AerospaceComputing, Inc.

Aerodynamics and Planetary Entry

Leslie A. Yates
Gary T. Chapman

Presented at JPL
June 6, 2002

Overview

- Background
- Objectives
  - General description of planetary entry
  - Impact of aerodynamics on trajectory
  - Review sources of aerodynamic information
  - Review status of aerodynamics
- Concluding remarks, issues, and future directions

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Background

- Extensive interest in the 1960's to 70's
  - Research
  - Probes to Venus, Mars, and Jupiter
- Renewed interest in the 90's
  - Probes to Mars, Stardust, Huygen, Genesis
- Project driven environment leads to:
  - Erosion of expertise and database
  - Limits innovation
- Greater demand on aerodynamics
  - Increased program requirements
  - Aeroassist to reduce costs

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Objectives

- **General Description of Planetary Entry**
- **Demonstrate role of aerodynamics on planetary entry**
- **Review sources of aerodynamic information**
- **Review status of aerodynamics of planetary entry shapes**

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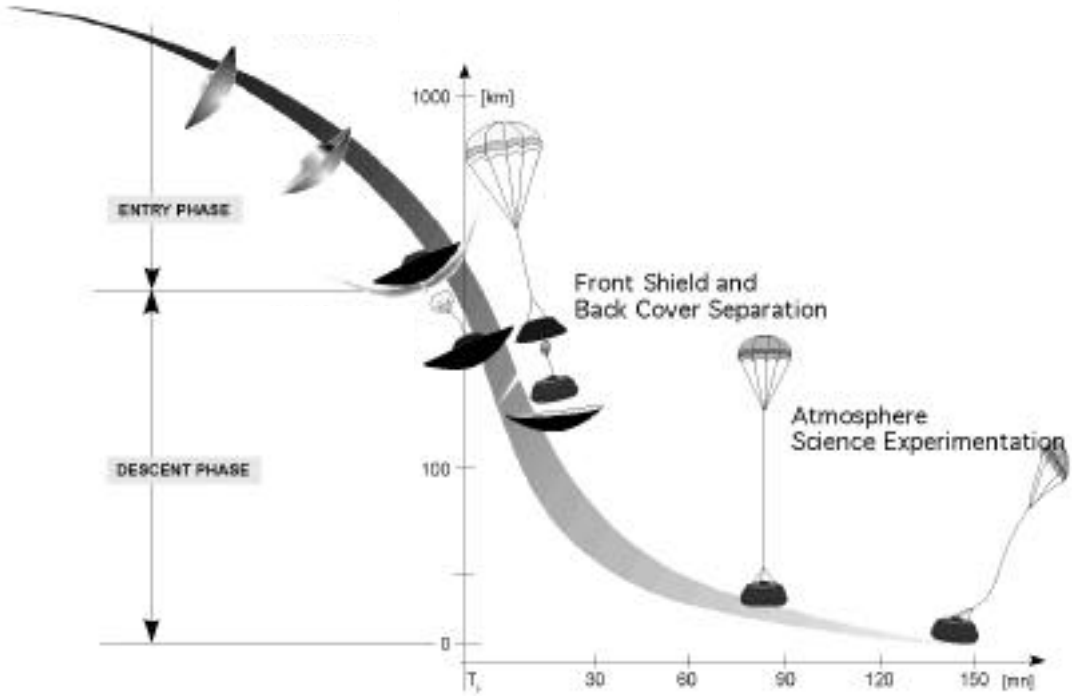
Schematic of Planetary Entry



- **Entry**
  - **Max. loads**
  - **Max. heating**
- **Special events**
  - **Parachute deployment**
- **Unplanned events**
  - **Vehicle breakup**

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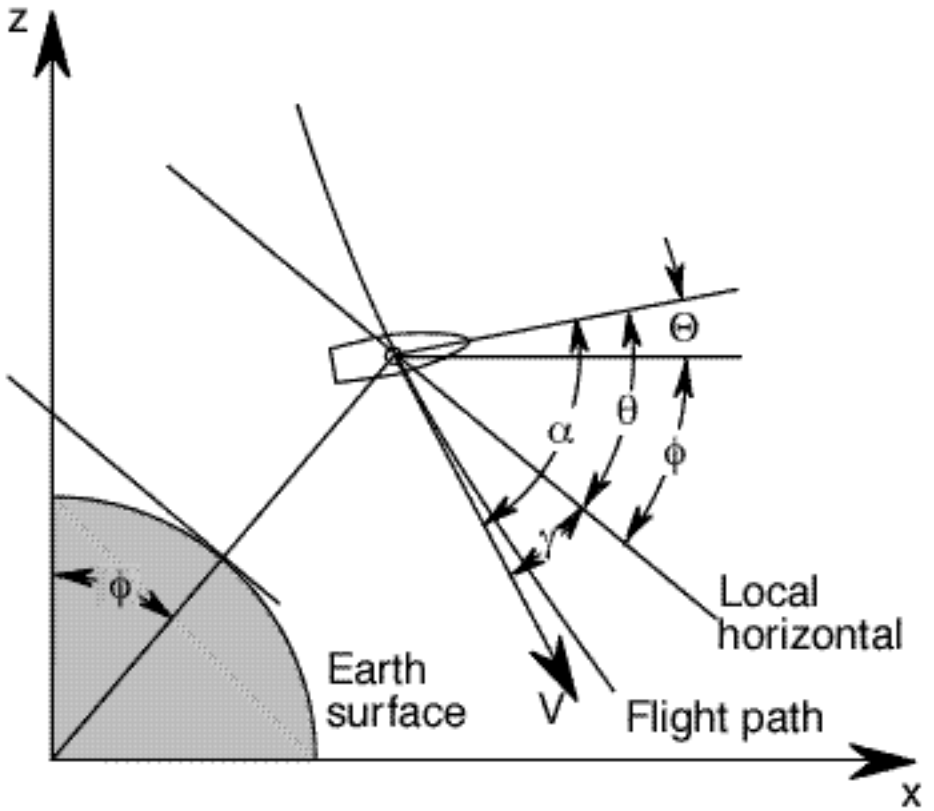
Planar Planetary Entry



- **Equations**

$$m\dot{V} = -qAC_D + mg\sin\gamma$$

$$mV\dot{\gamma} = -qAC_L + m\left(\frac{V^2}{r} - g\right)\cos\gamma$$

$$I\ddot{\Theta} = qAl\sum C_m$$

where

$$C_L = C_{L_0} + C_{L_\alpha}(\alpha - \alpha_t)$$

$$\sum C_m = C_{m_\alpha}(\alpha - \alpha_t) + C_{m_q}\frac{\dot{\Theta}l}{V} + C_{m_{\dot{\alpha}}}\frac{\dot{\alpha}l}{V} + C_{m_\delta}\delta$$

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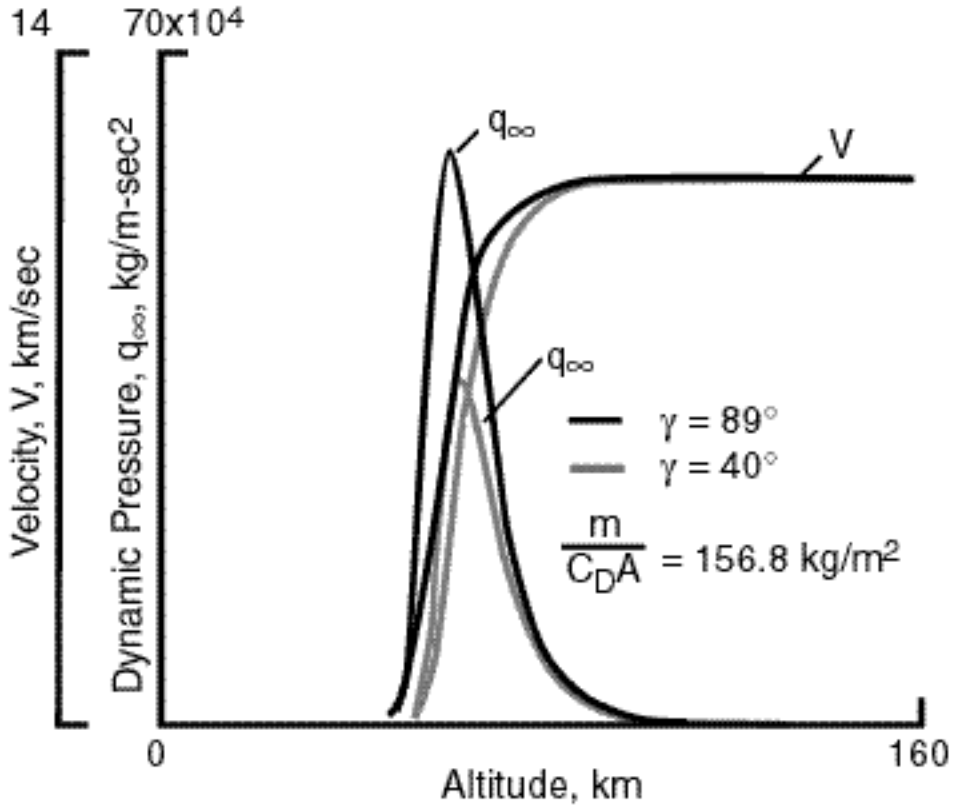
Point Mass Behavior



- **Equations of motion:**

$$m\dot{V} = -qAC_D + mg\sin\gamma_s$$

$$mV\dot{\gamma}_s = -qA\left[C_{L_0} + C_{L_\alpha}(\alpha_t + \alpha_s)\right] - m\left(\frac{V^2}{r}\right) - g\cos\gamma_s$$

- **Important events / issues**
  - **Maximum q**
  - **Maximum heating**
  - **Mach at impact / parachute deploy**
  - **Landing footprint**

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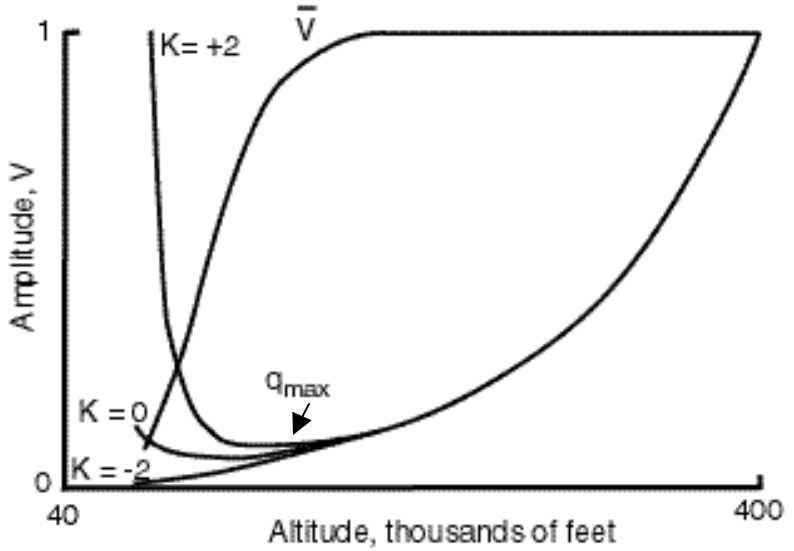
Oscillatory Behavior



- **Equations of Motion**

$$I\ddot{\theta}_0 = qA\left[C_{m_\alpha}\alpha + C_{m_q}\frac{\dot{\theta}_0 l}{V} + C_{m_{\dot{\alpha}}}\frac{\dot{\alpha}_0 l}{V}\right]$$

- **Stability Criteria**
  - **Static:** $C_{m_\alpha} < 0$
  - **Dynamic:**

$$\frac{\rho A C_D}{m}K < \frac{\partial q/\partial s}{q} + \frac{\partial C_{m_\alpha}/\partial s}{C_{m_\alpha}}$$

$$K = \frac{1}{C_D}\left[-C_{L_\alpha} + \left(\frac{l}{\sigma}\right)^2\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)\right]$$

- **Important events / issues**
  - **Control system design**
  - **Amplitude at impact / parachute deploy**

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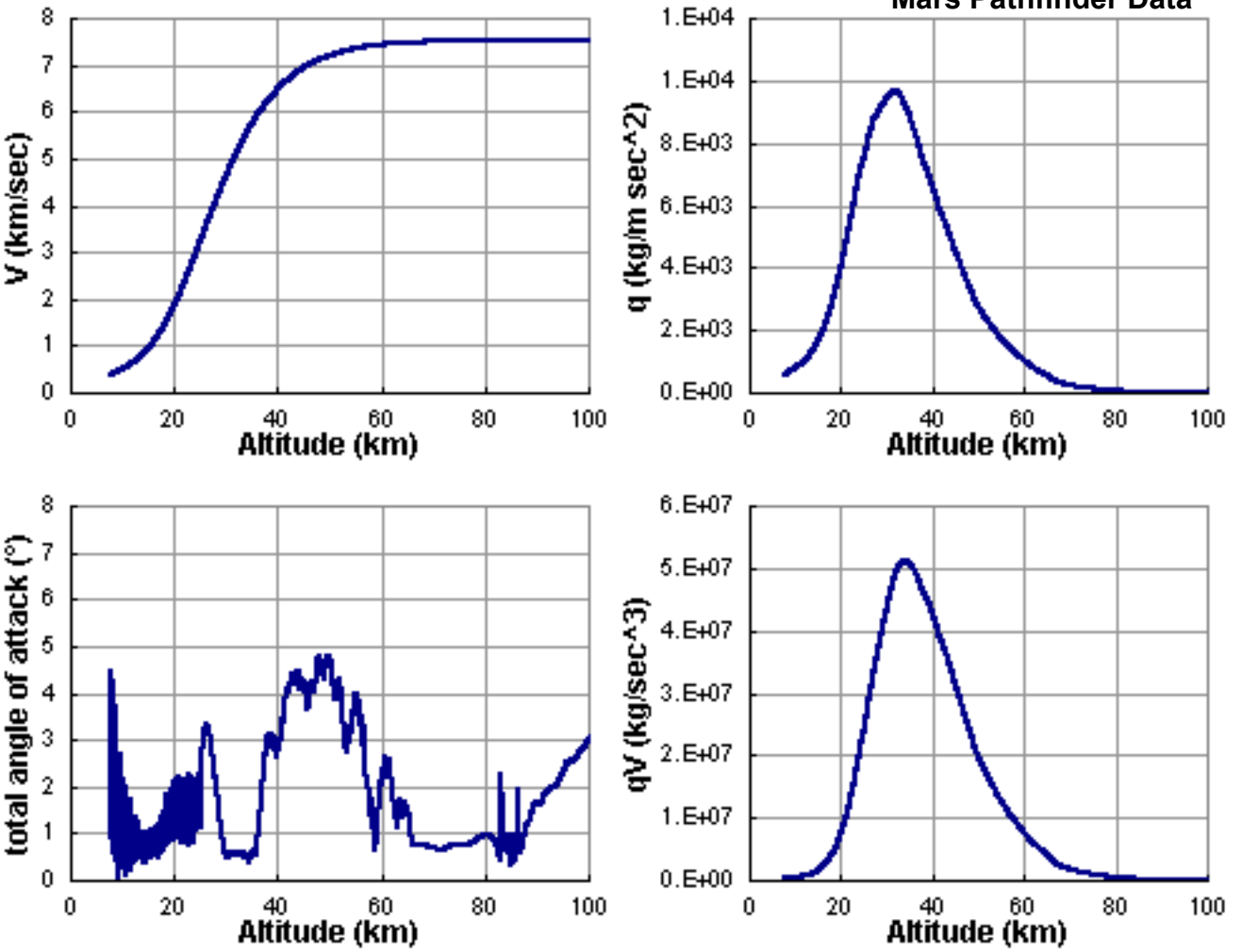
Typical Planetary Entry

Important Events / Effects

- Impact velocity / parachute deploy
- Maximum dynamic pressure
- Maximum heating
- Amplitude growth
- Minimum amplitude
- Impact angle

Mars Pathfinder Data



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Objectives

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Impact of Aerodynamics on Trajectory

- Impact demonstrated using trajectory simulations
- Conventions and definitions
  - Coordinate systems used for aerodynamic forces / moments
  - Nondimensionalization of the aerodynamic forces / moments
  - Static and dynamic stability
- Simulations - Description and examples

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Aerodynamic Forces and Moments

- Three coordinate systems used to describe motion: inertial, wind, and body
- Forces - two conventions used
  - Parallel and normal to flight path
    Drag, lift, and side force
  - Parallel and normal to body axes
    Axial, normal, and side force
- Moments
  - Pitching / yawing referenced to body axes and center of gravity
    - Static
    - Dynamic
  - Rolling referenced to body axes and center of gravity

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Nondimensionalization

- Reduces number of simulation variables, resulting terms valid over wider range of conditions

- Forces: $C_D = D / 0.5\rho V^2 A$

- Moments: $C_m = M / 0.5\rho V^2 A d$

- Rates: $\bar{\dot{\alpha}} = \dot{\alpha} d / 2V$

- Caution: Various quantities used to nondimensionalize variables (l or d, V or $2V$)

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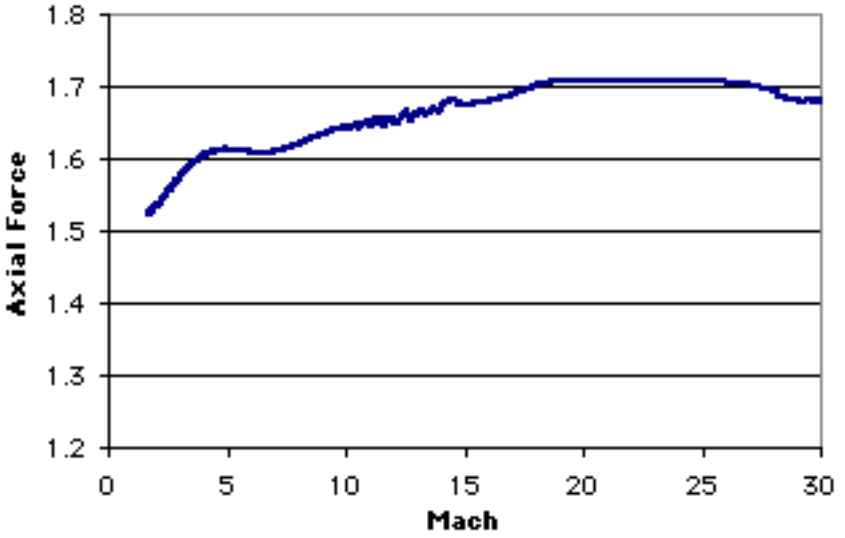
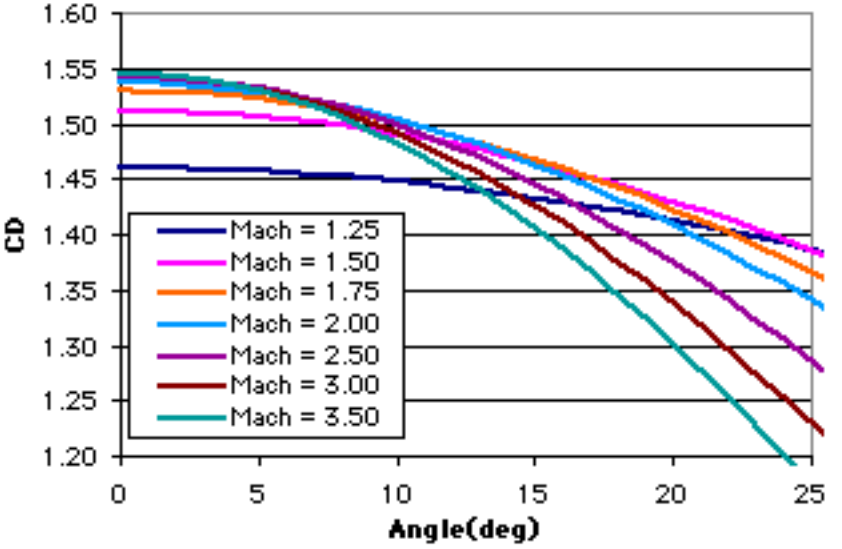
Coefficient Math Models

