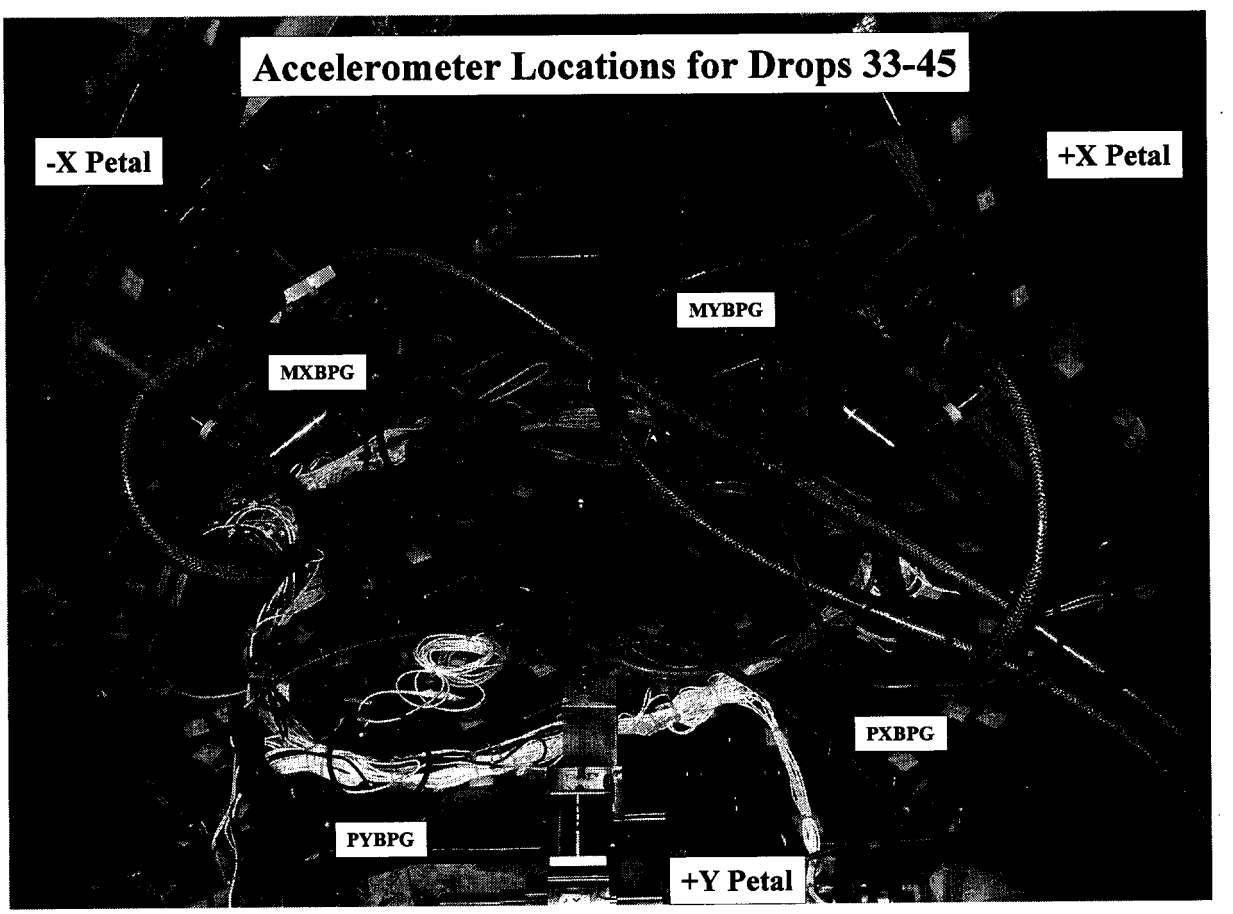
- **Five pressure transducers**
- **Three-axis rate gyro**
- **Four tri-axis accels**
  - **Cruciform pattern**
  - **Drops 1-7, 33-45**



Triangular Accelerometer Pattern

- **Four tri-axis accels**
  - **Constant radius from center**
  - **Evenly spaced at 120°**
  - **Drops 8-32**
- **Average of ring = center**
  - **True in general**





Kinematic Relations

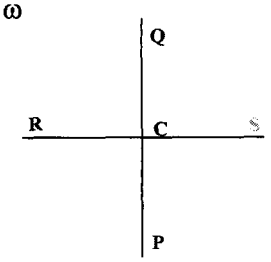
- **Express the acceleration at each location w.r.t. the base plate center**
  - **Use rigid body transformations**
  - **Measured quantities are $\mathbf{a}_P$, $\mathbf{a}_Q$, $\mathbf{a}_R$, and $\mathbf{a}_S$**
  - **Unknowns are $\mathbf{a}_C$ (at the center of the base plate), α, and ω**

$$\mathbf{a}_P = \mathbf{a}_C + \boldsymbol{\alpha} \times \mathbf{r}_{P/C} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}_{P/C}$$

$$\mathbf{a}_Q = \mathbf{a}_C + \boldsymbol{\alpha} \times \mathbf{r}_{Q/C} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}_{Q/C}$$

$$\mathbf{a}_R = \mathbf{a}_C + \boldsymbol{\alpha} \times \mathbf{r}_{R/C} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}_{R/C}$$

$$\mathbf{a}_S = \mathbf{a}_C + \boldsymbol{\alpha} \times \mathbf{r}_{S/C} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}_{S/C}$$



- **Utilizing the symmetry of the cruciform geometry**

$$\mathbf{r}_{P/C} = -\mathbf{r}_{Q/C} \text{ and } \mathbf{r}_{R/C} = -\mathbf{r}_{S/C}$$

  - **Acceleration at the centroid can be expressed in two independent ways**

$$\mathbf{a}_C = \frac{\mathbf{a}_P + \mathbf{a}_Q}{2} \qquad \mathbf{a}_C = \frac{\mathbf{a}_R + \mathbf{a}_S}{2}$$

- **Finally, to get acceleration at the center of gravity $\mathbf{a}_G$**

$$\mathbf{a}_G = \mathbf{a}_C + \boldsymbol{\alpha} \times \mathbf{r}_{G/C} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}_{G/C}$$

