2007 Mars Phoenix Entry, Descent, and Landing Simulation and Modeling Analysis

Jill Prince
Rob Grover
Prasun Desai
Eric Queen

25 June 2007
Phoenix Overview

- Surface operations:
  - EDL
    - 600kg entry vehicle
    - Ballistic 3-axis stabilized entry
    - Propulsive terminal descent

June 26, 2007
**EDL Overview**

- **Final EDL Parameter Update:** E-12hr; **Entry State Initialization:** E-10min
- **Cruise Stage Separation:** E-7min
- **Entry Turn Starts:** E-6.5min. Turn completes by E-5min.
- **Entry:** E-0s, L-435s, 125 km*, r=3522.2 km, 5.7 km/s, $\gamma = -13$ deg

- **Peak Heating:** 44 W/cm² **Peak Deceleration:** 9.25G

- **Parachute Deployment:** E+220s, L-215s, **13 km**, Mach 1.7
- **Heat Shield Jettison:** E+235s, L-200s, **11 km**, 130 m/s

- **Leg Deployments:** E+245s, L-190s
- **Radar Activated:** E+295s, L-140s
- **Lander Separation:** E+399s, L-36s, **0.93 km**, 54 m/s

- **Throttle Up:** E+402s, L-33s, **0.75 km**
- **Constant Velocity Achieved:** E+425s, L-10s, **0.025 km**, 2.5 m/s
- **Touchdown:** E+435s, L-0s, 0 km, $v=2.5 \pm 1$ m/s, $h<1.4$ m/s

- **Vent Pressurant:** L+7Sec
- **Dust Settling/Gyrocompassing:** L+0 to L+15 min
- **Solar Array Deploy:** L+15min
- **Fire Pyros for Deployments:** ASAP

* Entry altitude referenced to equatorial radius. All other altitudes referenced to ground level

Note: Nominal Entry Shown. Dispersions exist around all values.

Landing at -3.4 km Elevation (MOLA relative)
EDL Simulation

• Program to Optimize Simulated Trajectories II (POST2)
  6-DOF simulation used to assess metrics, determine entry characteristics to meet EDL requirements
  – POST heritage: MGS, ODY, MER, MPF, MRO, Stardust, Genesis, etc
  – Simulation comparisons have been performed with additional simulation capabilities

• Metrics to track include:
  – Parachute deployment conditions – mach, dynamic pressure, opening loads
  – Lander separation conditions – altitude, velocity, time on parachute
  – Landing – footprint, fuel used, landing velocity
EDL Models

- IMU model
- Active hypersonic control system
- Atmosphere profiles
- Aerodynamics database
- Parachute
  - Deployment algorithm
  - Inflation model
  - Drag model
- Wind profiles
- Radar
- Terminal descent guidance
- Propulsive control model
<table>
<thead>
<tr>
<th></th>
<th>Pathfinder</th>
<th>MER A/B</th>
<th>Phoenix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, m</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
</tr>
<tr>
<td>Entry Mass, kg</td>
<td>585</td>
<td>840</td>
<td>602</td>
</tr>
<tr>
<td>Relative Entry Vel., km/s</td>
<td>7.6</td>
<td>5.5</td>
<td>5.9</td>
</tr>
<tr>
<td>Relative Entry FPA, deg</td>
<td>-13.8</td>
<td>-11.5</td>
<td>-13</td>
</tr>
<tr>
<td>m/(C_D*A), kg/m²</td>
<td>62.3</td>
<td>89.8</td>
<td>65</td>
</tr>
</tbody>
</table>

June 26, 2007
• The Phoenix entry trajectory is most similar to the MER entries
Aerodynamics Database Structure

- The database is divided into flight regimes that reflect different analysis methods and aerodynamics characteristics
  - v2.0 will have updated CFD data for hypersonic/supersonic continuum regimes and Viking data for $0.8 < \text{Mach} \leq 1.5$
  - Still using MER free-molecular, transitional, and dynamics data

<table>
<thead>
<tr>
<th>Rarefied</th>
<th>Transitional</th>
<th>Hypersonic</th>
<th>Supersonic</th>
<th>Supersonic Dynamics</th>
<th>Transonic/Subsonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Kn} &gt; 1000$</td>
<td>$1000 &gt; \text{Kn} &gt; 0.001$</td>
<td>$30.29 &gt; \text{Mach} &gt; 6.3$</td>
<td>$6.3 &gt; \text{Mach} &gt; 1.5$</td>
<td>$5 &gt; \text{Mach} &gt; 0.7$</td>
<td>$1.5 &gt; \text{Mach} &gt; 0.8$</td>
</tr>
</tbody>
</table>