- Aerodynamic coefficients functions of Mach Number, Reynolds Number, angles, angular rates, control deflections, …
- Look up tables, polynomials, and complicated functions used to model coefficients



Mars Pathfinder



Mars 03, Ballistic Range

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Definitions

- **Static stability**
  - **If displaced from equilibrium vehicle tends to return to or pass through equilibrium point**
- **Dynamic stability**
  - **Amplitude of oscillatory motion decreases with time**
- **Limit cycle**
  - **Motion approaches constant amplitude**

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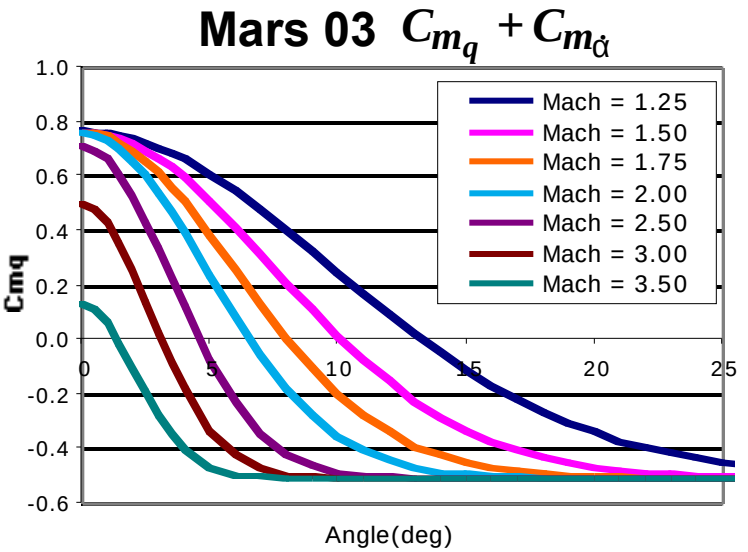
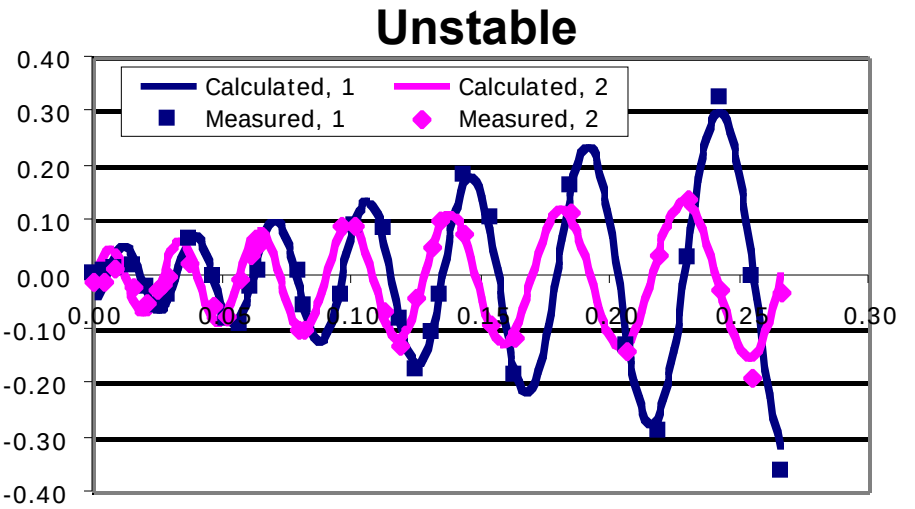
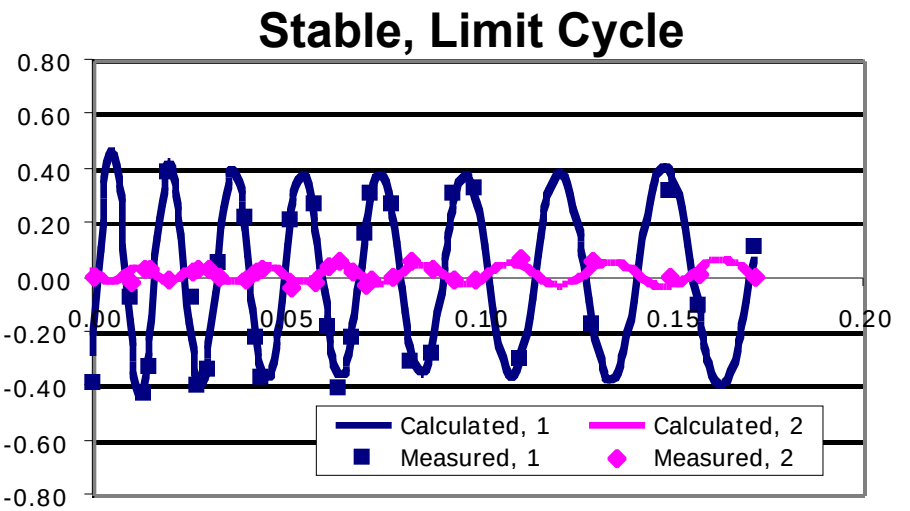
Stability – Limit Cycle







When damping coefficient is nonlinear function of angle, Mach, complicated behaviors occur.

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Trajectory Simulations

- **Brief description of simulations**
- **Examples**
  - **Linear aerodynamics**
  - **Nonlinear aerodynamics**

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Linear Aerodynamics Simulations

- Six-degree-of-freedom, nonlinear math models
- Density profiles, gravitational forces, and rotational rates consistent with Mars
- Vehicle specifications and aerodynamics consistent with axisymmetric probe configurations
- Shallow entry for longer flight paths and better demonstration of effects
- Not modeled - winds, controls

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Linear Aerodynamics Simulations (concluded)

- Emphasis - the effect of aerodynamic errors, uncertainties on the entry
- Varied parameters:
  - Drag, lift coefficient slope, trim lift, trim angle, moment coefficient slope, damping, roll
- Comparative effects
  - Forces, moments proportional to dynamic pressure
    - 5% variation in density produces similar effect as 5% variation in aerodynamic coefficient
    - 5% variation in velocity produces similar effect as 10% variation in aerodynamic coefficient

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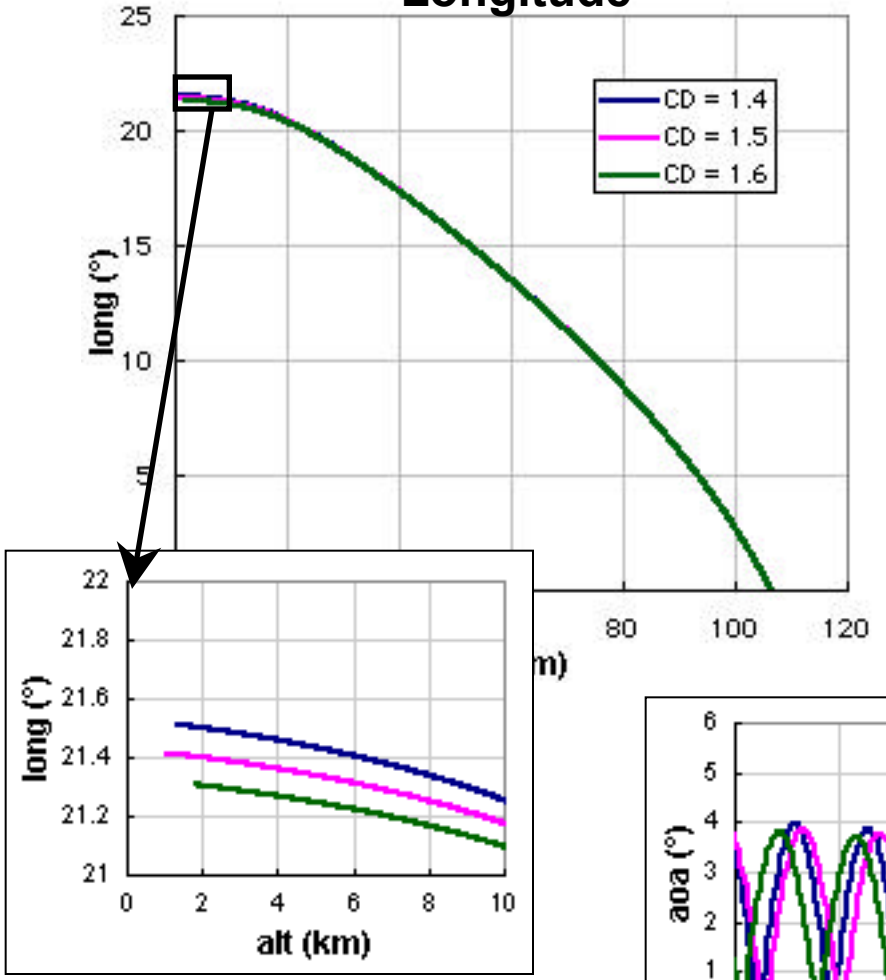
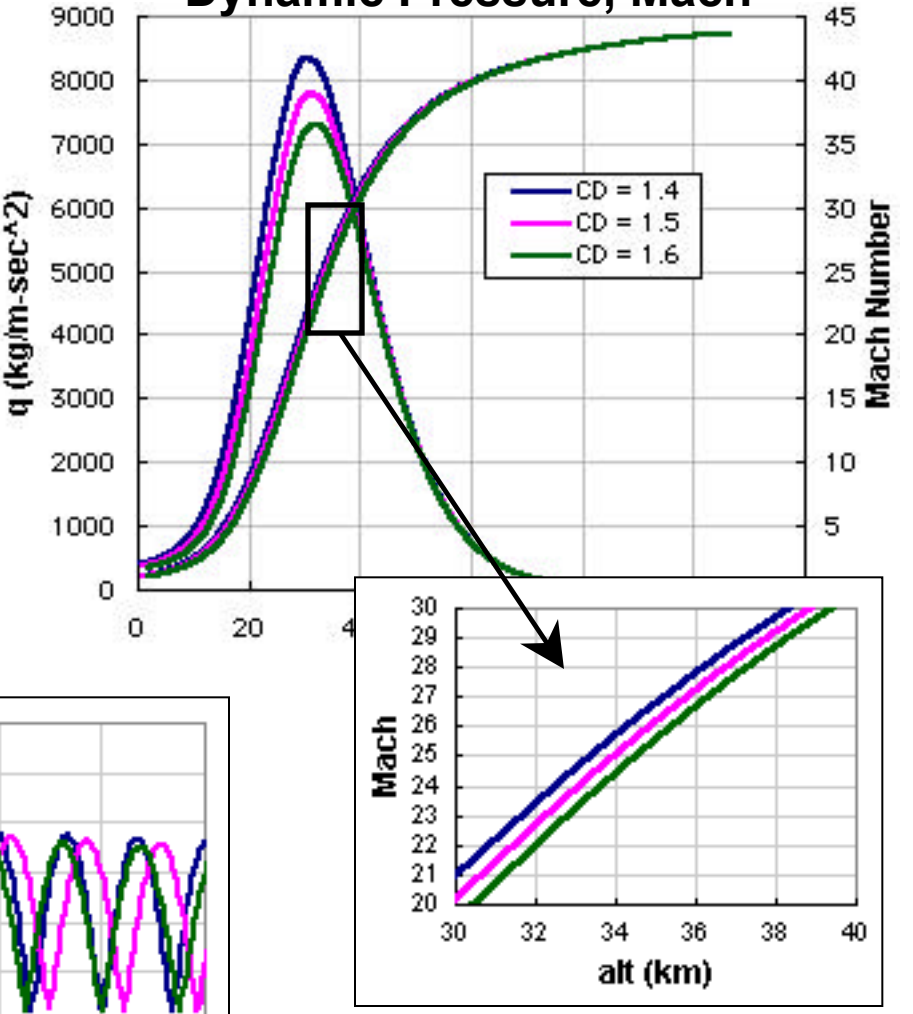
Drag Coefficient

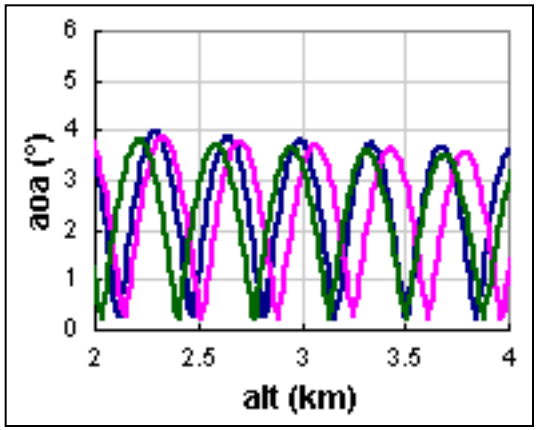
Longitude



1° of longitude translates to ≈60 km

Dynamic Pressure, Mach





Total Angle

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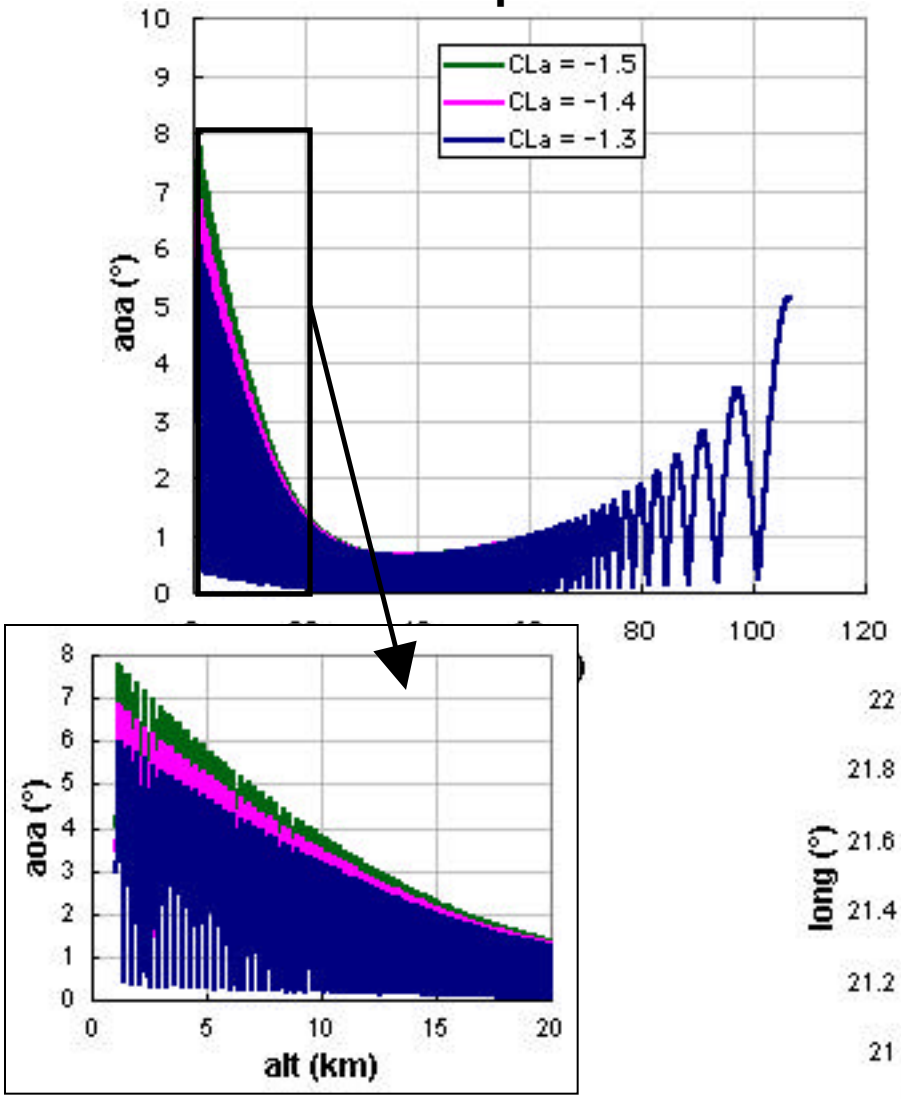
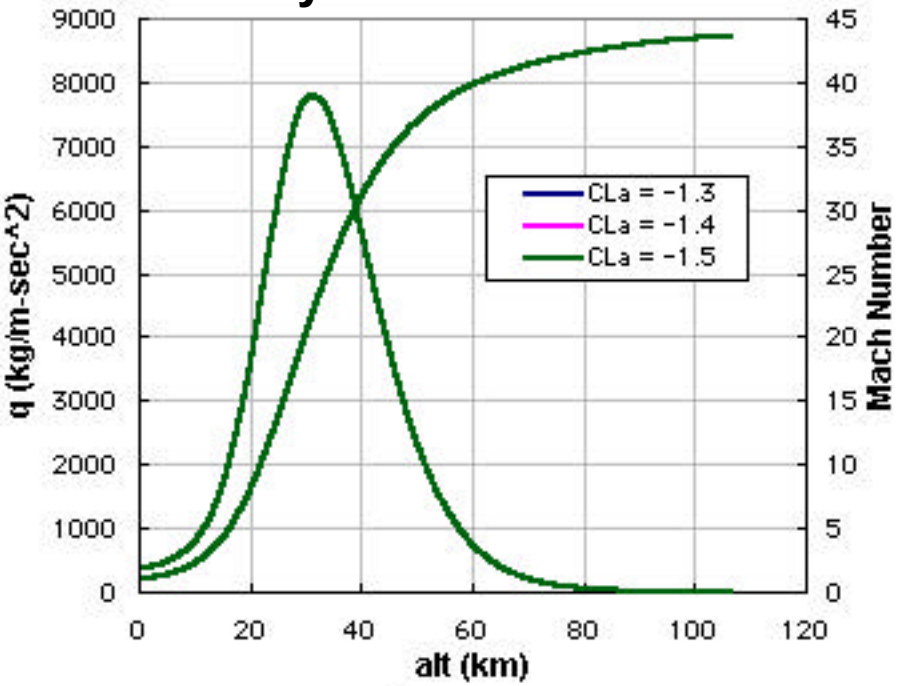
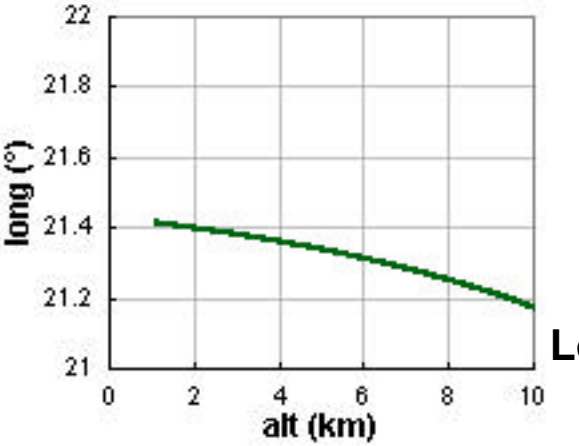
Lift Coefficient Slope