Matrix Relations for Point Accelerations

- **The cruciform configuration simplifies the matrix form**
  - **Results in a large number zero terms that would otherwise be populated**

$$\begin{bmatrix} a_{P_x} \\ a_{P_y} \\ a_{P_z} \\ a_{Q_x} \\ a_{Q_y} \\ a_{Q_z} \\ a_{R_x} \\ a_{R_y} \\ a_{R_z} \\ a_{S_x} \\ a_{S_y} \\ a_{S_z} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & -L_p & -L_p & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & L_p & 0 & 0 & 0 & L_p & 0 & 0 \\ 0 & 0 & 1 & 0 & -L_p & 0 & 0 & 0 & 0 & 0 & L_p & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & -L_Q & -L_Q & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & L_Q & 0 & 0 & 0 & L_Q & 0 & 0 \\ 0 & 0 & 1 & 0 & -L_Q & 0 & 0 & 0 & 0 & 0 & L_Q & 0 \\ 1 & 0 & 0 & 0 & 0 & -L_R & 0 & 0 & 0 & L_R & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & -L_R & 0 & -L_R & 0 & 0 & 0 \\ 0 & 0 & 1 & L_R & 0 & 0 & 0 & 0 & 0 & 0 & 0 & L_R \\ 1 & 0 & 0 & 0 & 0 & -L_S & 0 & 0 & 0 & L_S & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & -L_S & 0 & -L_S & 0 & 0 & 0 \\ 0 & 0 & 1 & L_S & 0 & 0 & 0 & 0 & 0 & 0 & 0 & L_S \end{bmatrix} \begin{bmatrix} a_{C_x} \\ a_{C_y} \\ a_{C_z} \\ \alpha_x \\ \alpha_y \\ \alpha_z \\ \omega_x^2 \\ \omega_y^2 \\ \omega_z^2 \\ \omega_x\omega_y \\ \omega_x\omega_z \\ \omega_y\omega_z \end{bmatrix}$$

- **Expressed in matrix notation**

$$\mathbf{A}_{meas} = \mathbf{K}\mathbf{A}_{calc}$$

$$\boxed{\mathbf{A}_{calc} = \mathbf{K}^{-1}\mathbf{A}_{meas}}$$

Angular Rate Determination

- **The ω terms can be found by examining the point velocity expressions**

$$\mathbf{v}_P = \mathbf{v}_C + \boldsymbol{\omega} \times \mathbf{r}_{P/C}$$

$$\mathbf{v}_Q = \mathbf{v}_C + \boldsymbol{\omega} \times \mathbf{r}_{Q/C}$$

$$\mathbf{v}_R = \mathbf{v}_C + \boldsymbol{\omega} \times \mathbf{r}_{R/C}$$

$$\mathbf{v}_S = \mathbf{v}_C + \boldsymbol{\omega} \times \mathbf{r}_{S/C}$$

Velocities found by integrating the body frame measured accelerations (results in incorrect velocities but angular rates are not affected.)

- **For the cruciform pattern these reduce to**

$$\begin{bmatrix} v_{P_y} \\ v_{P_z} \\ v_{Q_y} \\ v_{Q_z} \\ v_{R_x} \\ v_{R_z} \\ v_{S_x} \\ v_{S_z} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & L_P \\ 0 & 0 & 1 & 0 & -L_P & 0 \\ 0 & 1 & 0 & 0 & 0 & L_Q \\ 0 & 0 & 1 & 0 & -L_Q & 0 \\ 1 & 0 & 0 & 0 & 0 & -L_R \\ 0 & 0 & 1 & L_R & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & -L_S \\ 0 & 0 & 1 & L_S & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{C_x} \\ v_{C_y} \\ v_{C_z} \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

- **Expressed in matrix notation**

$$\mathbf{V}_{meas} = \mathbf{W}\mathbf{V}_{calc}$$

$$\boxed{\mathbf{V}_{calc} = \left[\mathbf{W}^T\mathbf{W}\right]^{-1}\mathbf{W}^T\mathbf{V}_{meas}}$$

Determination of Acceleration Terms

- **Moving ω terms to the left hand side we can solve for the accelerations**

$$\begin{bmatrix} a_{P_x} + \omega_y^2 \cdot L_p + \omega_z^2 \cdot L_p \\ a_{P_y} - \omega_x\omega_y \cdot L_p \\ a_{P_z} - \omega_x\omega_z \cdot L_p \\ a_{Q_x} + \omega_y^2 \cdot L_Q + \omega_z^2 \cdot L_Q \\ a_{Q_y} - \omega_x\omega_y \cdot L_Q \\ a_{Q_z} - \omega_x\omega_z \cdot L_Q \\ a_{R_x} - \omega_x\omega_y \cdot L_R \\ a_{R_y} + \omega_x^2 \cdot L_R + \omega_z^2 \cdot L_R \\ a_{R_z} - \omega_y\omega_z \cdot L_R \\ a_{S_x} - \omega_x\omega_y \cdot L_S \\ a_{S_y} + \omega_x^2 \cdot L_S + \omega_z^2 \cdot L_S \\ a_{S_z} - \omega_x\omega_y \cdot L_S \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & L_P \\ 0 & 0 & 1 & 0 & -L_P & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & L_Q \\ 0 & 0 & 1 & 0 & -L_Q & 0 \\ 1 & 0 & 0 & 0 & 0 & -L_R \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L_R & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & -L_S \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L_S & 0 & 0 \end{bmatrix} \begin{bmatrix} a_{C_x} \\ a_{C_y} \\ a_{C_z} \\ \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix}$$

- **Expressed in matrix notation**

$$\mathbf{A}_{meic} = \tilde{\mathbf{K}}\tilde{\mathbf{A}}_{calc}$$

$$\boxed{\tilde{\mathbf{A}}_{calc} = \left[\tilde{\mathbf{K}}^T\tilde{\mathbf{K}}\right]^{-1}\tilde{\mathbf{K}}^T\mathbf{A}_{meia}}$$

Dynamic Center of Rotation?

- The acceleration at the cg can now be determined

$$\mathbf{a}_G = \mathbf{a}_C + \boldsymbol{\alpha} \times \mathbf{r}_{G/C} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}_{G/C}$$

- While the lander is rigid it moves and rotates within the deforming airbag and is not guaranteed to have the same center of rotation
- Is it possible to determine the dynamic center of rotation?
  - Due to the presence of an unmeasured force (the ramp) the center of rotation cannot be uniquely determined from the accelerometer and rate gyro information
- How to proceed?
  - Assume the center of rotation is fixed at the cg and does not migrate significantly
  - This introduces an unknown error that is better quantified by looking at the processed data

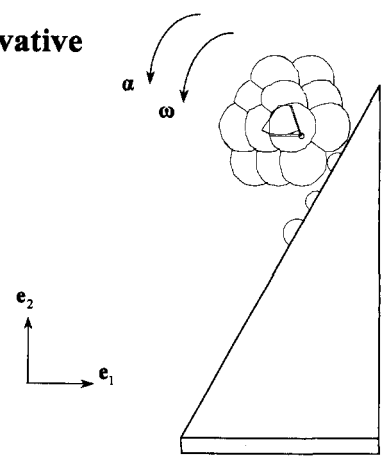
Worst-case Point Acceleration

- Determine the worst case acceleration at any point in the lander
  - Assume planar motion s.t. alpha & omega vectors are perpendicular
  - The RSS of these will then be the maximum rotational acceleration
- Superimposing the linear and rotational acceleration gives maximum
- Initially used α_{pseudo} to estimate acceleration
- Determined later that α_{pseudo} is overly conservative
  - Including ω contribution inflated α loads
  - Remains a good indicator of planar rotation