**Analysis:**
- DAC DSMC code

**Current Data:**
- Phoenix Database Version 1.4.1

**Heritage:**
- Flight: MPF, MER
- Computation: MPF, MER

**Analysis:**
- LAURA CFD (forebody)
- Current Data:
  - Phoenix Database Version 1.4.1
  - Heritage:
    - Flight: Viking, MPF, MER
    - Experiment: Viking
    - Computation: MPF, MER

**Analysis:**
- Viking Forced Oscillation
- Current Data:
  - Phoenix Database Version 1.4.1
  - Heritage:
    - Flight: Viking, MPF, MER
    - Experiment: Viking
    - Computation: MPF, MER

June 26, 2007
Aerodynamics Database Implementation

- For rarefied flow, $C_A, C_N, C_m = f(\alpha_T \text{ and } Kn)$

![Diagram with labeled axes and sections for Dynamics and Statics, showing data sources and weighted averages for different flow regimes.]

June 26, 2007

JLP-9
Nominal Attitude Profile

June 26, 2007
Monte Carlo Parameters

- 2000 atmosphere profiles
- 2000 wind profiles
- Aerodynamics
- Mass properties
- Entry state
- Initial attitude
- Tip-off rates
  - Cruise stage separation
  - Lander separation
- Radar parameters
  - Slope distribution
  - Ground effects
- Propulsion parameters
  - RCS
  - TCM
Performance Criteria

Two basic categories of performance criteria form the basis for performance assessments

- Entry and Descent (ED) Criteria
  - Attitude behavior
  - Heating and loads
  - Deployment/separation conditions
  - Timeline and event timing
  - Sensor performance and state knowledge
  - Vehicle state at touchdown

- Landing (L) Dynamics Criteria
  - Touchdown/tip-over dynamics
  - Rock contact at landing
  - Rock contact during solar array deployments
Hypersonic Flight Statistics

- Vertical Velocity, m/s
- Horizontal Velocity, m/s
- Time from Entry, sec
- Total Fuel Usage, kg
Chute Deploy Statistics

- Total AoA, deg
- RSS (pitch rate, yaw rate)
- Mach
Summary

• All results shown are for 68N landing site at open of launch window
• Results vary with latitude and launch date – Monte Carlos are analyzed for several launch and landing site opportunities
• Many trade studies and sensitivities have been analyzed but not discussed here
Backup
Atmospheric Variability
Wind Variability

June 26, 2007
## Aerodynamic Uncertainties

<table>
<thead>
<tr>
<th>Flight Regime</th>
<th>Coefficients</th>
<th>Uncertainty</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Molecular</td>
<td>$C_A$, $C_N$, $C_Y$, $C_m$, $C_n$, $C_|l</td>
<td>$</td>
<td>$\pm5%$, $\pm0.01$ (Adder), $\pm20%$ (Multiplier), $\pm0.005$ (Adder), $\pm20%$ (Multiplier), $1.24e-6$</td>
</tr>
<tr>
<td>Hypersonic Continuum (Kn &lt; 0.001, M &gt; 10)</td>
<td>$C_A$, $C_N$, $C_Y$, $C_m$, $C_n$, $C_|l</td>
<td>$</td>
<td>$\pm3%$, $\pm0.01$ (Adder), $\pm20%$ (Multiplier), $\pm0.003$ (Adder), $\pm20%$ (Multiplier), $1.24e-6$</td>
</tr>
<tr>
<td>Supersonic Continuum (Kn &lt; 0.001, M &lt; 5)</td>
<td>$C_A$, $C_N$, $C_Y$, $C_m$, $C_n$, $C_|l</td>
<td>$</td>
<td>$\pm10%$, $\pm0.01$ (Adder), $\pm20%$ (Multiplier), $\pm0.005$ (Adder), $\pm20%$ (Multiplier), $1.24e-6$</td>
</tr>
<tr>
<td>Free Molecular/Hypersonic Dynamics (M &gt; 6)</td>
<td>$C_{mq}$</td>
<td>$\pm0.15$</td>
<td>Normal</td>
</tr>
<tr>
<td>Supersonic Dynamics (M &lt; 3)</td>
<td>$C_{mq}$</td>
<td>$-50%$ to $100%$ (Multiplier), $0$ to $0.1$ (Adder)</td>
<td>Normal/Uniform</td>
</tr>
</tbody>
</table>