Amplitude



Dynamic Pressure





Longitude

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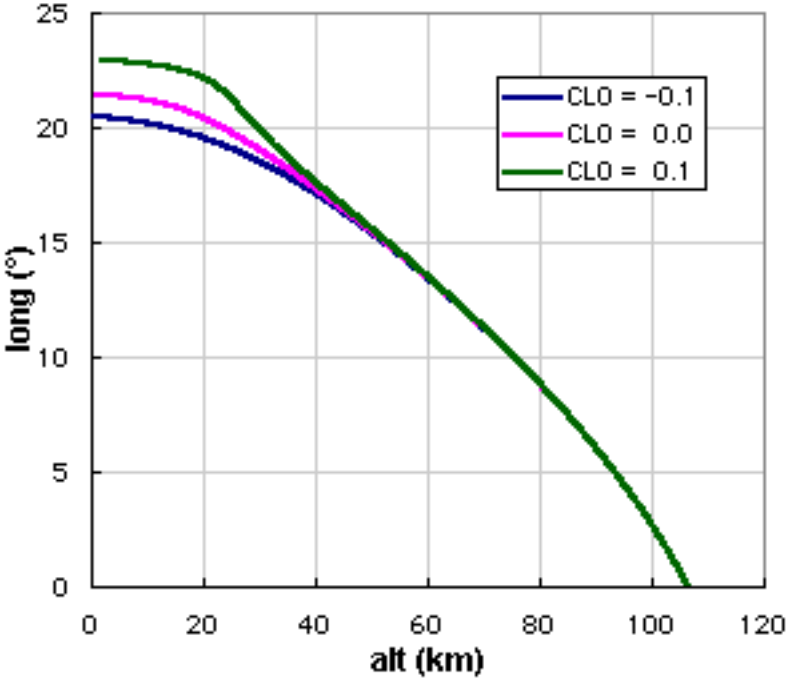
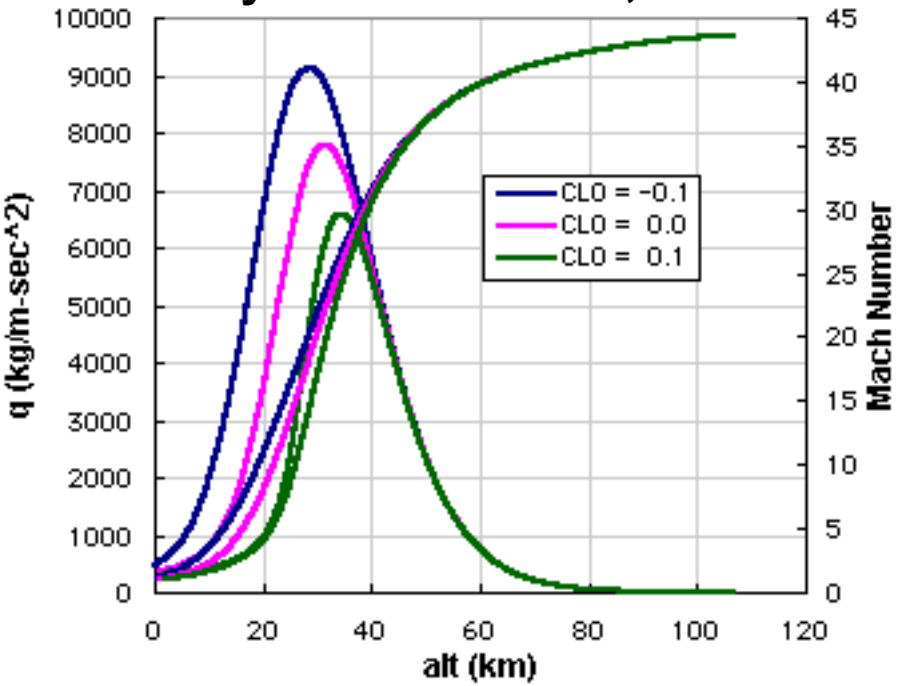
Trim Lift Coefficient

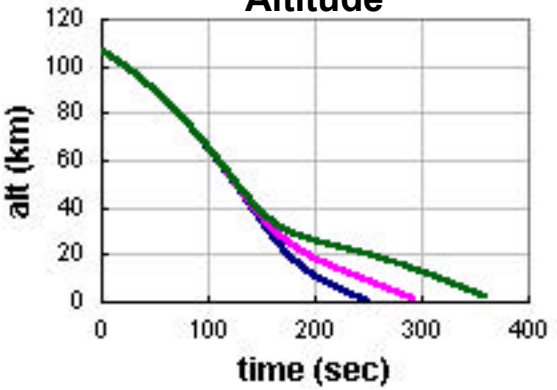
Longitude



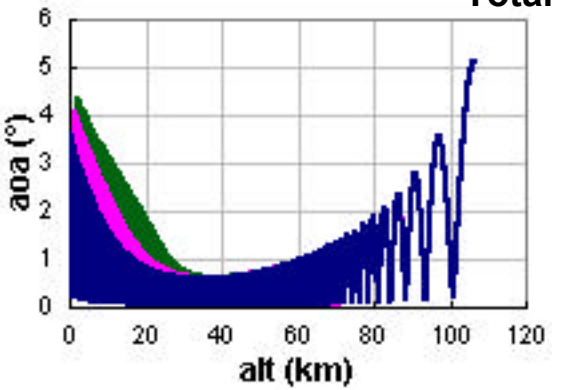
Dynamic Pressure, Mach

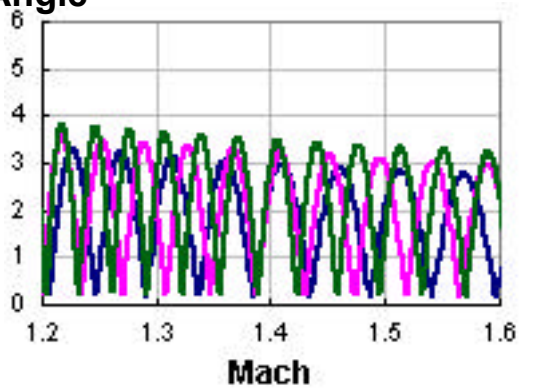


Altitude



Total Angle





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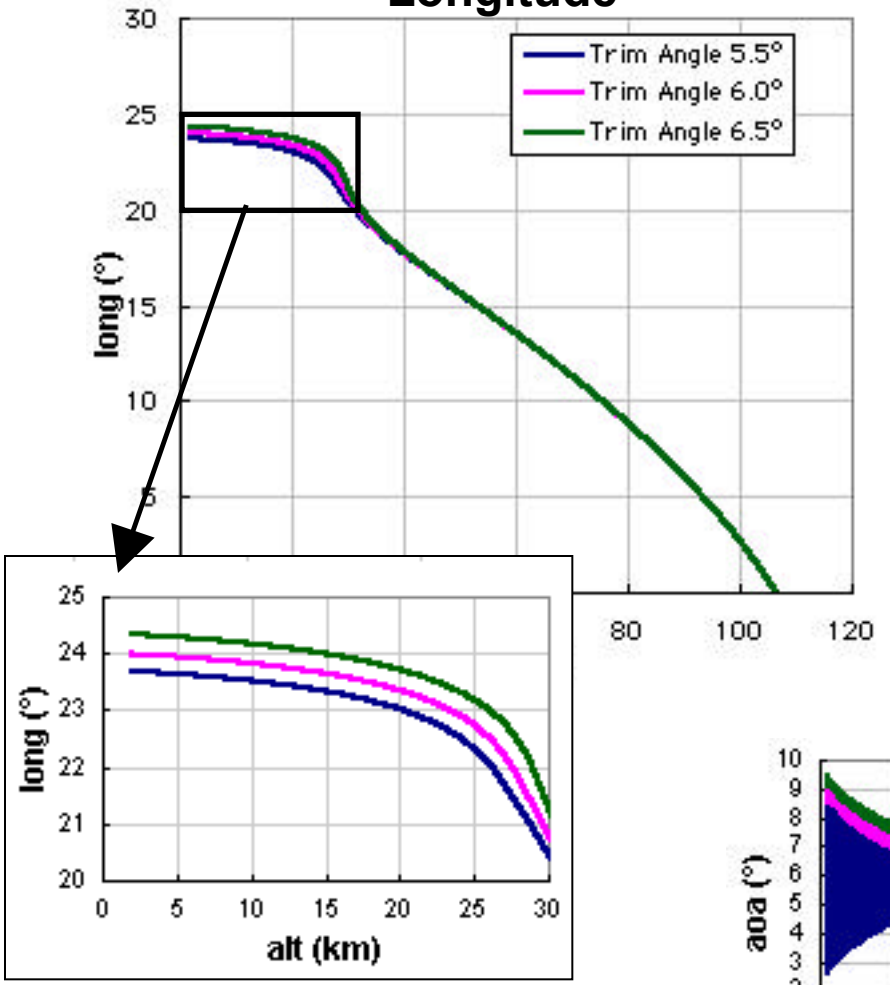
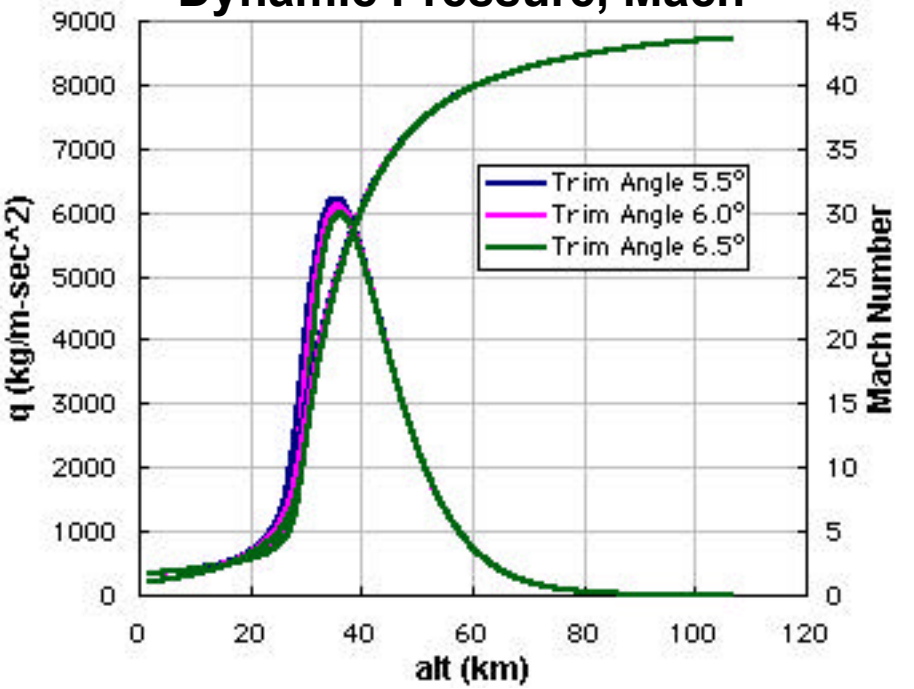
Trim Angle Variation

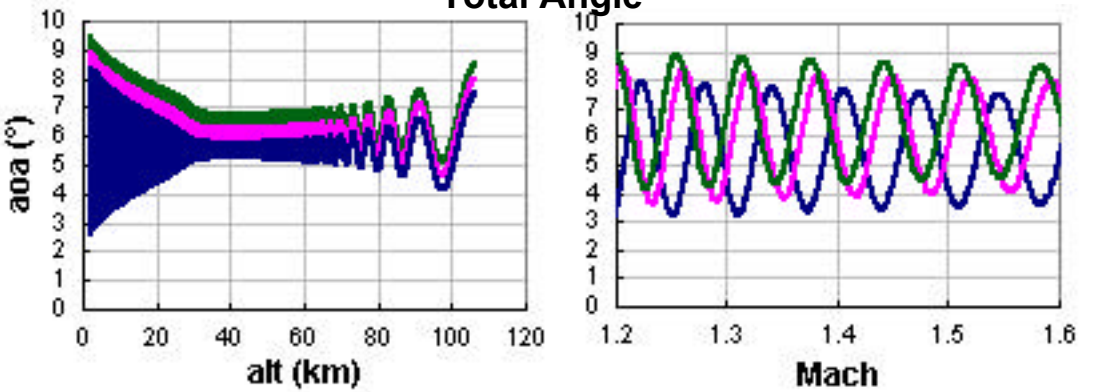
Longitude



Dynamic Pressure, Mach



Total Angle



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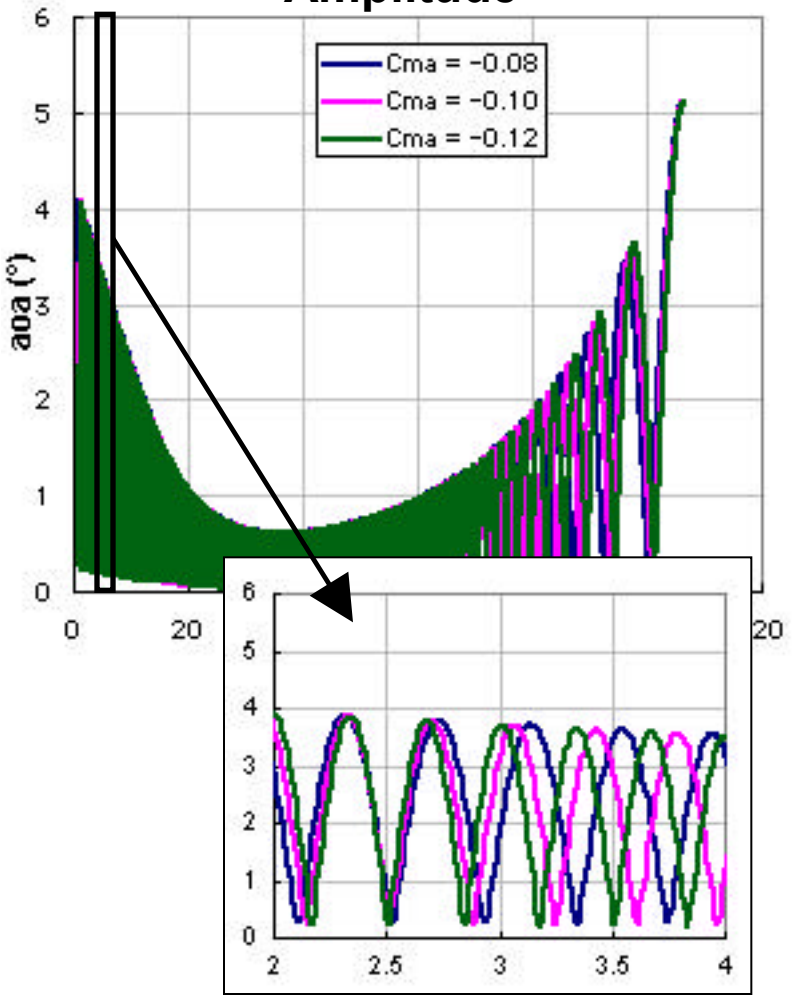
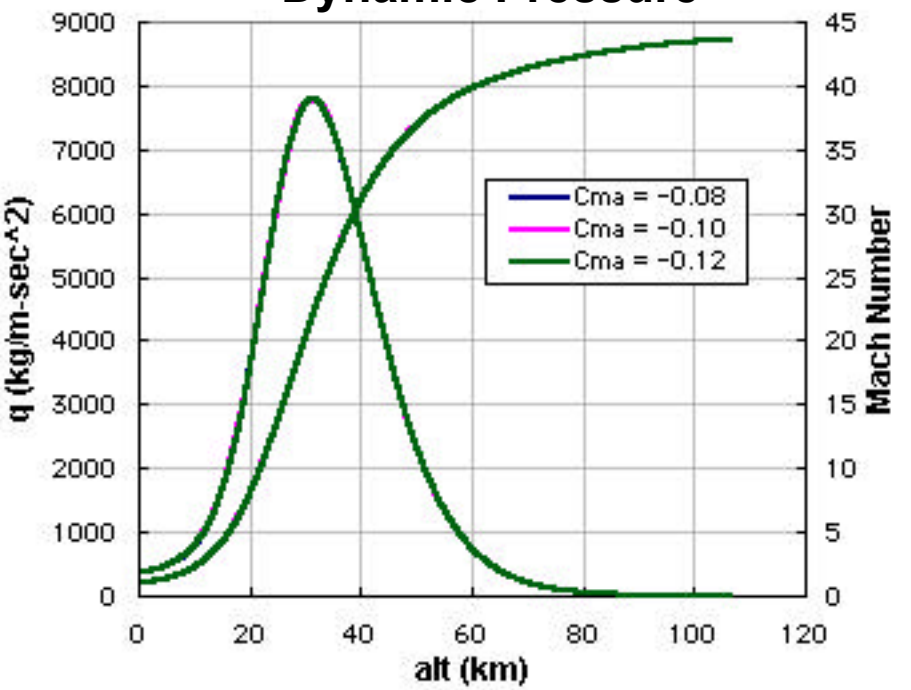
Pitching Moment Coefficient