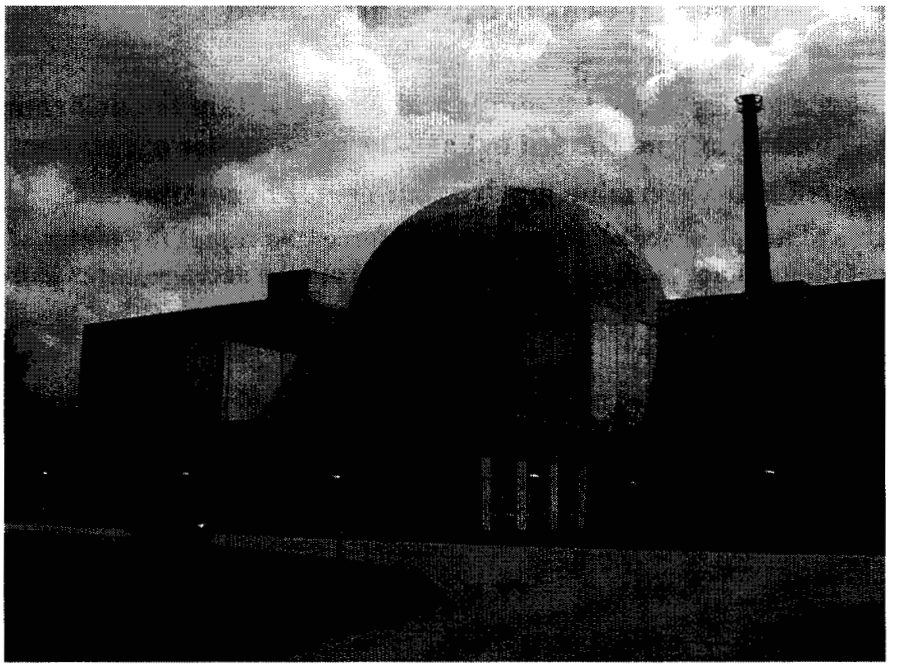
$$\mathbf{a}_{C.P.} = \mathbf{a}_G + \boldsymbol{\alpha} \times \mathbf{r}_{C.P./G} + \boldsymbol{\omega} \times \boldsymbol{\omega} \times \mathbf{r}_{C.P./G}$$

$$\|\mathbf{a}\|_{max} = \left(\|\mathbf{a}_G\| + \sqrt{(\alpha r)^2 + (\omega^2 r)^2} \right)_{max}$$

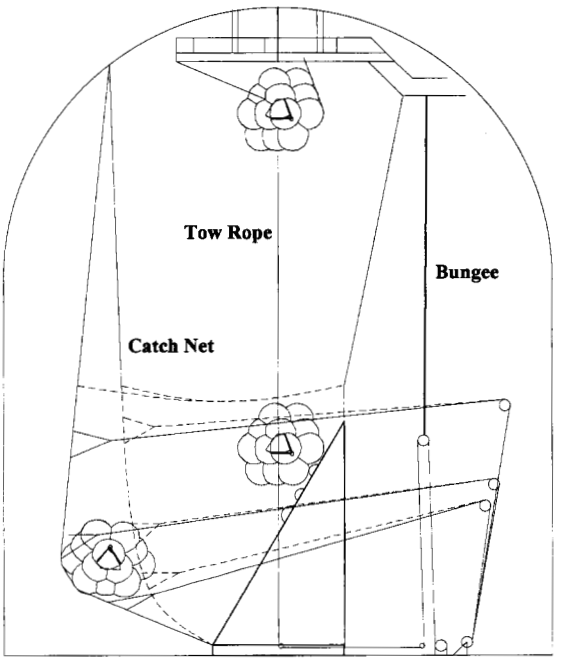
$$\alpha_{pseudo} = \sqrt{\alpha^2 + (\omega^2)^2} = \frac{\|\mathbf{a}\|_{max} - \|\mathbf{a}_G\|}{r}$$

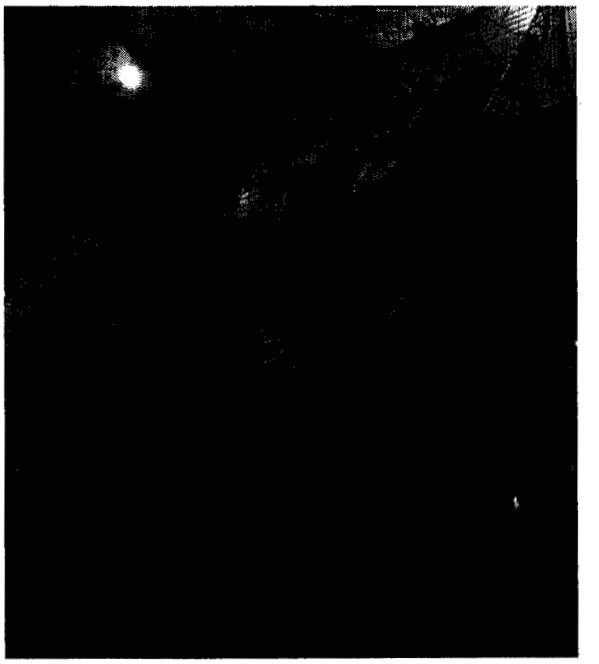


NASA Plumbrook's Space Power Facility



SPF Vacuum Chamber Drop Test Setup





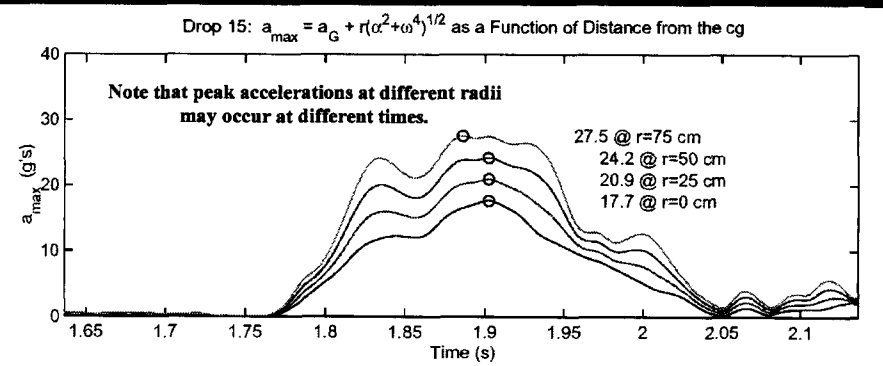
Data Analysis & Verification of Results

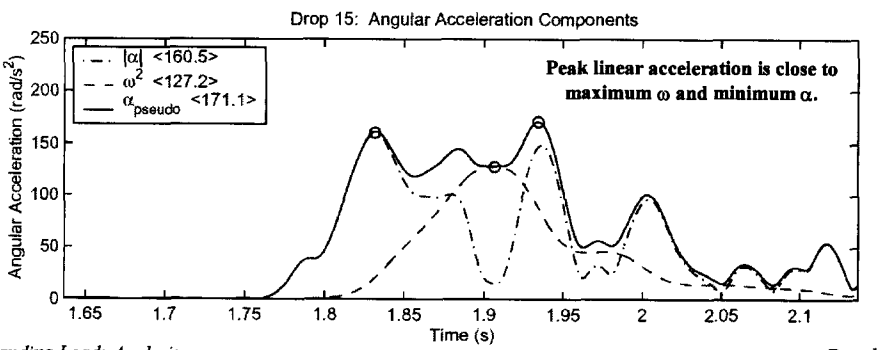
- Onboard IDDAS data sampled at 2 kHz
- Typically processed 3 seconds of data (the exciting part)
- Assessment of data quality and results
  - Reconstruction of acceleration measurements using the calculated rigid body motion
  - Comparison of independent ω measurements (gyro and integration)
- Note the torsional oscillation (natural frequency) in α plots
- Uncertainty in initial attitude lead to some errors in acceleration
  - Affected the accuracy of subtracting Earth's gravity vector to determine sensed acceleration (vs. inertial acceleration)

$$\vec{a}_{sensed} = \vec{a}_{inertial} - \vec{g}$$

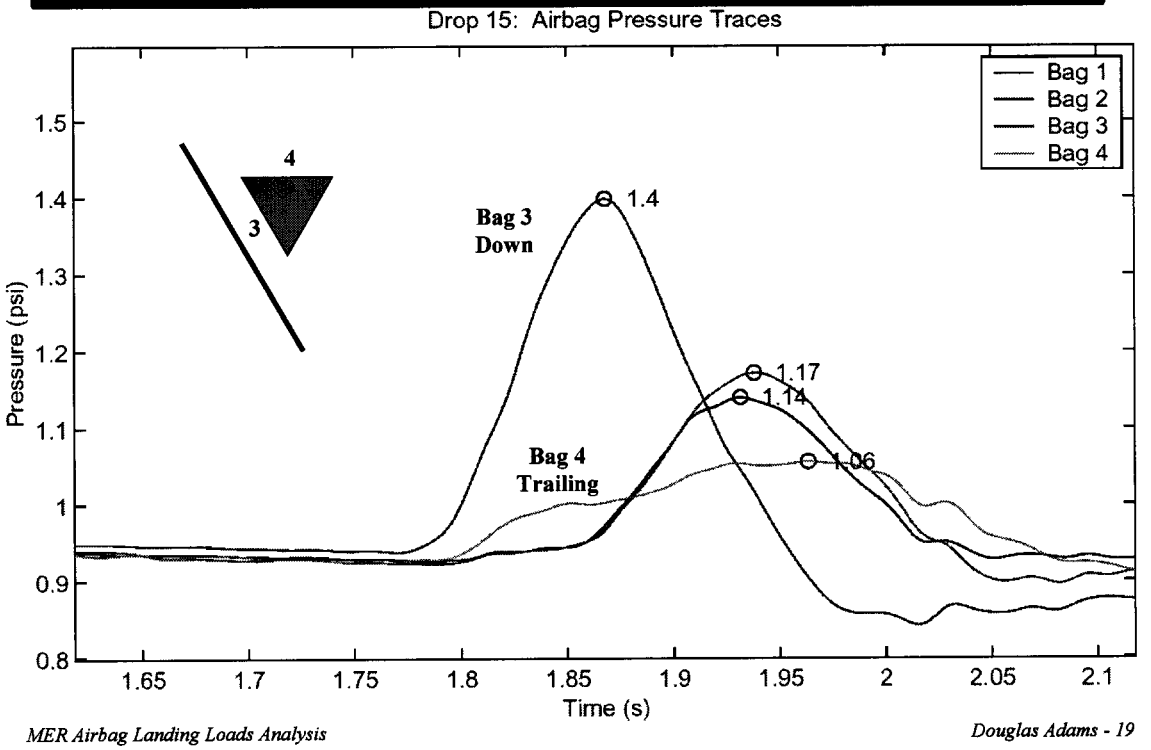
(e.g., at rest an on-board observer senses an acceleration of 1-g upward in inertial space.)