Amplitude



Dynamic Pressure



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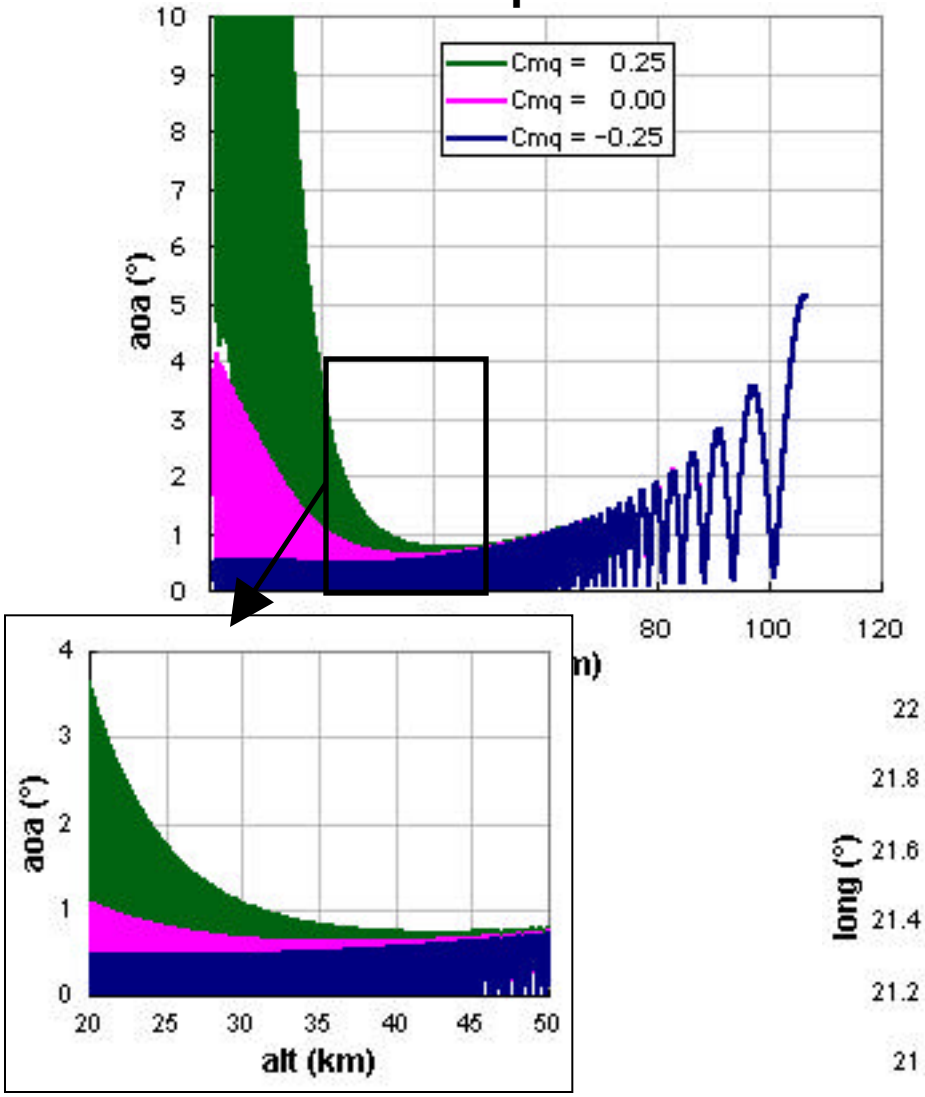
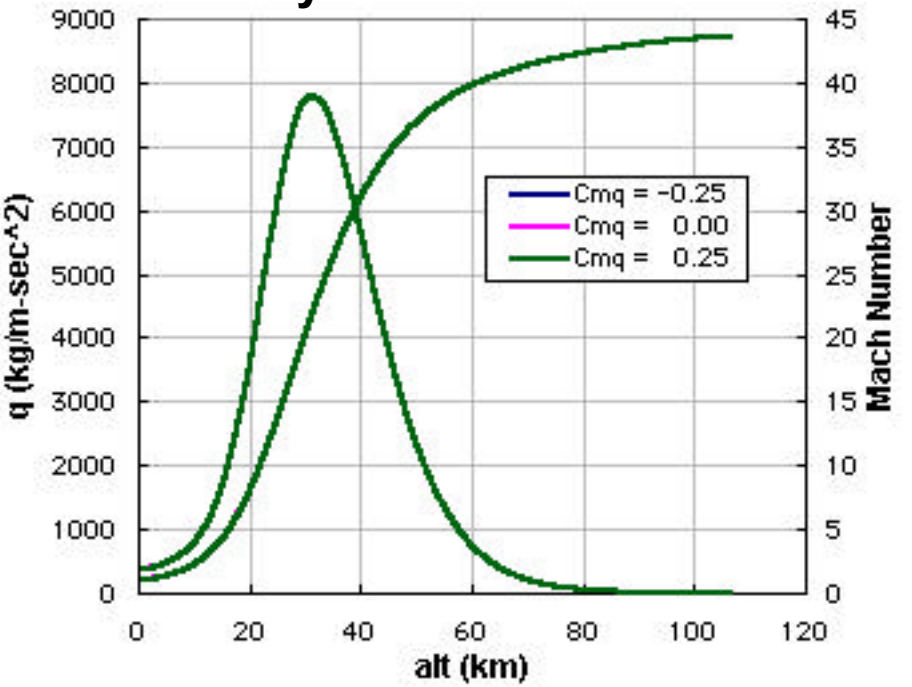
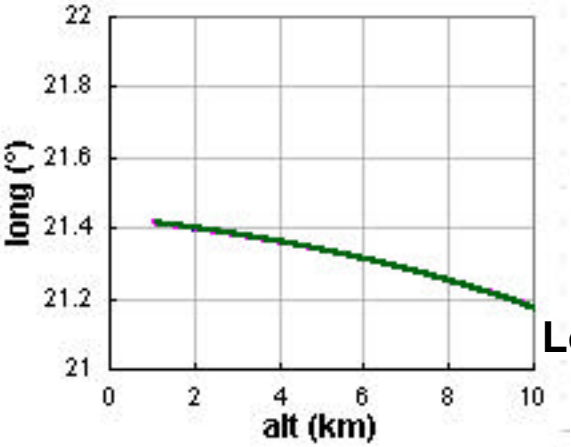
Damping Parameter

Amplitude



Dynamic Pressure





Longitude

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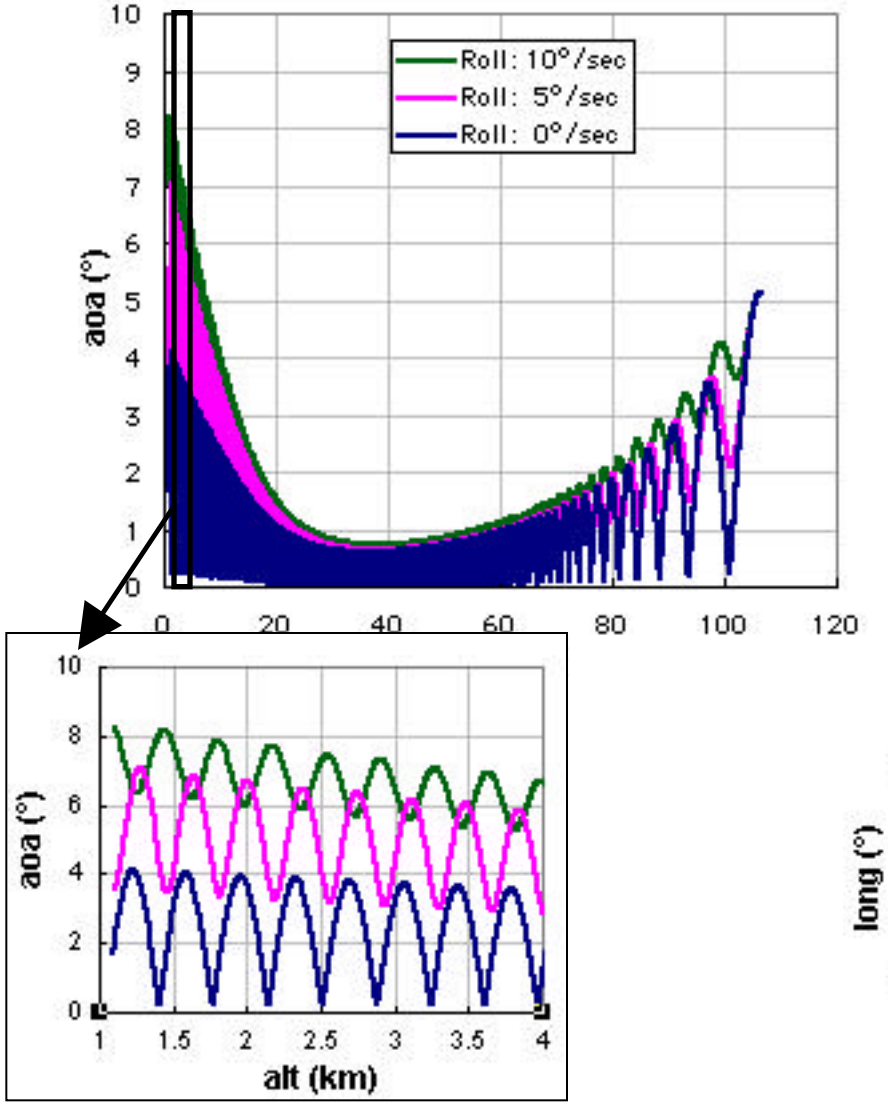
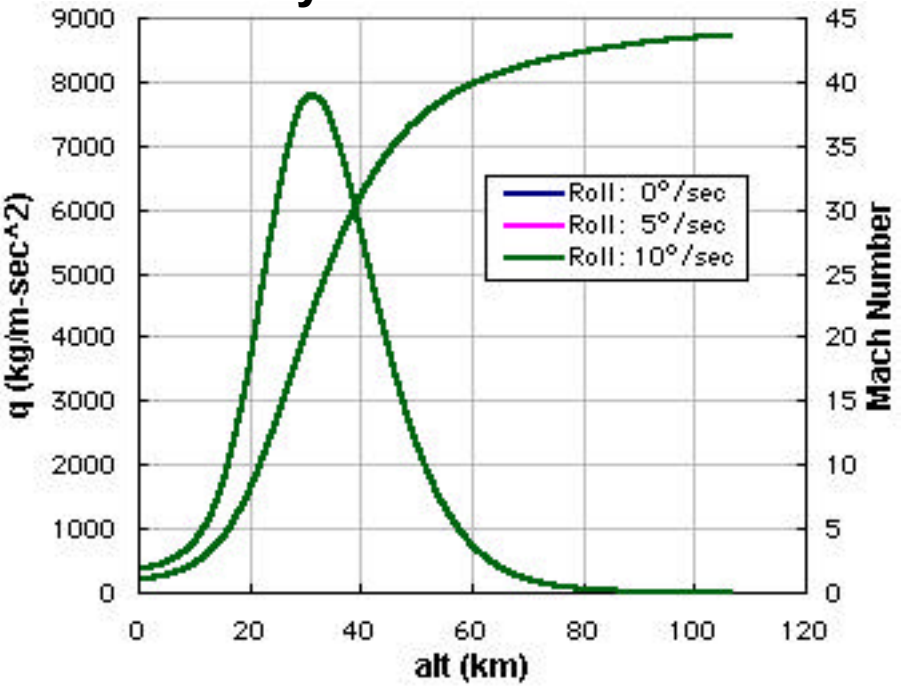
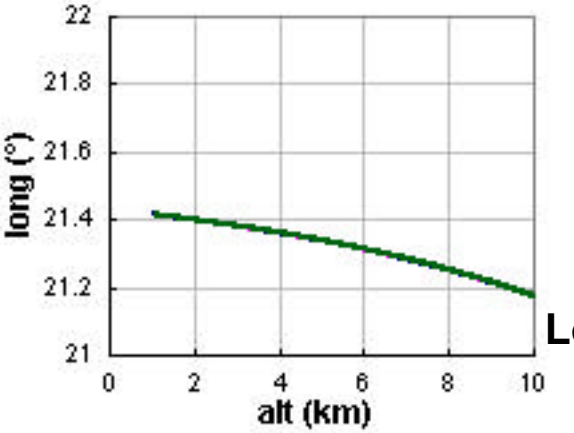
Roll Rate

Amplitude



Dynamic Pressure





Longitude

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Summary of Linear Aerodynamics Simulations

- **Landing footprint**
  - Drag, Trim Lift, Trim angle have large effect
  - Moment, Damping, and Roll have little or no effect
- **Amplitude**
  - Drag, Trim Lift, Trim angle have little effect
  - Moment has little effect
  - Lift slope has small effect
  - Roll and damping coefficient have large effect
- **If effective damping, K, used, position and angular motion largely independent of each other**

$$K = \frac{1}{C_D}\left[-C_{L_\alpha} + \left(\frac{d}{\sigma}\right)^2\left(C_{m_q} + C_{m_{\dot\alpha}}\right)\right]$$

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Effects of Nonlinear Aerodynamics on Trajectory

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Nonlinear Aerodynamics Simulations

- Density profiles, gravitational forces identical to those used in linear simulations
- Vehicle specifications identical to those used in linear simulations
- Shallow entry for better demonstration of effects
- Nonlinearities consistent with observed for planetary entry vehicles

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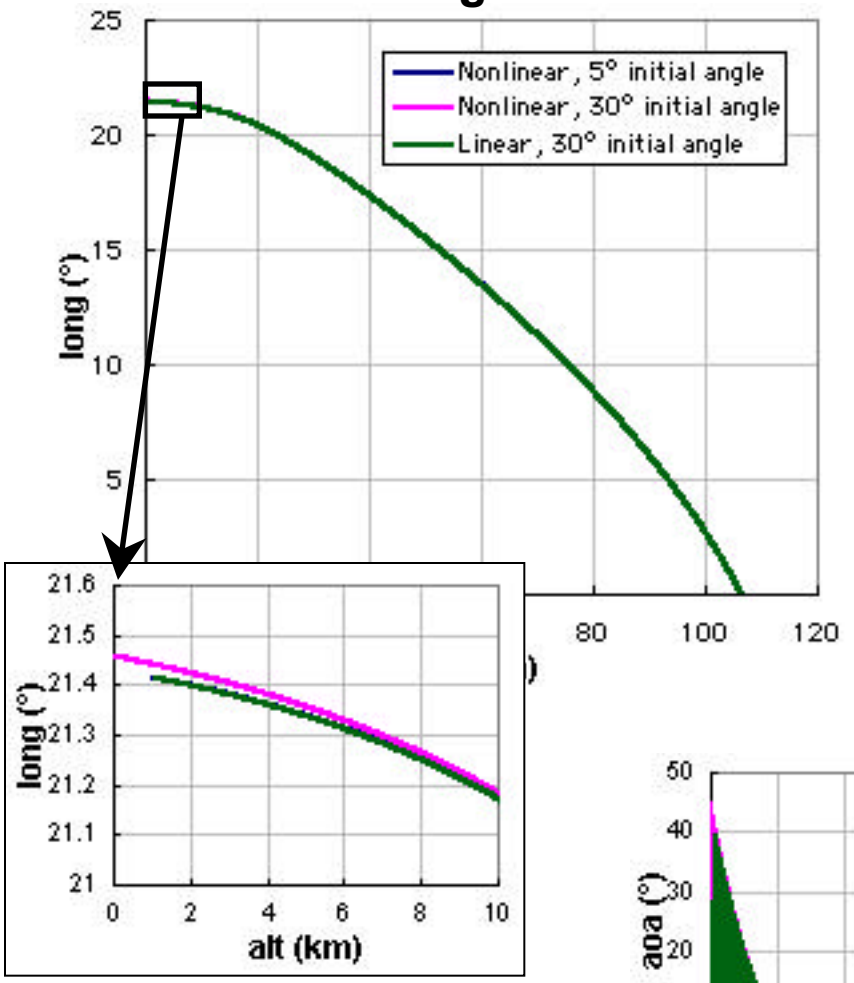
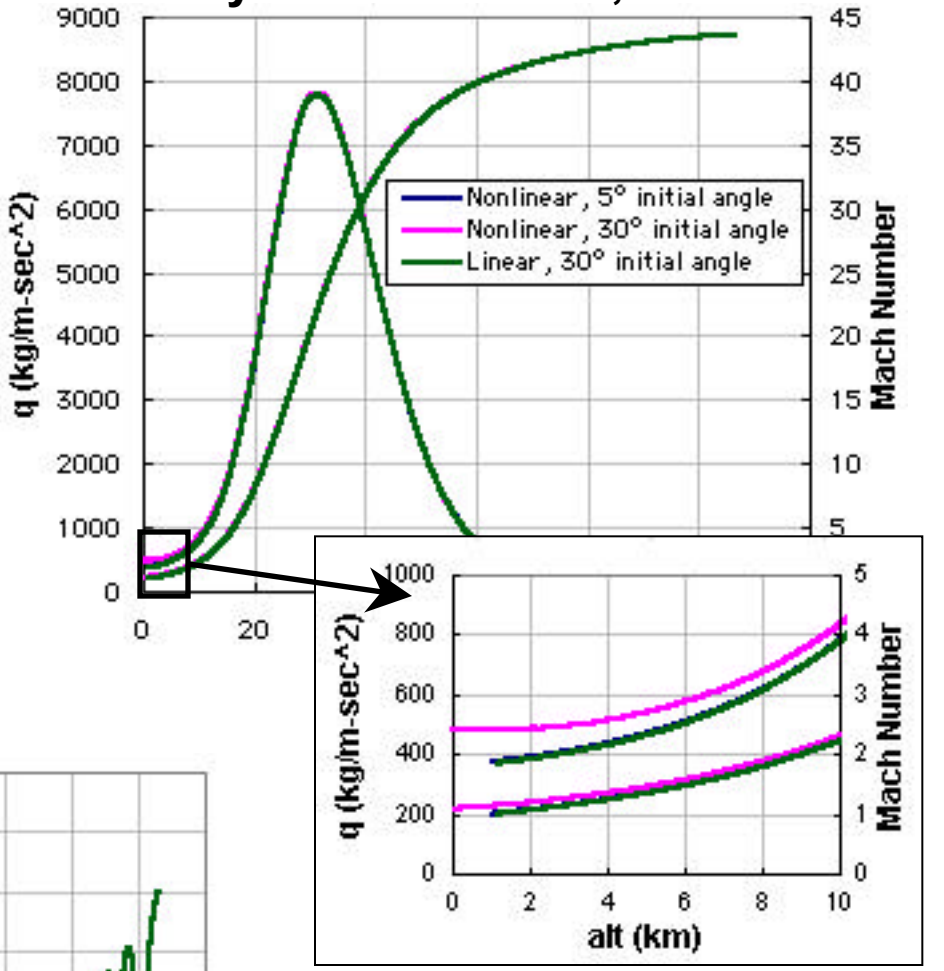
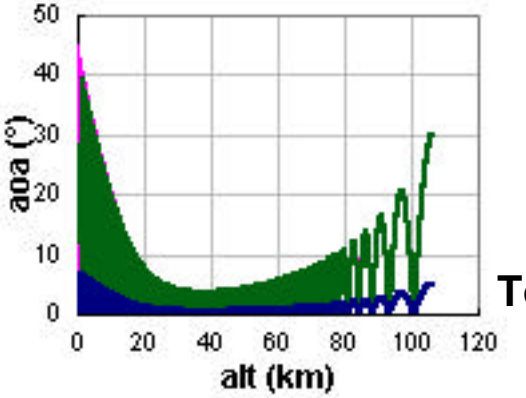
Drag Coefficient ($C_D = 1.5 - 2 \sin^2\sigma$)

Longitude



Dynamic Pressure, Mach





Total Angle

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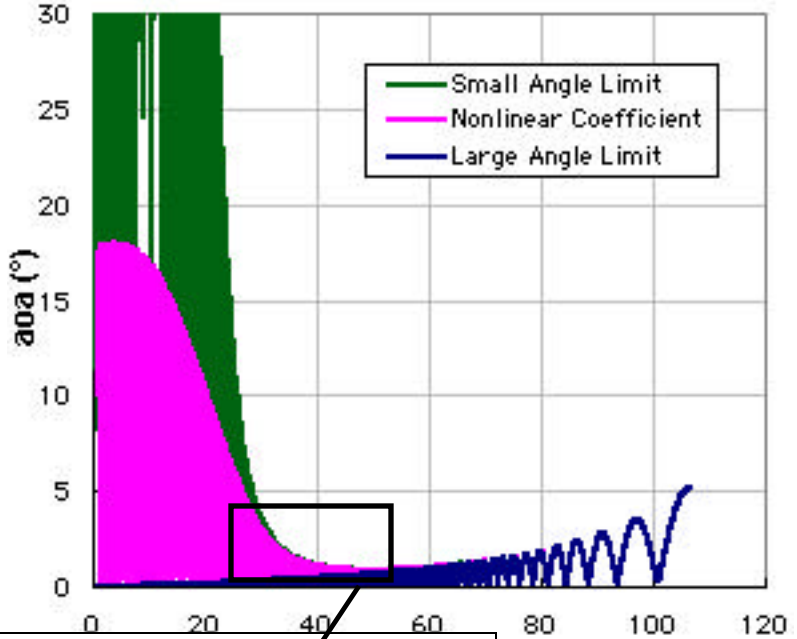
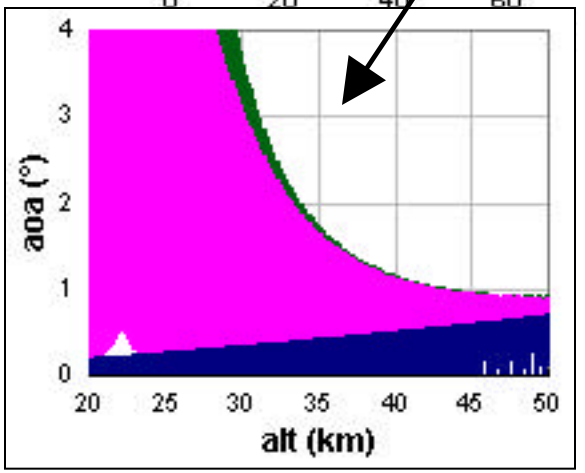
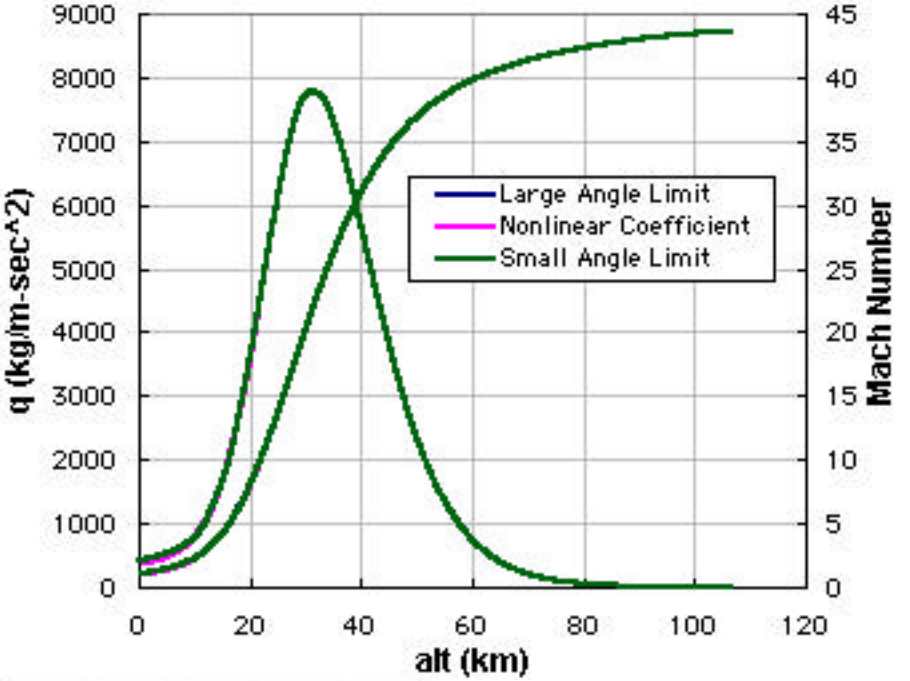
Damping Parameter ($c_{m_q} + c_{m_{\dot{\alpha}}} = 1.5\, e^{A\sin^2\sigma} - 0.5$)