Drop 15: Acceleration and Angular Rate Results

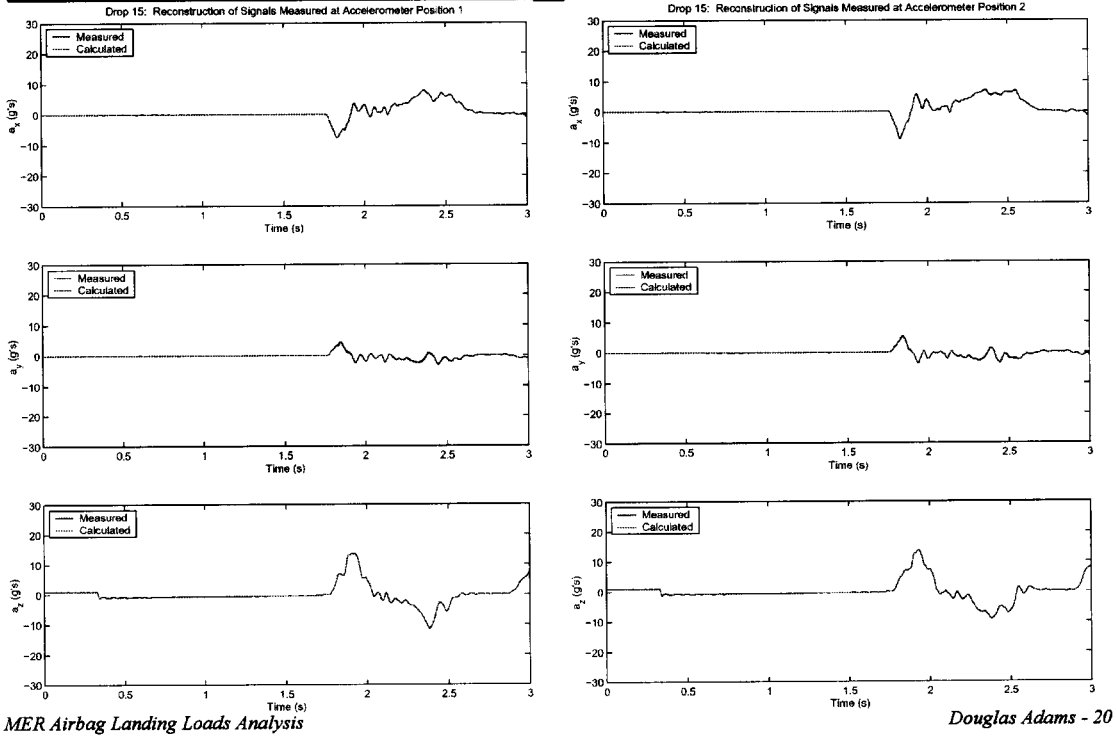




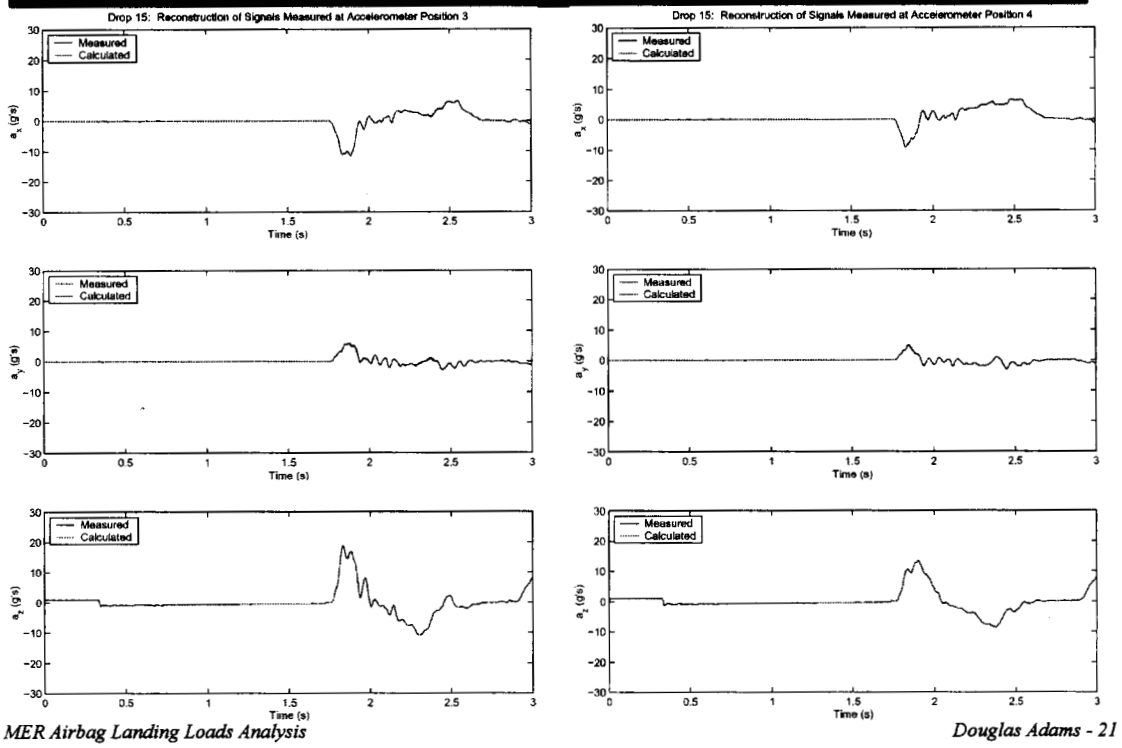
Drop 15: Airbag Pressure Traces



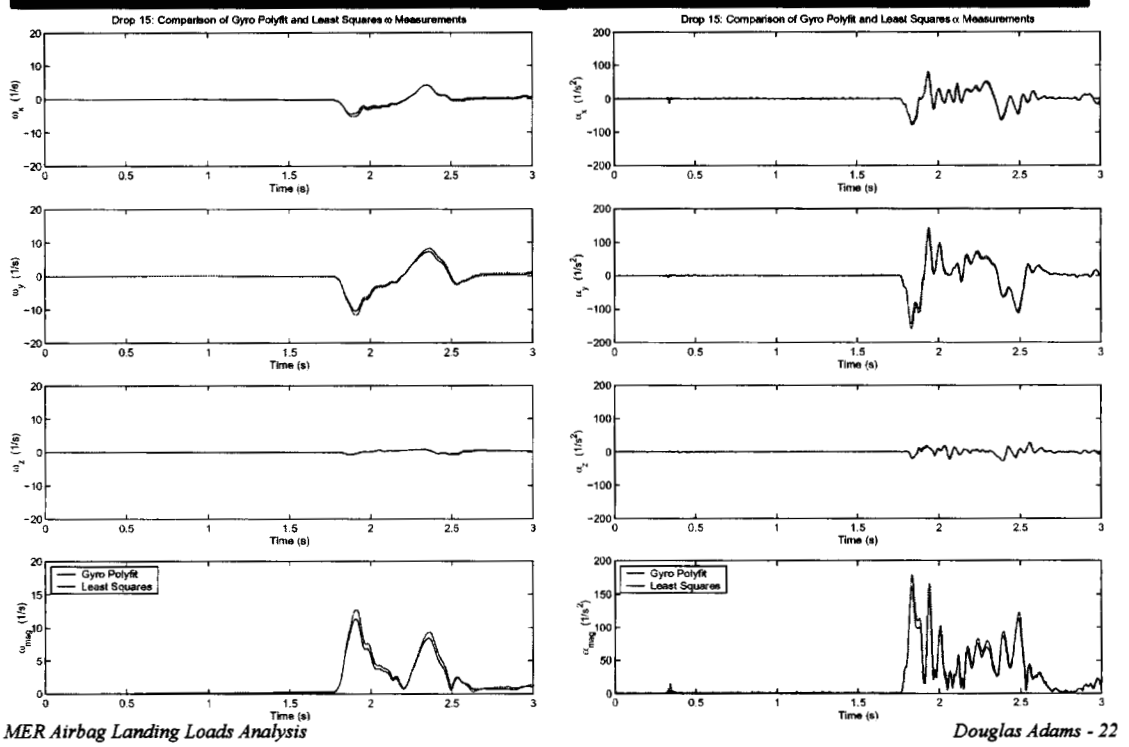
Drop 15: Pos. 1 & 2, Good Accel. Reconstruction



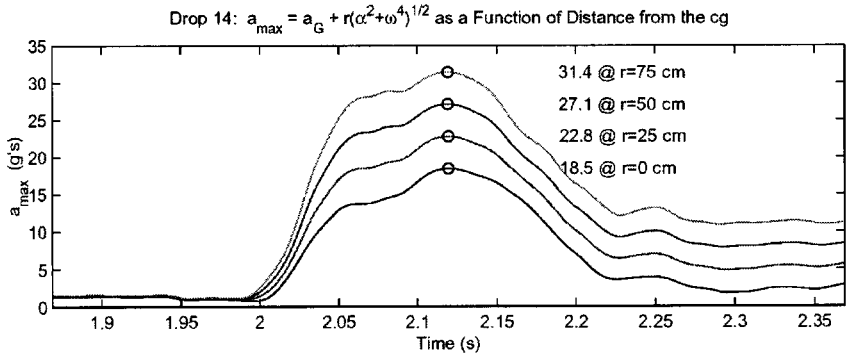
Drop 15: Pos. 3 & 4, Good Accel. Reconstruction