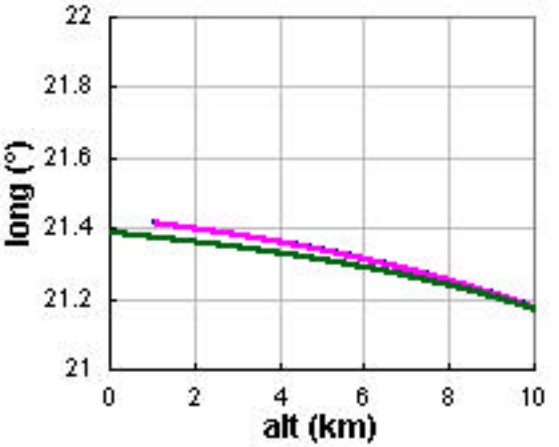
Amplitude





Dynamic Pressure





Longitude

Difference in small angle limit may be due to model tumbling and resulting errors

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Summary of Nonlinear Aerodynamics Simulations

- **Landing footprint**
  - Nonlinear drag has effect
  - Nonlinear moment, lift effect trim angle and trim lift; therefore they will have an effect
- **Amplitude**
  - Nonlinear damping coefficients have significant impact on amplitude
  - Impact of other terms small compared to nonlinear damping coefficient

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Impact of Accurate Aerodynamic Information

- Reduce risks
  - Parachute deployment
  - TPS
- Improve landing precision
  - Minimize foot print
- Expand landing alternatives
- Reduce control propellant mass margin

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Objectives

- General Description of Planetary Entry
- Demonstrate role of aerodynamics on planetary entry
- **Review sources of aerodynamic information**
- Review status of aerodynamics of planetary entry shapes

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Aerodynamic Information

- Effects of uncertainties and nonlinearities in aerodynamic coefficients demonstrated
- Sources
  - Types
  - Availability
  - Accuracy

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Sources of Aerodynamic Information

- Theories
- Computational Fluid Dynamics – CFD
- Ground based experiments
  - Wind tunnels
  - Ballistic ranges
- Flight tests

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Theories

- Inexpensive
- Limited to high Mach number
- Poorly known and not understood
- Useful in some cases for quick estimates and trends
- Not validated in all cases
- Examples
  - Free molecular
  - Newtonian

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CFD

- For simple configurations provides good results for static aerodynamics
- Not thoroughly validated
- Not readily used by non-expert
- Dynamic parameters untried and could be expensive
- Examples:
  - Euler - Inviscid
  - Navier Stokes - Viscid
  - Navier Stokes - Real Gas

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Ground Based Experiments

- Wind tunnels
  - Standard approach
- Ballistic ranges
  - More versatile
  - Under appreciated

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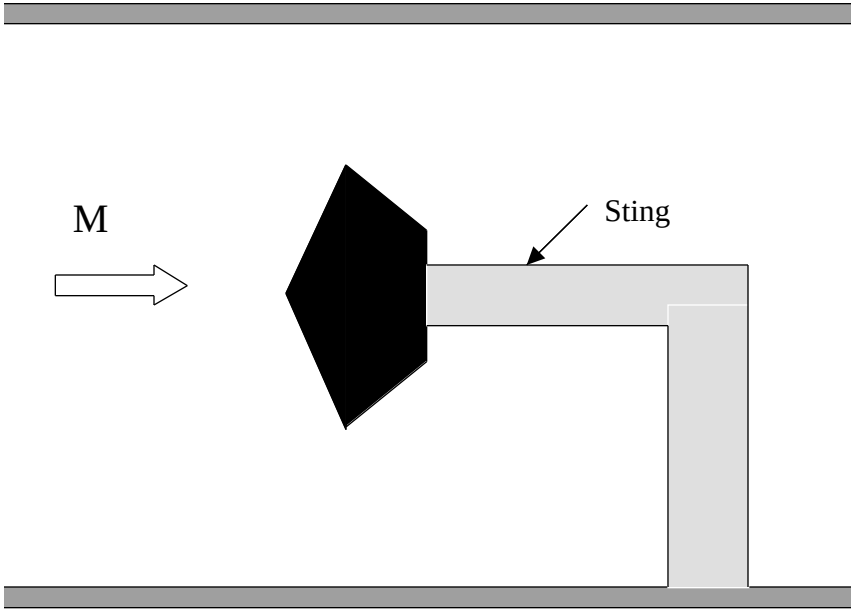
Wind Tunnels



- Many readily available
- No real gas effects
- Wall effects at transonic Mach numbers
- Sting effects in low supersonic / transonic Mach range
- Dynamic testing difficult / expensive

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Ballistic Ranges

- Overview given since community is less familiar with these types of facility
- Experimental approach
  - Free flying model
  - Trajectory measurements obtained from series of orthogonal shadowgraphs taken at known times
- Facility
  - Range & Launcher
    - Small model in sabot
    - Wide range of Mach, Reynolds numbers
    - Various gases, real gas effects
  - 6 DOF, nonlinear data analysis

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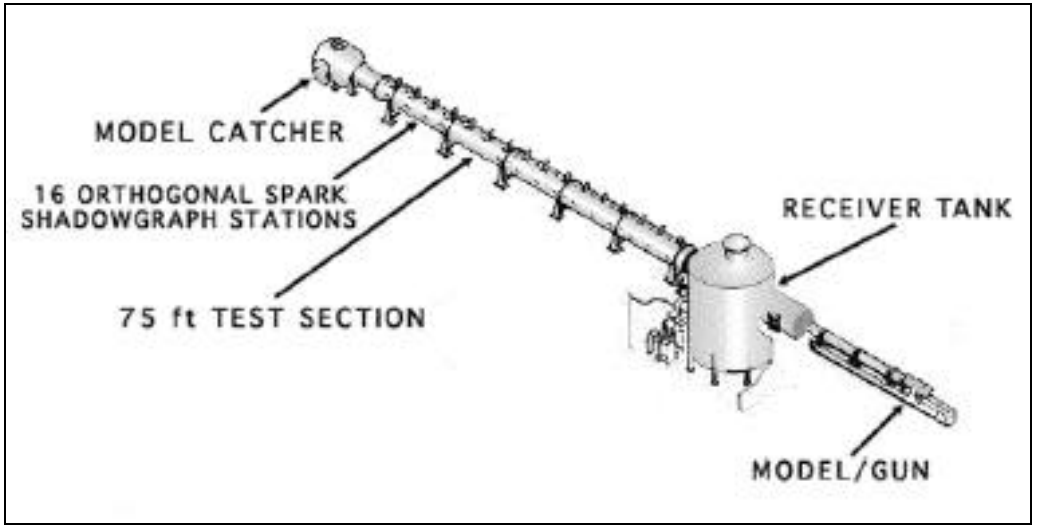
NASA Ames HFFAF

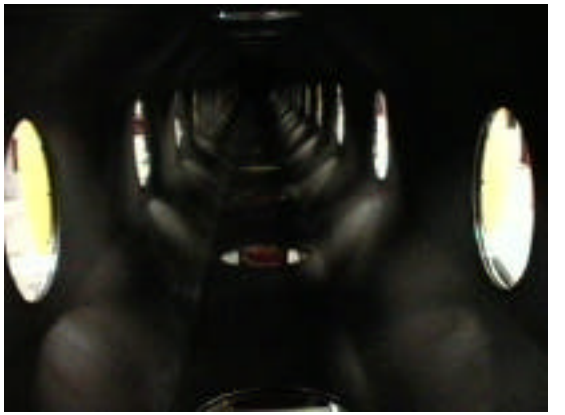


Model Assortment

Light-gas gun

Test section exterior and shadowgraph film planes

Test section interior



Images courtesy of NASA Ames Research Center

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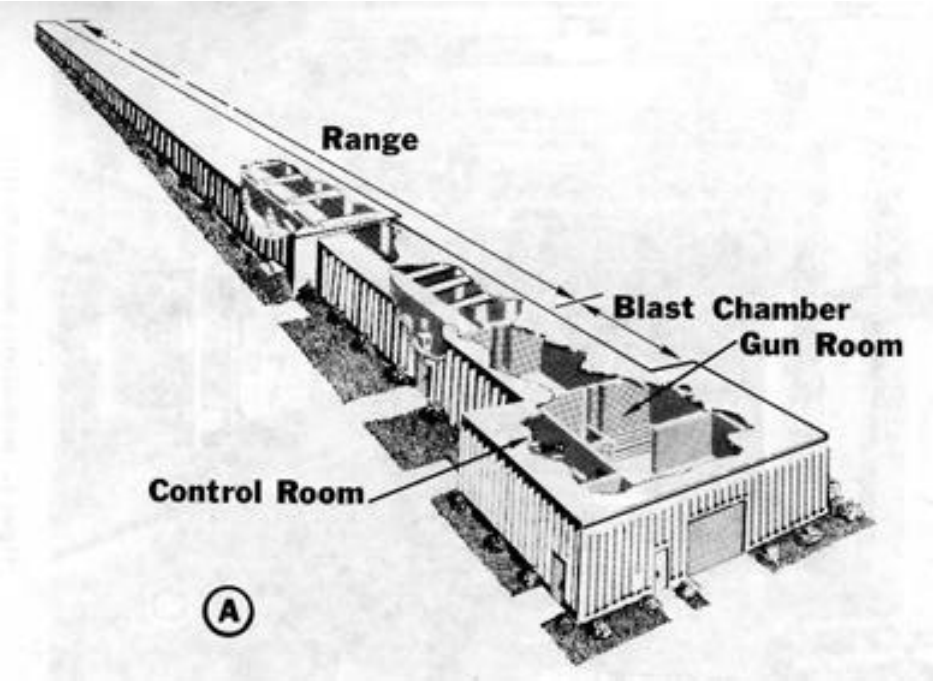
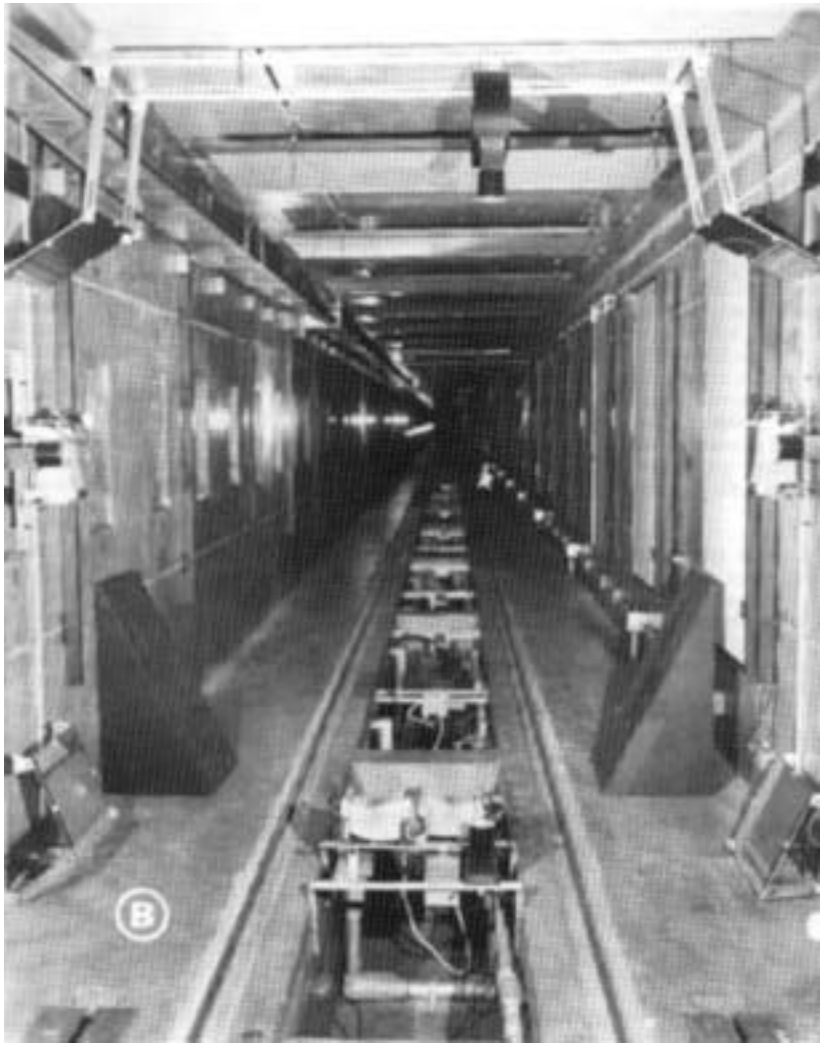
Eglin AFB's ARF



Schematic of the Aeroballistic Research Facility

Interior



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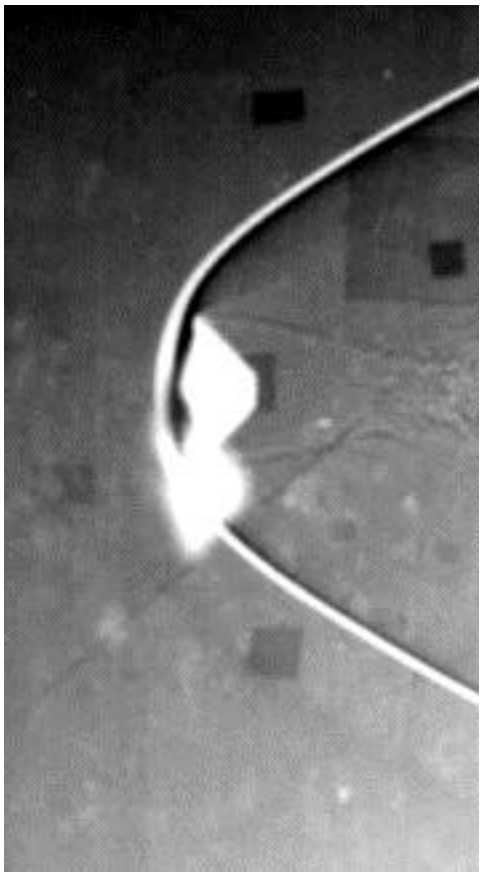
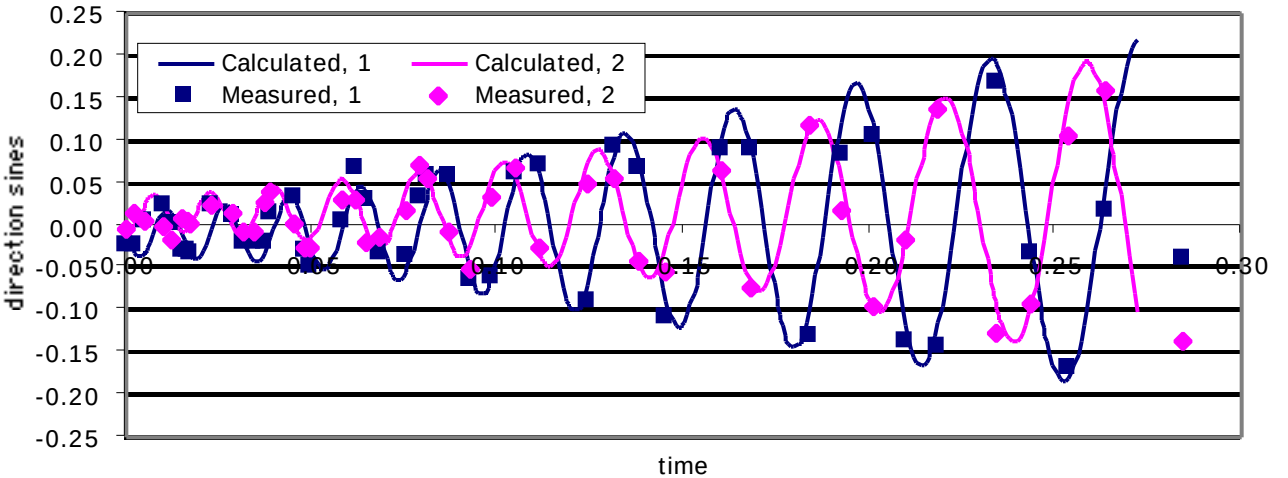
Ballistic Range Data

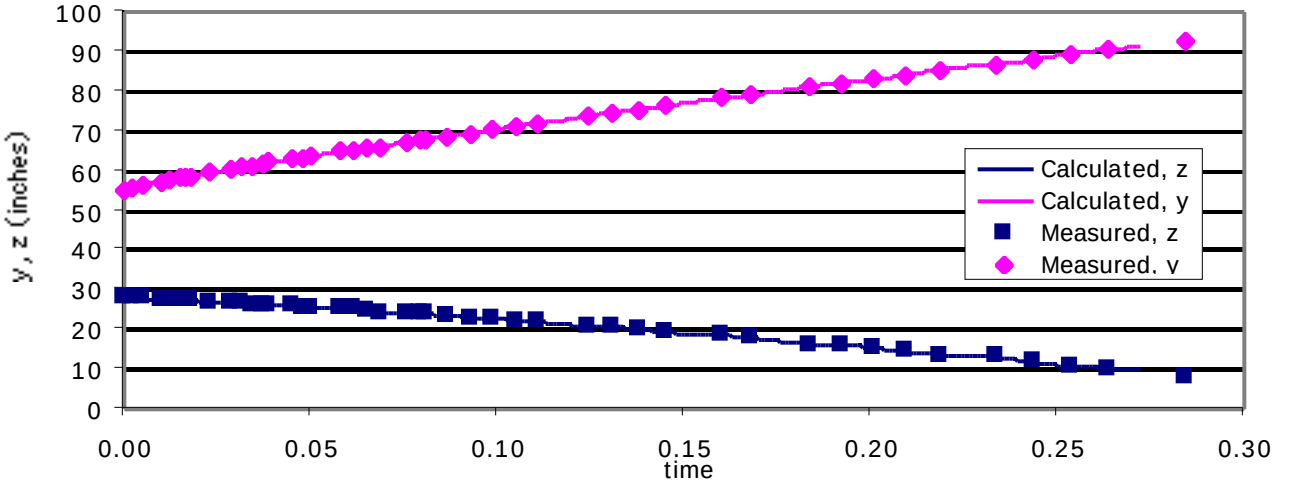
Sample Shadowgraph



Data from Eglin AFB Aerodynamic Research Facility

Projected angular and swerve motion





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Modern 6-DOF Analysis of Ballistic Range Data

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Parameter Estimation

- Coefficients found by fitting calculated trajectories to experimental measurements
- Trajectory defined by 12, first order, coupled, nonlinear differential equations in three coordinate systems
- Unknown parameters: nonlinear aerodynamic coefficient terms and initial conditions
- Differentiating equations of motion with respect to unknowns provide method for estimating corrections
- Trajectory calculated, corrections to unknowns estimated, trajectory re-calculated. Process repeated until convergence criteria met
- Single / multi fits
- Error estimates available

Equations (6-DOF)

Drag:

$$\dot{V} = -\frac{\rho A V^2}{2m} C_D - g \sin\theta_w$$

$$\dot{x}_E = V \cos\theta_w \cos\psi_w$$

Rolling Moment:

$$\dot{p} = \frac{\rho A l V^2}{2 I_z} C_p + \frac{I_{zx}}{I_z}\left(\dot{r} + pq\right) + \frac{\left(I_y - I_z\right)}{I_z} rp$$

$$\dot{\varphi}_w = p_w + \left(q_w \sin\varphi_w + r_w \cos\varphi_w\right) \tan\theta_w$$

Pitching, yawing moment:

$$\dot{\alpha} = q - q_w \sec\beta - \left(p \cos\alpha + r \sin\alpha\right) \tan\beta$$

$$\dot{\beta} = r_w \sec\beta + p \sin\alpha - r\cos\alpha$$

$$\dot{q} = \frac{\rho A l V^2}{2 I_y} C_M + \frac{I_{zx}}{I_y}\left(r^2 - p^2\right) + \frac{\left(I_z - I_x\right)}{I_y} rp$$

$$\dot{r} = \frac{\rho A l V^2}{2 I_z} C_N + \frac{I_{zx}}{I_z}\left(\dot{p} - qr\right) + \frac{\left(I_x - I_y\right)}{I_z} pq$$

Lift:

$$\dot{y}_E = V \cos\theta_w \sin\psi_w$$

$$\dot{z}_E = -V \sin\theta_w$$

$$\dot{\theta}_w = q_w \cos\varphi_w - r_w \sin\varphi_w$$

$$\dot{\psi}_w = \left(q_w \sin\varphi_w + r_w \cos\varphi_w\right) \sec\theta_w$$

where

$$q_w = \frac{\rho A V}{2m} C_L - g \cos\theta_w \cos\varphi_w$$

$$r_w = -\frac{\rho A V}{2m} C_Y + g \cos\theta_w \sin\varphi_w$$

$$p_w = \left(p \cos\alpha + r \sin\alpha\right) \cos\beta + \left(q - \dot{\alpha}\right) \sin\beta$$

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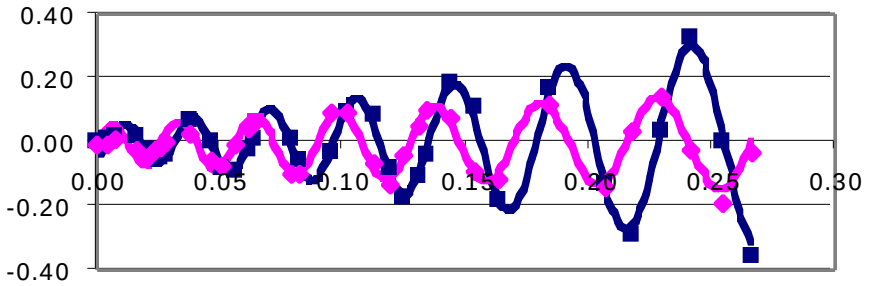
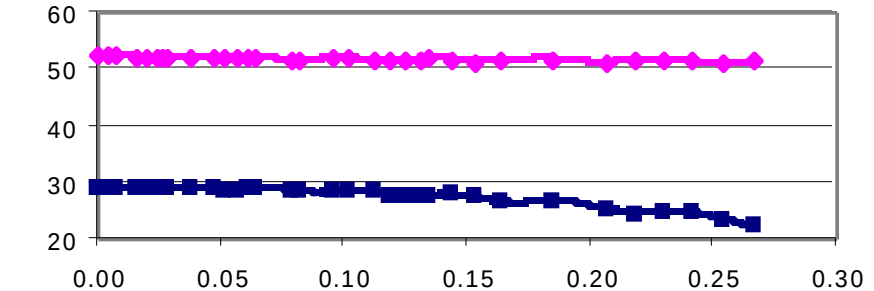
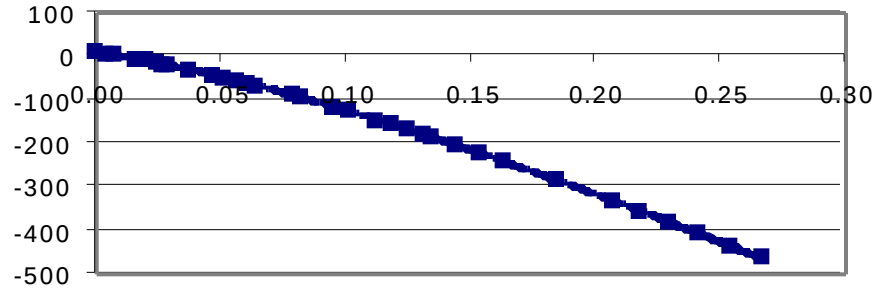
Parameter Identification - Example



Direction sines vs. time



Swerve vs time



Down range distance vs time

Coefficient Expansions

Moment

$$C_m = \left[C_{m_1} + C_{m_2}(M-2.5) + \frac{C_{m_3}\sin^2\alpha}{1+C_{m_4}\sin^2\alpha}\right]\sin\alpha$$

Damping

$$C_{m_q} = C_{m_{q,0}} + C_{m_{q,1}}\frac{\exp\left[-C_{m_{q,2}}\ M^{C_{m_{q,3}}}\ \sin^2\alpha\right]}{1+\left[C_{m_{q,4}}(M-1)\right]^6}$$

Lift

$$C_L = \left[C_{L_1} + \frac{C_{L_2}\sin^2\alpha}{1+C_{L_3}\sin^2\alpha}\right]\sin\alpha$$

Drag

$$C_D = C_{D_0} + \frac{C_{D_1} + \left[C_{D_3} + C_{D_4}(M-1)\right]\sin^2\alpha}{\sqrt{1+C_{D_2}(M-1)^2}}(M-1)$$

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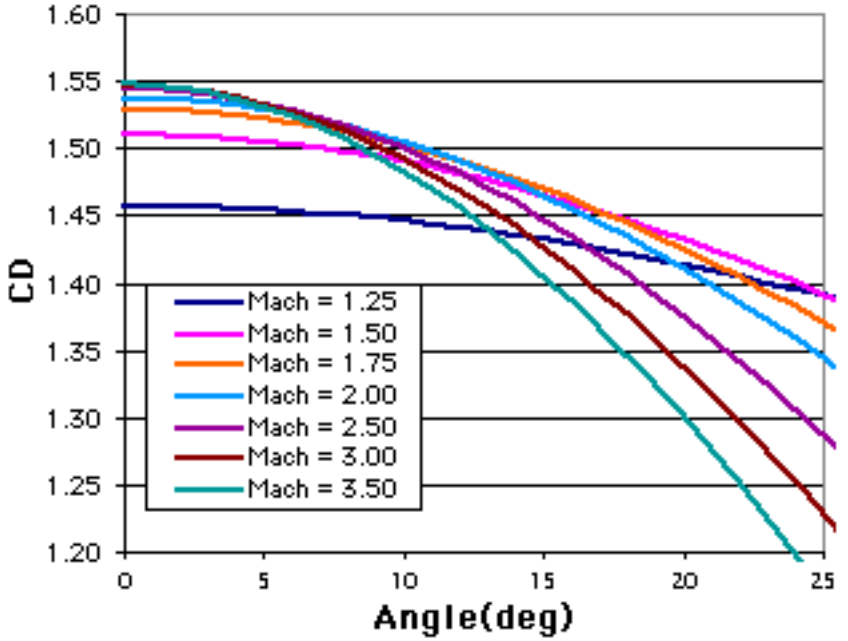
Sample Ballistic Range Results (MER)

Drag

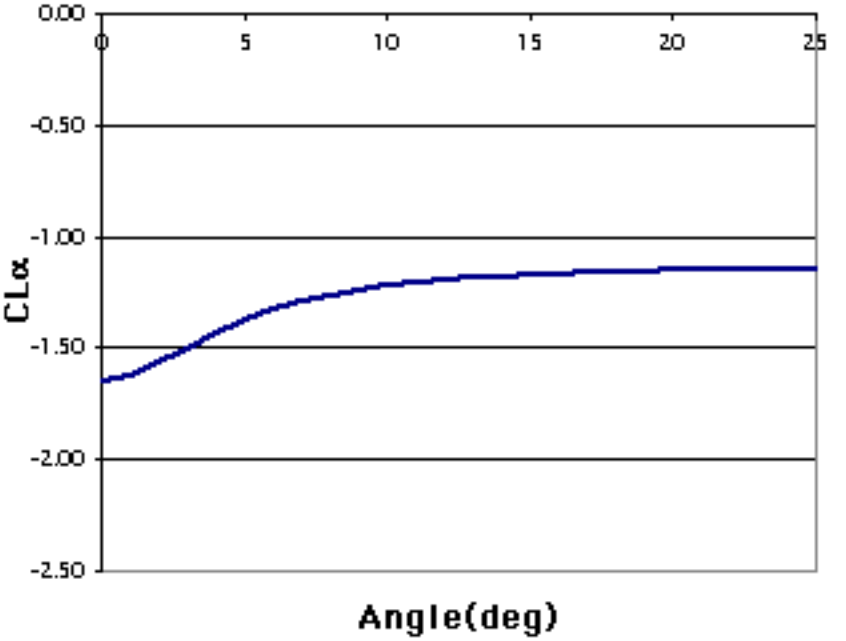
$$C_D = C_{D_0} + \frac{C_{D_1} + \left[C_{D_3} + C_{D_4}(M-1)\right]\sin^2\alpha}{\sqrt{1 + C_{D_2}(M-1)^2}}(M-1)$$



Results						
c.g.	CD0	CD1	CD2	CD3	CD4	x rms (ft)
0.27D	1.327	0.641	8.31	-1.369	-1.92	0.0234
±	0.005	0.028	0.40	0.055	0.06	

Lift

$$C_L = \left[C_{L_1} + \frac{C_{L_2}\sin^2\alpha}{1 + C_{L_3}\sin^2\alpha}\right]\sin\alpha$$



Results				
c.g.	CL1	CL2	CL3	y, z rms (ft)
0.27D	-1.650	75.02	142.6	0.008
±	fixed	3.40	fixed	

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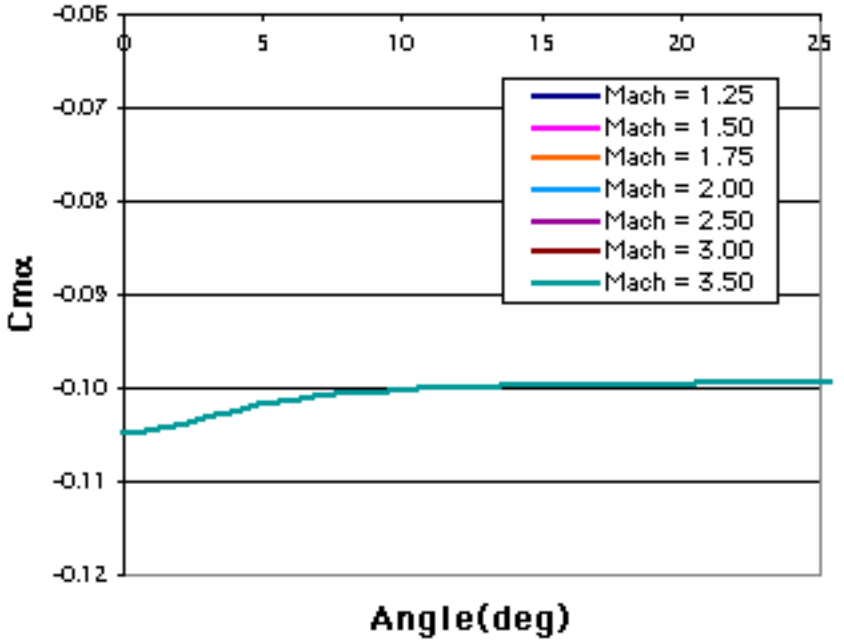
Sample Ballistic Range Results (MER)

Moment

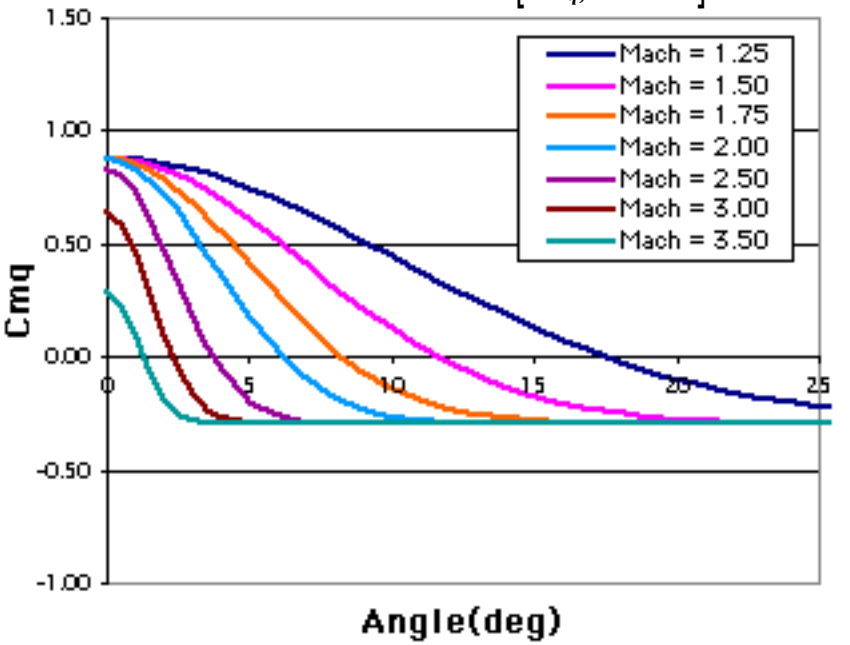
$$C_m = \left[C_{m_1} + C_{m_2}(M - 2.5) + \frac{C_{m_3} \sin^2 \alpha}{1 + C_{m_4} \sin^2 \alpha} \right] \sin\alpha$$



Results					
c.g.	Cm1	Cm2	Cm3	Cm4	α rms (°)
0.27D	-0.1049	0.00000	0.95	160.6	1.36
±	fixed	fixed	0.02	fixed	

Damping

$$C_{m_q} = C_{m_{q,0}} + C_{m_{q,1}} \frac{\exp\left[-C_{m_{q,2}} \; M^{C_{m_{q,3}}} \; \sin^2 \alpha\right]}{1 + \left[C_{m_{q,4}}(M - 1)\right]^6}$$



Results						
c.g.	Cmq,0	Cmq,1	Cmq,2	Cmq,3	Cmq,4	α rms (°)
0.27D	-0.298	1.177	5.73	4.37	0.40	1.32
	fixed	0.123	2.77	0.56	fixed	

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Other Applications of Modern 6-DOF Analysis Tools

- Vertical Wind Tunnel
- Flight Tests
  - Helicopter Drop Tests
  - Atmospheric Entry

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Flight Tests

- Expensive
- Can be dangerous for lifting bodies
- Time consuming
- Data acquisition difficult
- Analysis subject to unknowns
  - Winds
  - Atmospheric properties

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Summary of Data Sources

- Theory
  - Limited
- CFD
  - Good capability
  - Validation required in some areas
  - Need to develop capability for damping
- Ground based testing
  - Wind tunnels - good static aerodynamics but limited in damping, real gas
  - Ballistic ranges - good static and dynamic aerodynamics for wide range of conditions but model size limited and no onboard instrumentation
- Flight testing
  - Expensive
  - Unknown or variable atmospheric conditions

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Objectives

- General Description of Planetary Entry
- Demonstrate role of aerodynamics on planetary entry
- Review sources of aerodynamic information
- **Review status of aerodynamics of planetary entry shapes**

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Aerodynamics by Flight Regime

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Flight Regimes

- Free molecular
- Transition
- Continuum
  - Entry
    - Hypersonic
  - After maximum dynamic pressure
    - Supersonic
    - Transonic
    - Subsonic

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Free Molecular Regime

- Knudsen number: $Kn = \lambda / d > o(1)$
- Theory – Free molecular flow
- Direct Monte Carlo simulation – DMS
- Ground base facilities non-existent
- Accuracy not critical in many cases

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Free Molecular Flow

- Molecules hit surface and are reflected in a specular or diffuse manner with no collisions
- Example-Sharp cones
  - Specular reflection $C_{D_0} = 4\sin^2\theta$
  - No reflection $C_{D_0} = 2\sin^2\theta$
- Type of reflection depends on surface

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Transition

- Knudsen number: $Kn = \lambda / d \quad o(1)$
- Direct Monte Carlo simulations-DMS
- Low Reynolds number CFD
- Empirical bridging functions
- Experimental facilities non-existent

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Continuum Entry-Hypersonic

- **Knudsen number:** $Kn = \lambda / d << o(1)$
- **Mach number:** $M = V / a > 5$
- **Theory**
  - **Newtonian**
    - **Normal component of momentum converted to pressure**
    - **Mach number independent**
    - **Capable of calculating both static and dynamic coefficients**
- **CFD**
- **Ground based experiments**
  - **Wind tunnel**
  - **Ballistic range**

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Examples of Hypersonic Aerodynamics