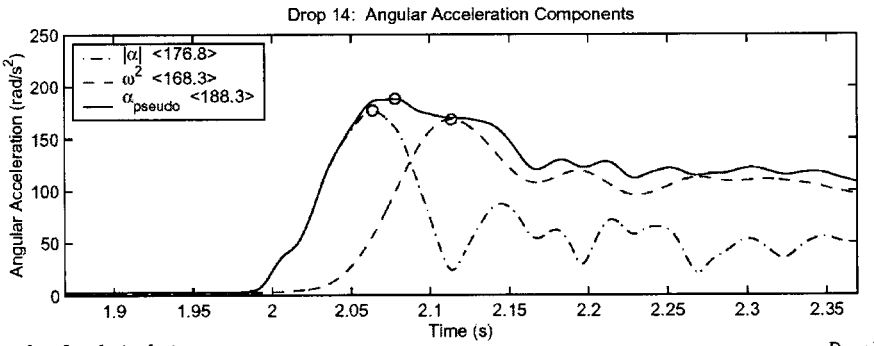


Drop 15: Gyro vs. Angular Rate Results

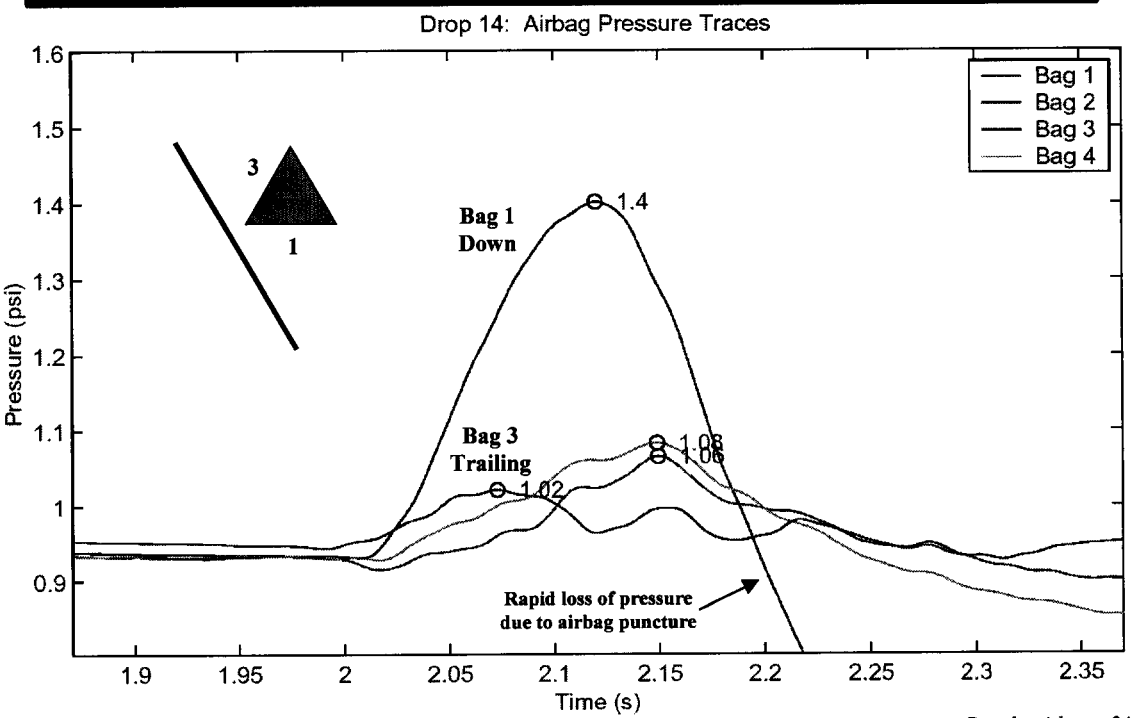


Drop 14: Acceleration and Angular Rate Results

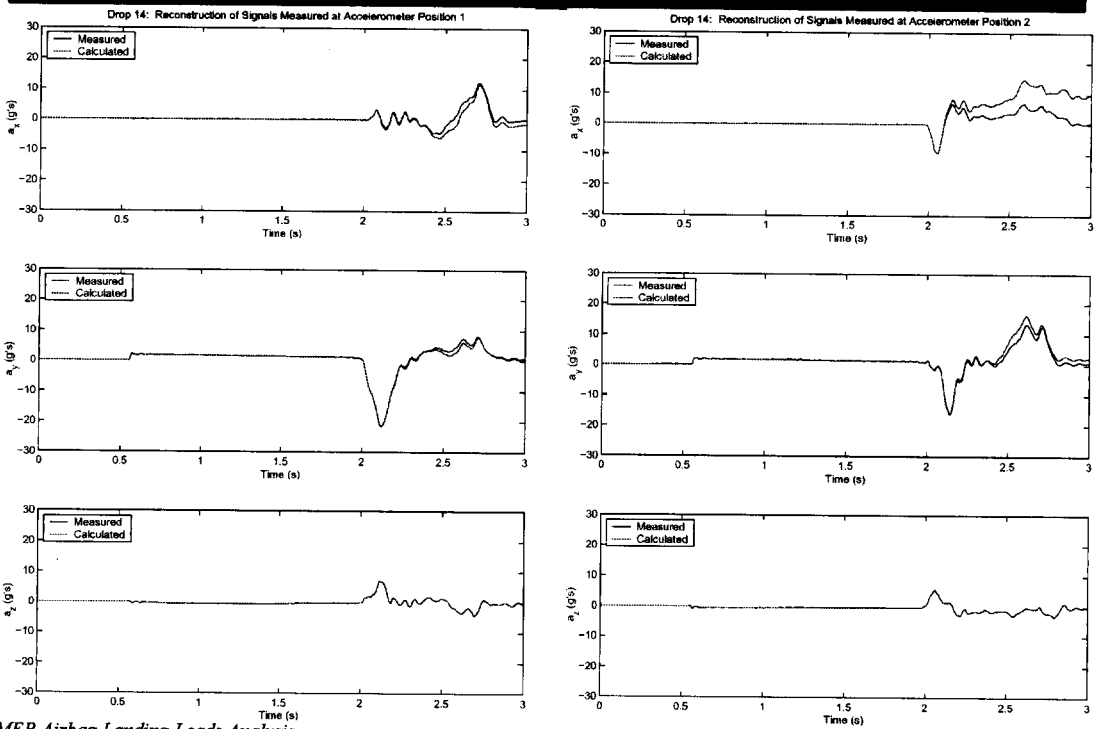




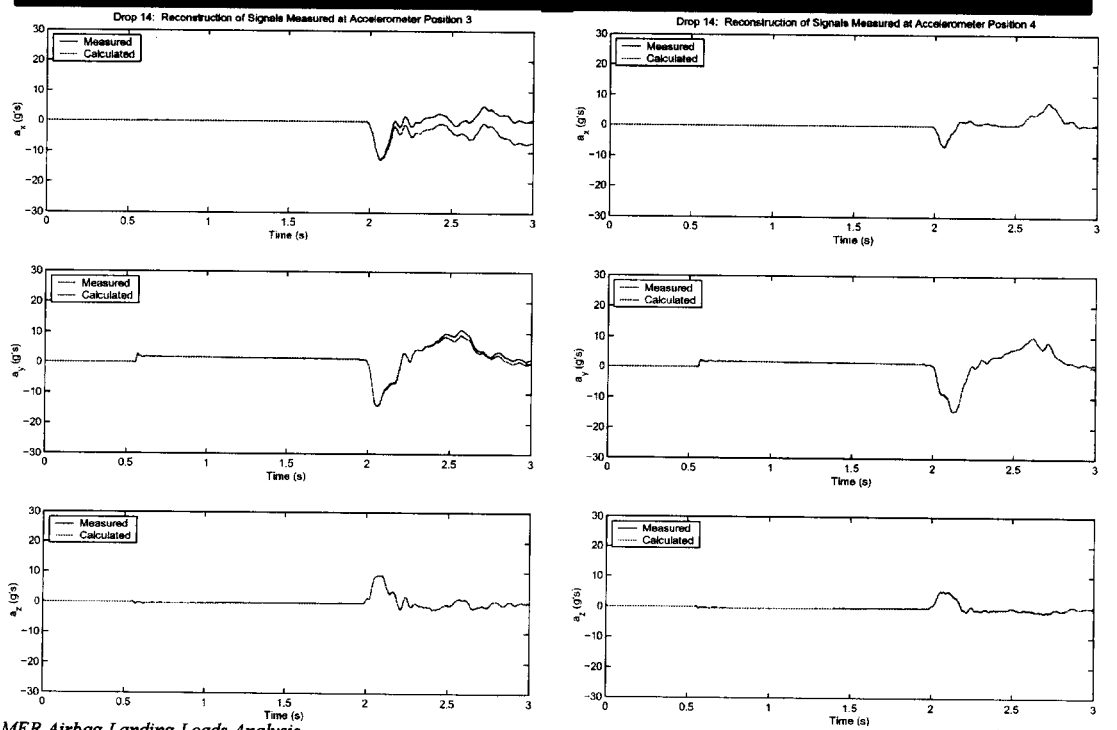
Drop 14: Airbag Pressure Traces



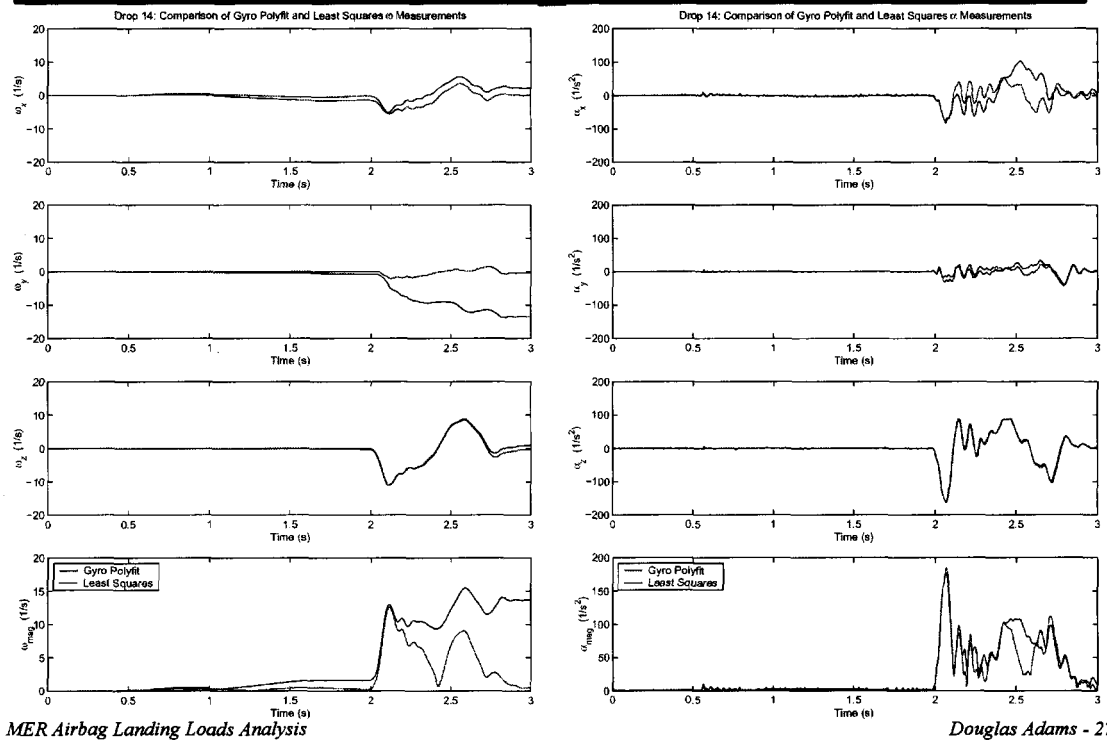
Drop 14: Pos. 1 & 2, Poor Accel. Reconstruction



Drop 14: Pos. 3 & 4, Poor Accel. Reconstruction



Drop 14: Gyro vs. Angular Rate Results



0° Ramp "Superflat" Results