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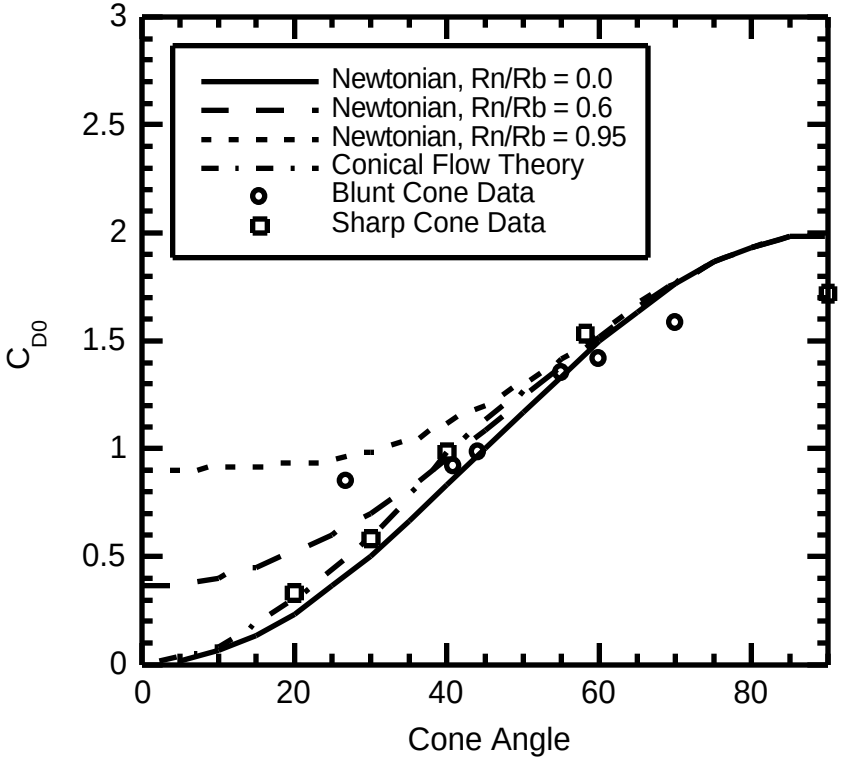
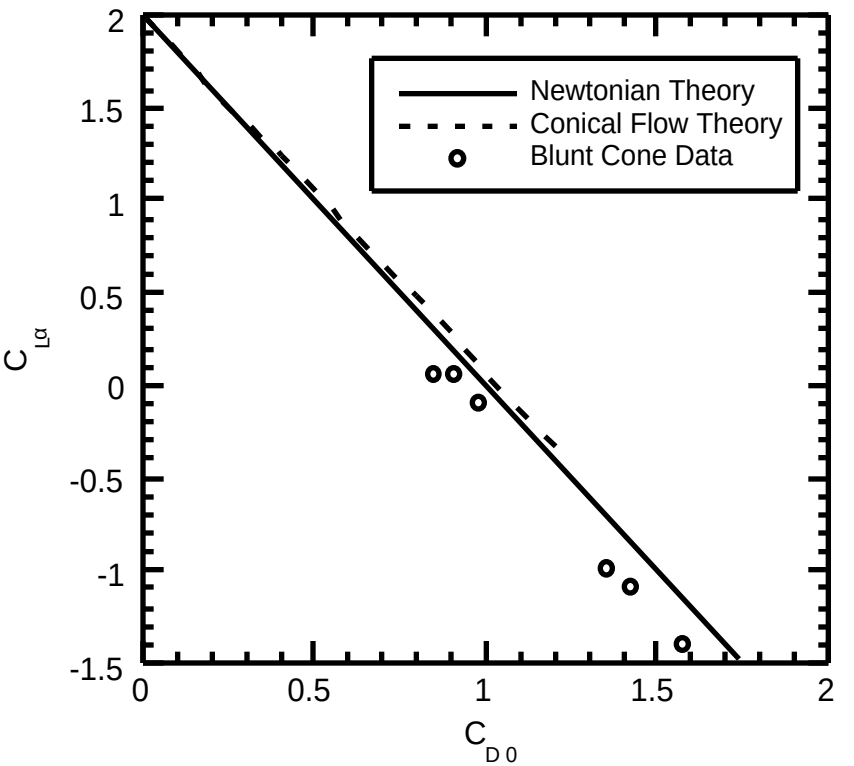
Drag and Lift on Simple Shapes (Mach > 5)

Drag



Lift: $C_{L\alpha} = C_{Pmax} - 2C_D$



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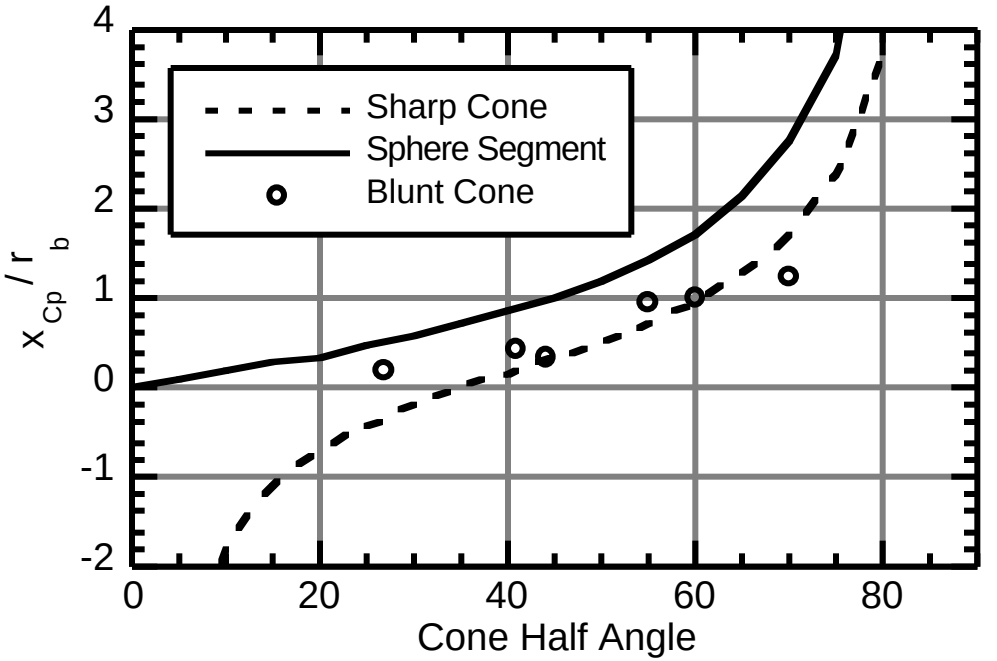
Center of Pressure (Mach > 5)



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Dynamic Stability

For Sharp Cones

$$C_{m_{q_x}} = C_{m_{q_0}} + C_{N_{q_0}} \frac{x}{l} - C_{m_{\alpha_0}} \frac{x}{l} - C_{N_{\alpha_0}} \left(\frac{x}{l}\right)^2$$

$$C_{m_{\dot{\alpha}_x}} \equiv 0 \quad \text{(plunging motion)}$$

where

$$C_{m_{q_0}} = -\left(1 + \tan^2\theta\right), \qquad C_{m_{\alpha_0}} = -4/3$$

$$C_{N_{\alpha_0}} = \frac{2}{1 + \tan^2\theta}, \qquad C_{N_{q_0}} = +4/3$$

$$C_{m_{q_x}} < 0 \quad \text{for large cone angles}$$

Based on reference length l and l/V (not $l/2V$)

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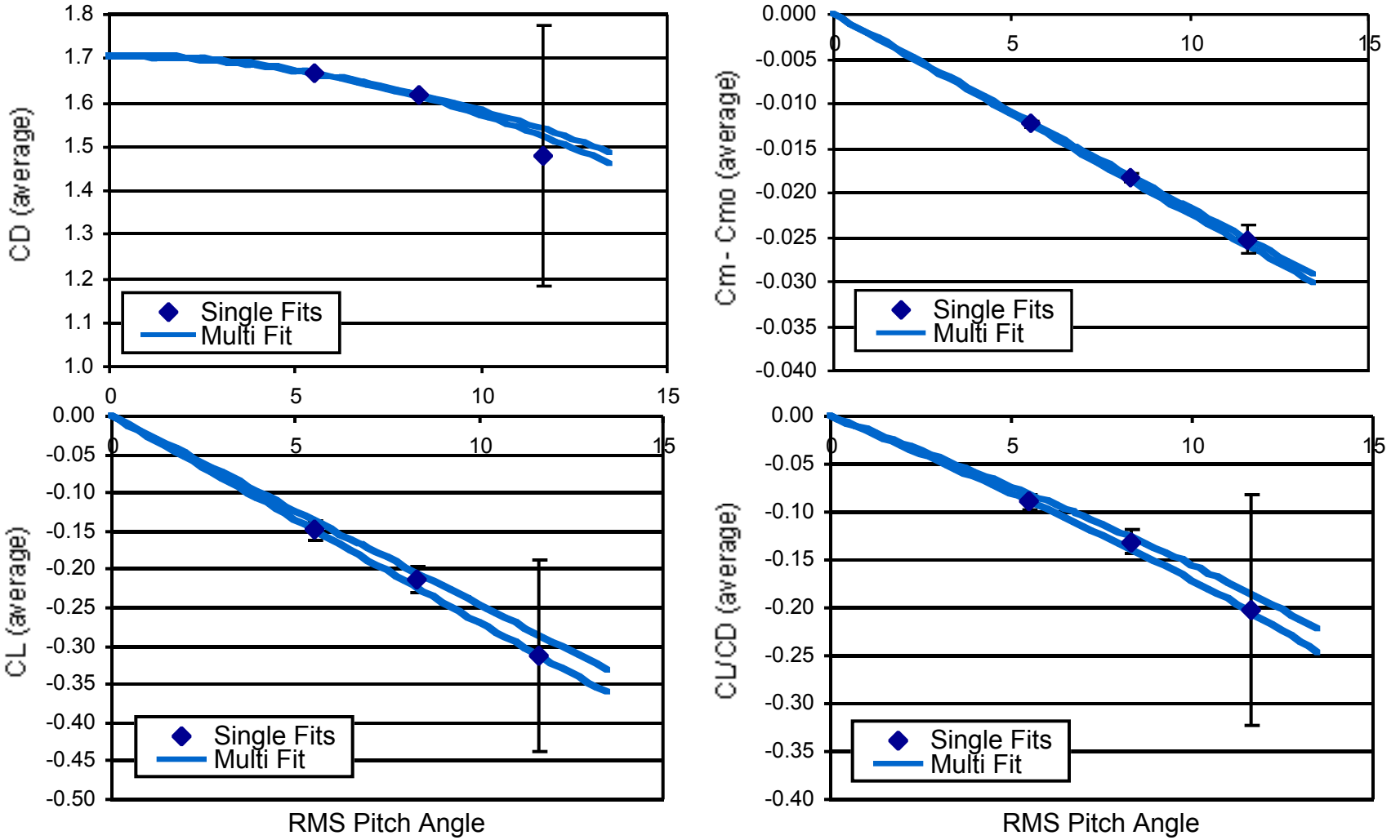
Ballistic Range Data

Mars Smart Lander, Axisymmetric Configuration (CO_2, M ≈ 18, NASA Ames Research Center)



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Supersonic/Transonic

- Mach number: $5 > M > 0.6$
- No theories for blunt bodies
- CFD
  - Used extensively
  - Not used for dynamics, could be expensive
- Ground based experimental
  - Wind tunnel
  - Ballistic range

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Examples of Supersonic/Transonic Aerodynamics

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Available Data Sets

- Pre 1975
  - Early research
  - PAET /Voyager/Viking
- Post 1985
  - Huygens Probe
  - Stardust
  - DS-2
  - Genesis
  - MER
  - Mars Smart Lander

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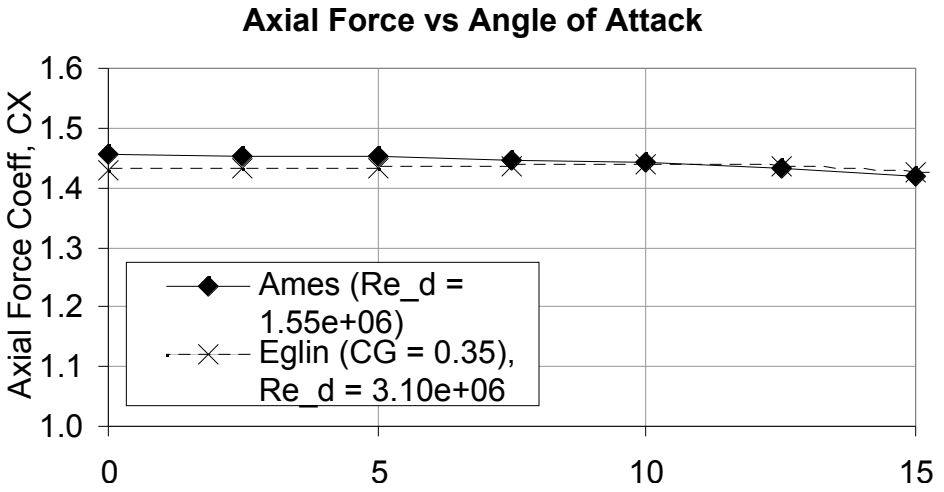
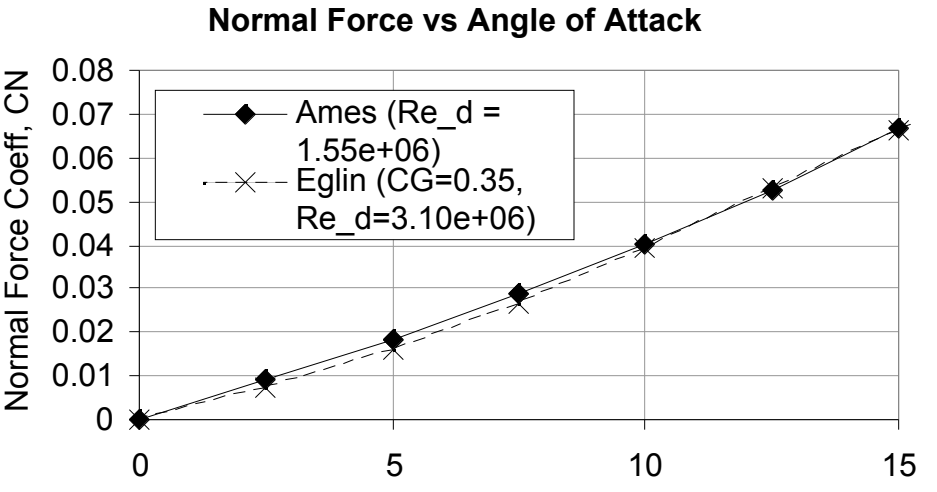
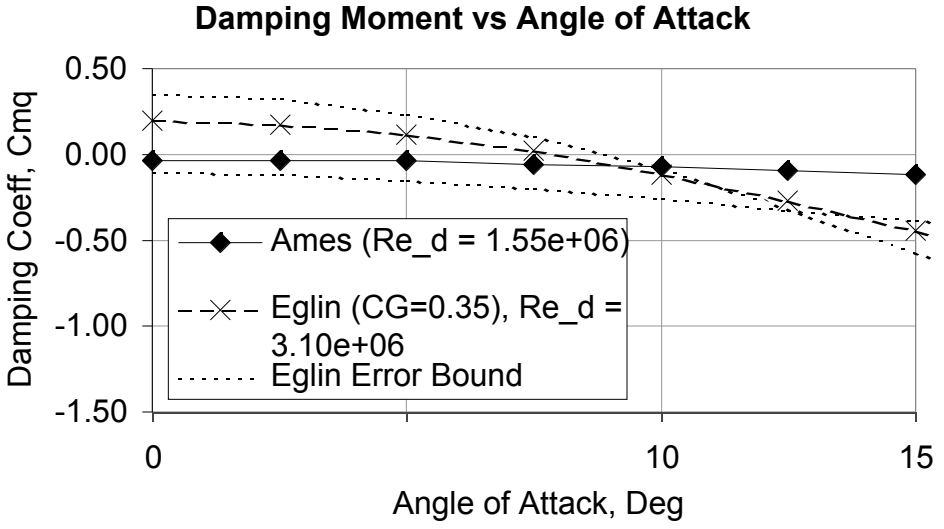
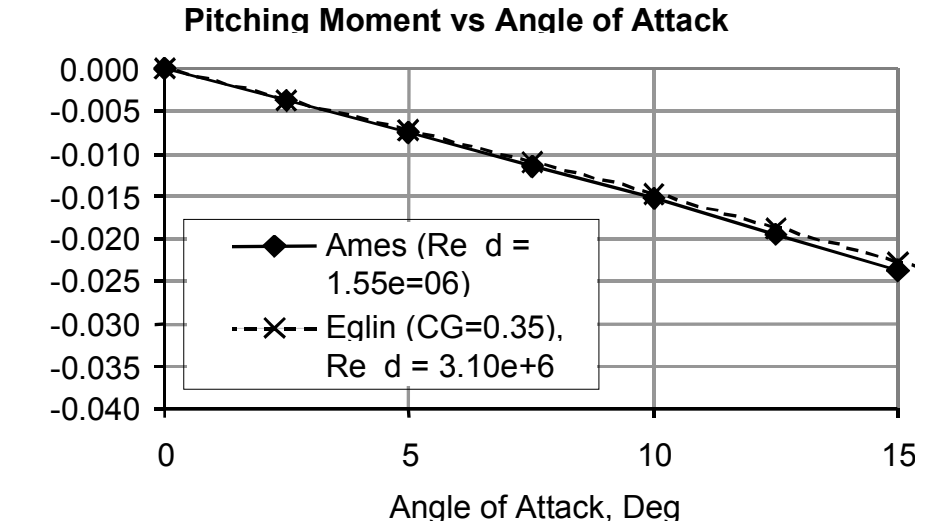
Stardust Ballistic Range Data (Air, Mach ≈ 2)









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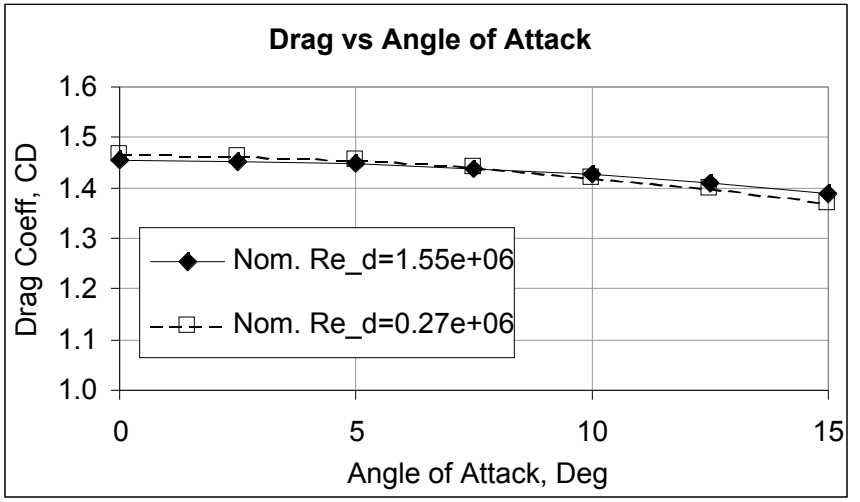
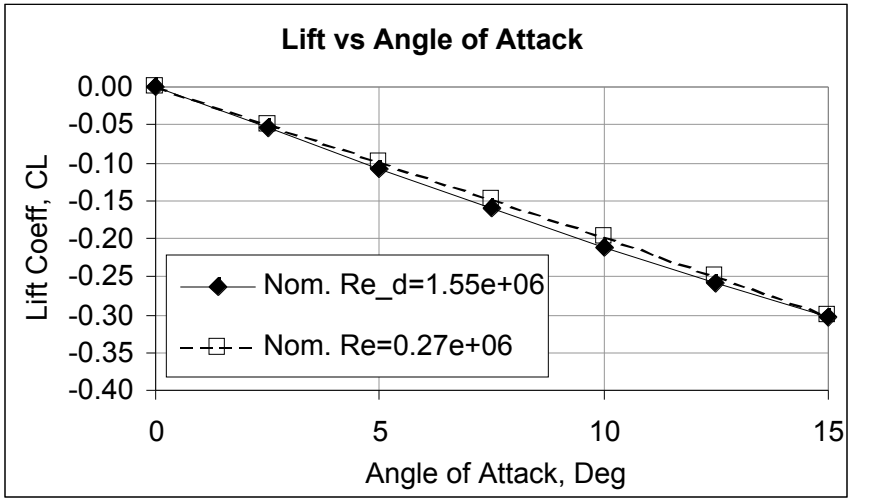
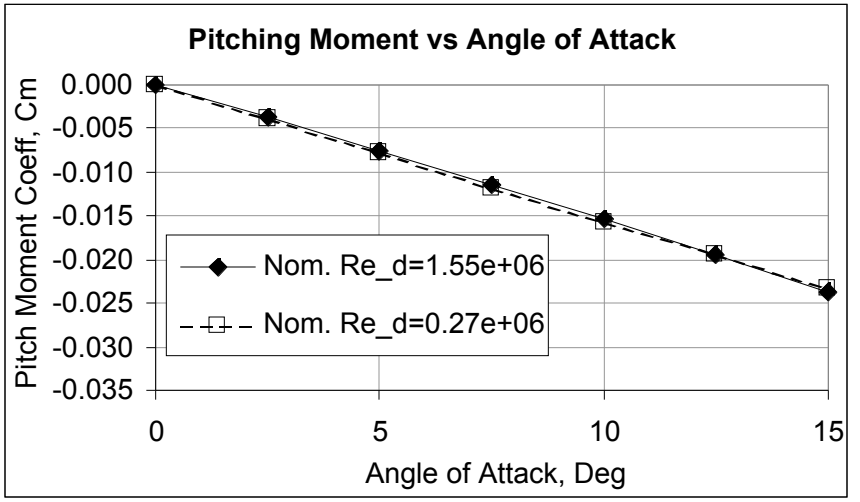
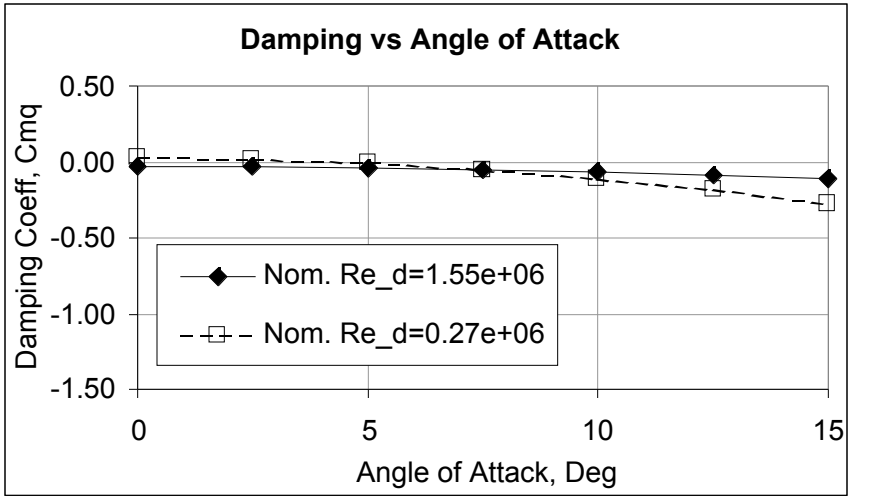
Stardust Ballistic Range Data (Air, Mach ≈ 2)









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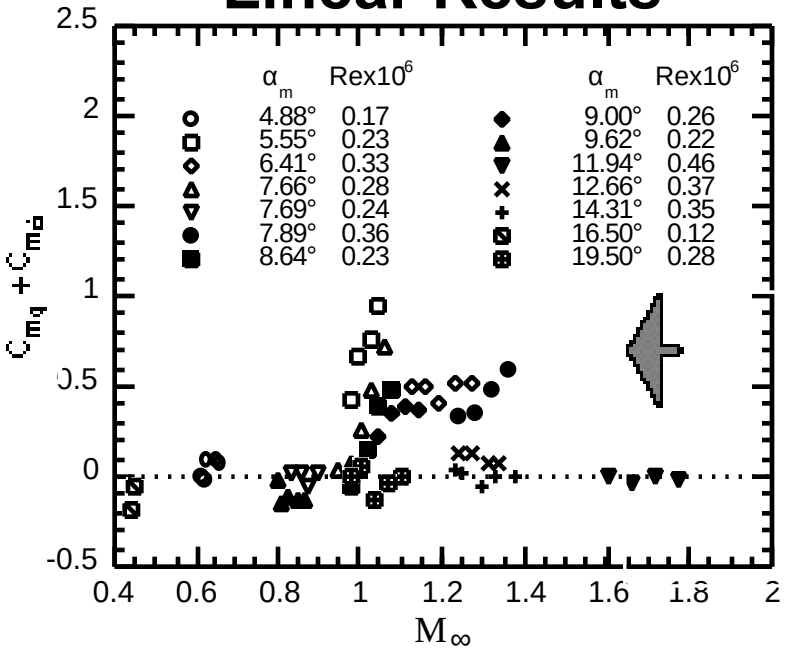
Ballistic Range Pitch Damping Data (Air, Mach ≈ 2)

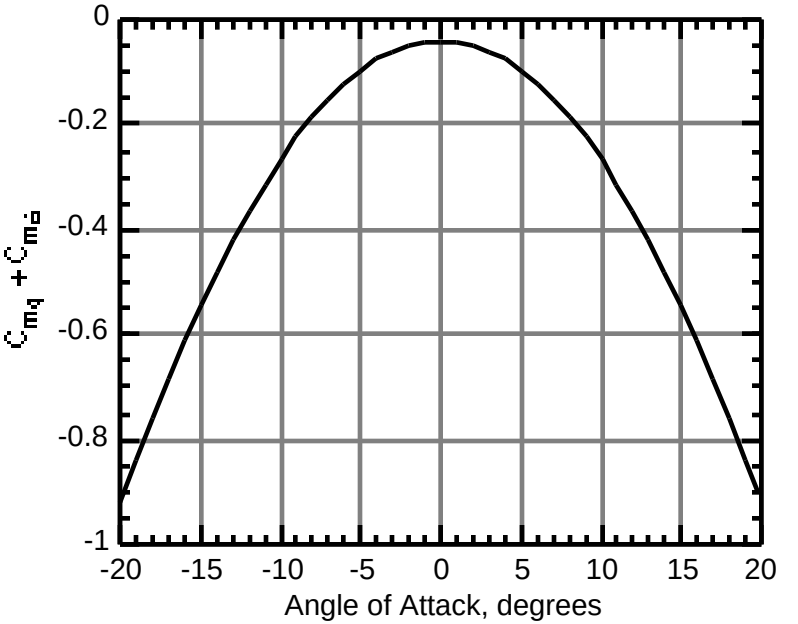
Pre 1975

Blunt Probes Linear Results



Post 1985

Huygen's Probe Noninear Results



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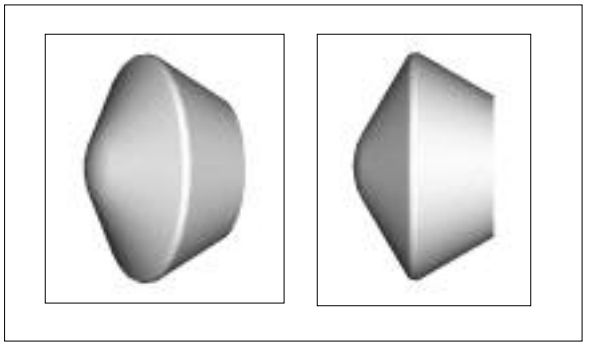
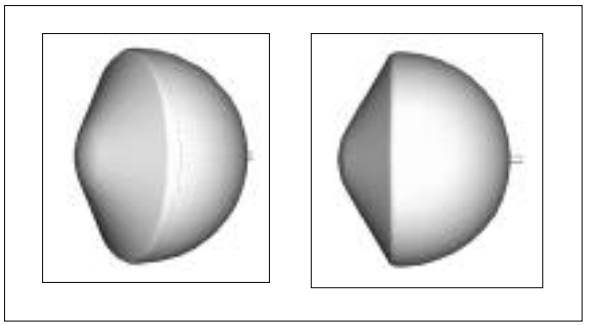
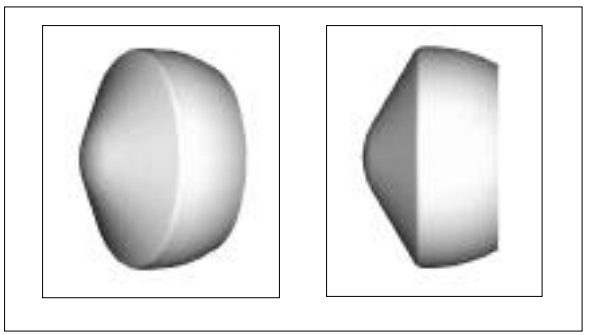
Impact of Afterbody on Dynamics (Air, Mach ≈ 2)



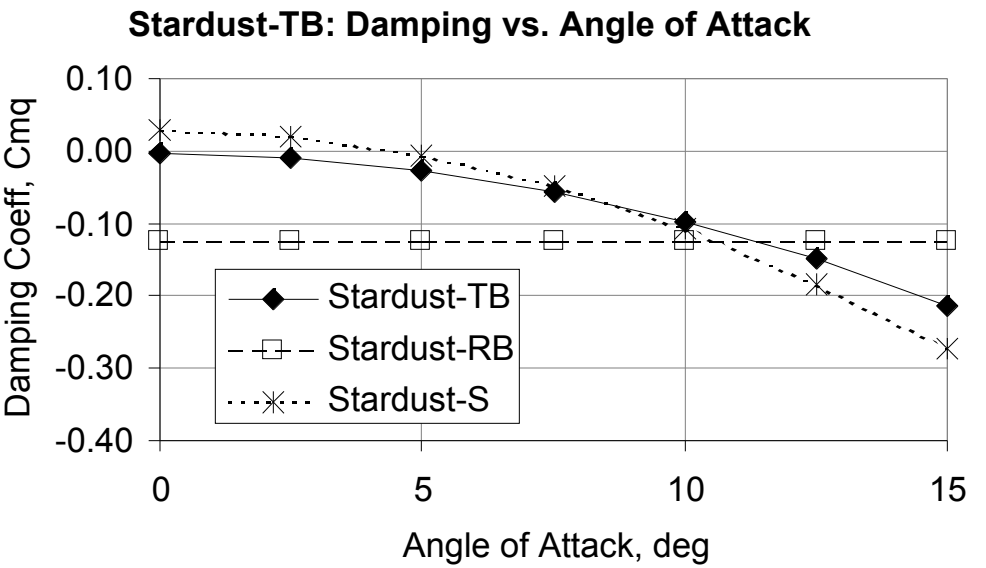
S



RB



TB



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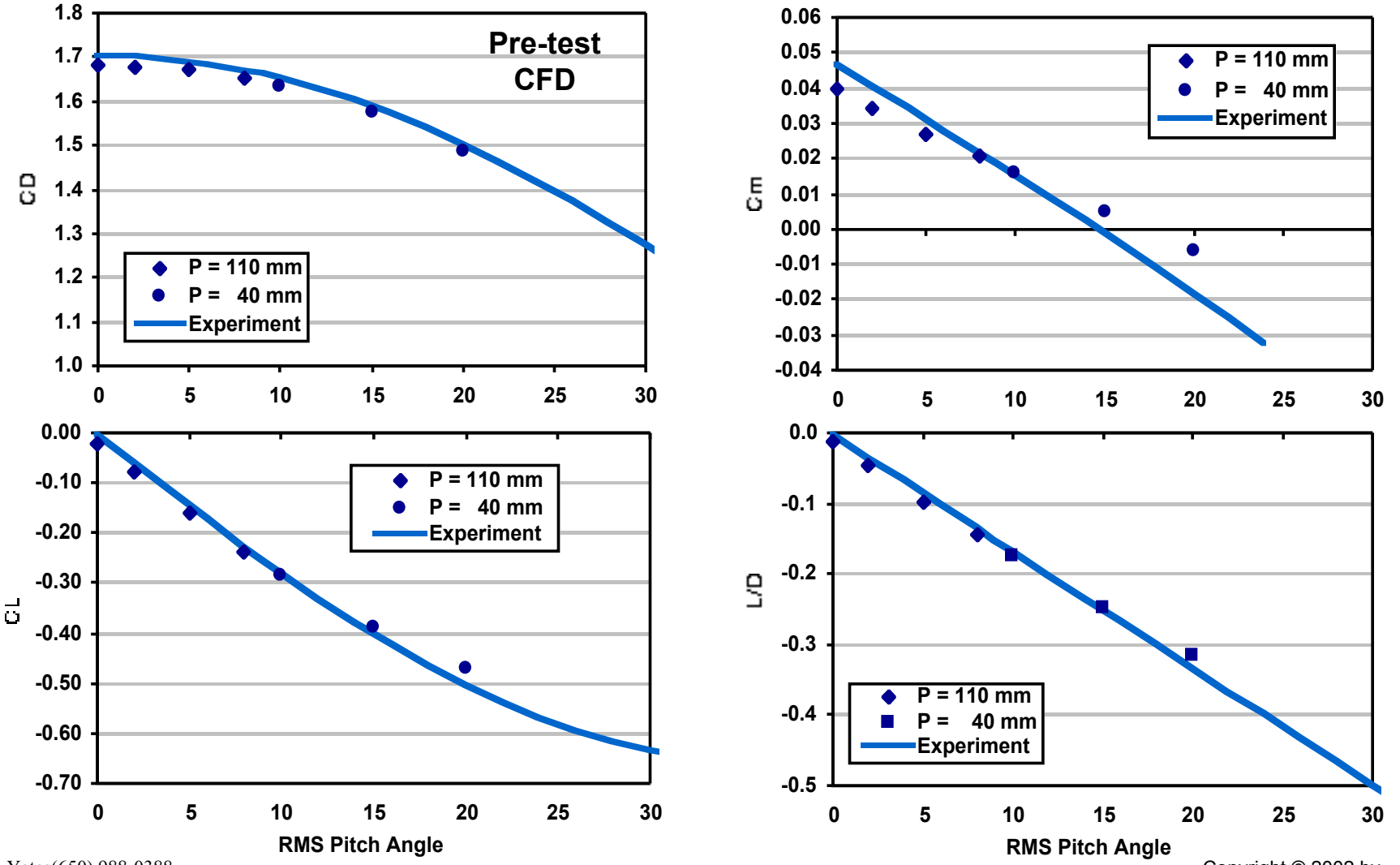
Ballistic Range Data

Mars Smart Lander, Tabbed Configuration
CO_2, Mach = 2.6, NASA Ames Ballistic Range



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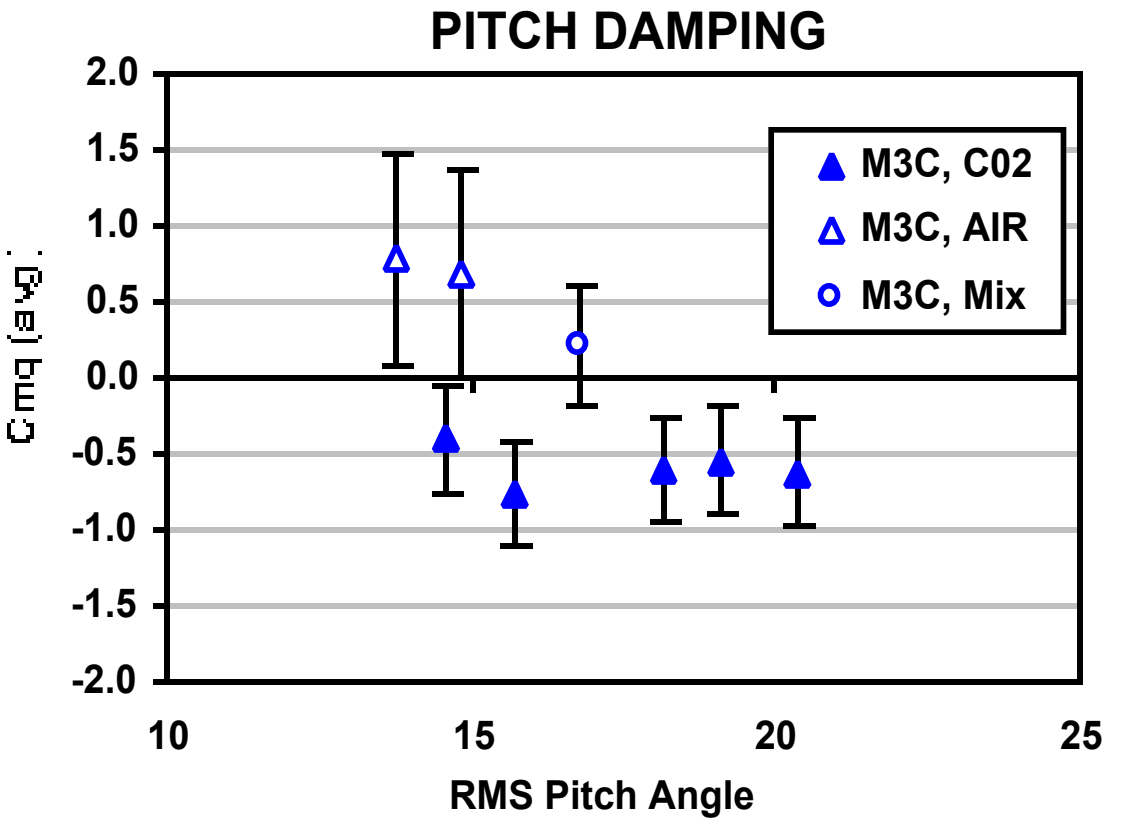

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Summary of Super/Transonic Aerodynamics

- Static aerodynamics
  - Well understood
- Dynamic aerodynamics
  - Strong base effects that are not understood
  - Potential gas dependence
- Tools
  - CFD, wind tunnels, and ballistic ranges needed for high quality data base

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Subsonic Aerodynamics

- **Mach number:** $M < 0.6$
- **No theories**
- **CFD**
  - Not used for dynamics, would be expensive
- **Ground based experimental**
  - Wind tunnel
    - Difficult for dynamics
    - Sting effects
  - Ballistic range
    - Difficult at low speeds

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Summary of Aerodynamics

- Free molecular
  - Reasonably well understood
  - Accuracy not critical
- Transition
  - DMS and low Reynolds number CFD plus bridging functions give reasonable estimates
- Continuum hypersonic
  - Statics: well understood
  - Dynamics: validated theory and CFD required
- Supersonic - Transonic
  - Statics: reasonably well understood
  - Dynamics: strong base effect; possible gas effect
- Subsonic
  - Shortage of data
  - Required only for missions without drogues / parachutes

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Concluding Remarks

- Aerodynamics plays major role in shaping trajectory
- Accurate aerodynamics database reduces foot-print size and reduces control fuel mass margins
- Aerodynamic understanding can provide mission design flexibility
- CFD, wind tunnels, and ballistic ranges all have a role in database generation
- Today's project driven environment limits innovation and is eroding expertise base

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Issues and Future Directions

- Loss of expertise
  - Develop user friendly training tools
  - Train new personnel
- Database erosion
  - Develop user friendly tool kits containing database, theory and simple CFD, and access tools for more complicated CFD
- Gaps in aerodynamic database
  - Pitch damping
    - Understand base effects
    - Determine effect of gas composition
    - Validate Newtonian Theory
    - Develop CFD approach / program

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