- **Simulations indicate a possible secondary impact with V_{norm} >12 m/s**
  - **Statistical limit taken as ~16 m/s**
- **Total of four "superflat" (horizontal ramp) drops**

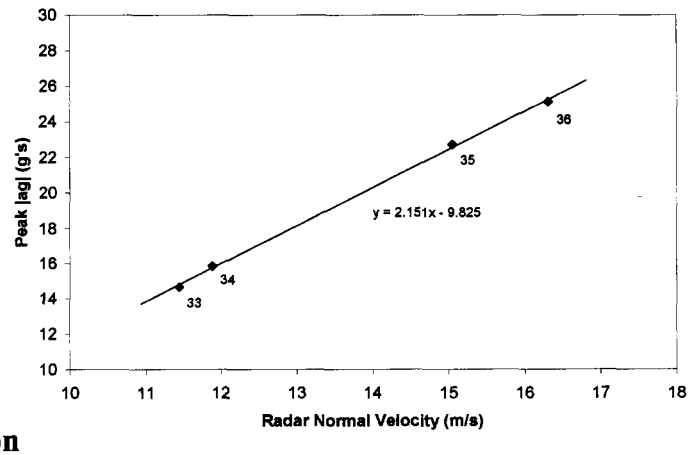
Drop Number	Vnorm (m/s)	|ag| (g's)
33	11.4	14.7
34	11.9	15.8
35	15.1	22.7
36	16.3	25.1

- **Least squares data fit**
  - **LUF = 1.1**
  - **Corrected to Mars gravity**

$$|a_g|_{16m/s} = 1.1*[(2.151*16-9.825)-5/8]$$

- **Peak non-rotating acceleration**

$$|a_g|_{16m/s} = 26.4\ g's$$



Superflat (0° ramp) peak cg acceleration versus normal velocity (no LUF).

Ramp Impact Results Summary

- Superflat drops represent lower bound
- P95/50 does well at capturing maximum acceleration
- Nominal target velocity of 12 m/s

11 m/s < Vnorm < 13 m/s

Drop Number	Vnorm (m/s)	|ag| (g's)
15	11.1	17.7
20	12.0	21.5
23	12.1	19.1
24	11.1	15.9
26	12.4	18.9
26A	12.2	19.1
27	12.0	19.7
30	12.2	19.2
31	12.1	19.7
32	12.7	20.6
38	11.2	18.1
39	11.4	19.0

|ag| Statistics

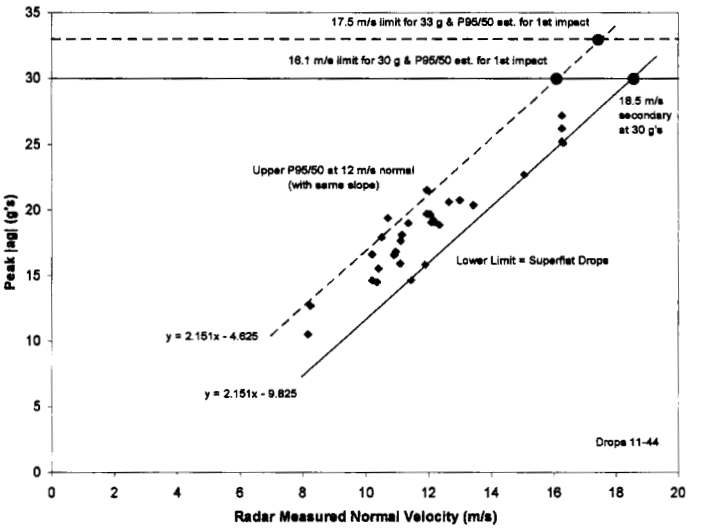
Max	21.5
Min	15.9
Mean	19.1
Sigma	1.4
P95/50	21.5

11.5 m/s < Vnorm < 12.5 m/s

Drop Number	Vnorm (m/s)	|ag| (g's)
20	12.0	21.5
23	12.1	19.1
26	12.4	18.9
26A	12.2	19.1
27	12.0	19.7
30	12.2	19.2
31	12.1	19.7

|ag| Statistics

Max	21.5
Min	18.9
Mean	19.6
Sigma	0.9
P95/50	21.2



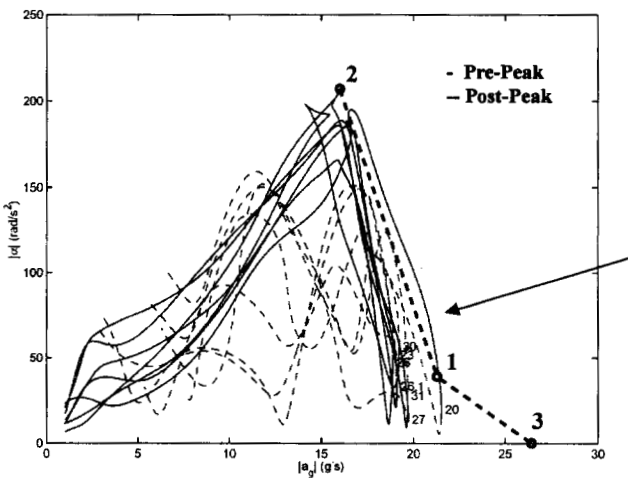
Note: Original result from Drops 12-15 was 21.3 g's with LUF=1.15

Phase Plot of Impact Accelerations

- **Three load cases used for FEM analysis**

Loading Event	|ag| (g's)	|a| (1/s^2)	|w| (1/s)	Notes:
1	21.3	39.1	13.8	Taken from Drop 14 with LUF=1.15
2	16.0	207.0	10.8	Taken from Drop 13 with LUF=1.15
3	26.4	0.0	13.0	16 m/s superflat with LUF=1.10 & expected ω

- **Load cases envelope acceleration environment**

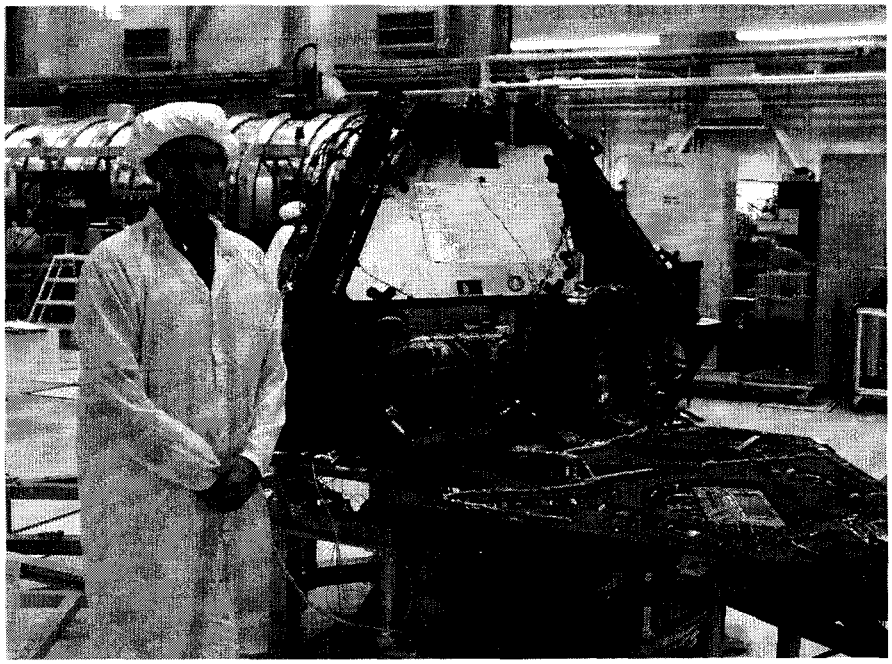


Drop 20 had anomalous angular rates.

Concluding Remarks

- Total of 44 drop tests performed
  - 31 with good data and appropriate mass and pressure
- Least squares accelerometer measurements shown to be capable of accurately reproducing angular rate terms
  - Verified with rate gyro measurements
- Observed scatter in cg acceleration for similar impact velocities
  - Most likely result from center of rotation migration from the cg location
- Non-rotating impacts shown to be the lower bound of cg acceleration
  - Secondary impact loads can be modeled as having little or no α
- Entire dynamic envelope is adequately described by three load cases
  - Used to determine worst-case internal structural loads

r (cm)	a_{cg} (g's)	$r\alpha_{pseudo}$ (g's)	2nd Impact (g's)	1st Impact (g's)
0	26.4	0.0	26.4	21.2
25	26.4	4.3	30.7	26.2
50	26.4	8.6	35.0	31.2
75	26.4	12.9	39.3	36.1

2nd impact assumes ω=13 rad/s

MER Rover with +X and +Y Petals Stowed