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Mars Pathfinder Entry Trajectory Design Using a Monte Carlo Approach

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The primary objective of the Mars Pathfinder mission is to demonstrate a low-cost, reliable system for entering the Martian atmosphere and placing a lander safely on the surface of Mars. Since the Pathfinder entry trajectory drives the design of the Entry, Descent, and Landing (EDL) System, an extensive analysis of the Pathfinder entry trajectory has been performed. While computationally intensive, the Monte Carlo approach can give insight into the behavior of systems that are too complex to be resolved analytically. Three degree-of-freedom (center of mass) and 6 degree-of-freedom (translational and rotational) Monte Carlo simulations have been developed, to obtain statistical information on entry conditions at critical points during the Pathfinder descent. The simulations include uncertainties in entry conditions, atmospheric density, entry body and parachute drag profiles, accelerometer measurement accuracy, parachute deployment timing, and landing site elevation. This paper will describe the current design of the Pathfinder entry trajectory, with an emphasis on the results of the Monte Carlo simulations.

The Pathfinder spacecraft will enter the Martian atmosphere directly from the Earth-to-Mars interplanetary transfer trajectory, along a Mars-centered approach hyperbola. The entry sequence of events is shown in Figure 1. Thirty minutes prior to atmospheric entry (defined at an altitude of 125 km above the Mars reference ellipsoid), the cruise stage will be jettisoned. The entry vehicle will enter the Mars atmosphere, reaching maximum stagnation point heating and peak dynamic pressure during the initial 70 seconds of the entry phase. Throughout the entry portion of the flight, vehicle spin and aerodynamic damping are relied upon to provide vehicle stability about the nominal 0° trim angle of attack. Six degree-of-freedom (DOF) trajectory analysis has shown that the Mars Pathfinder aeroshell is aerodynamically stable over a large portion of the atmospheric flight. However, two low angle of attack static instabilities (hypersonic) and a low angle of attack dynamic instability (supersonic) have been identified and shown to cause an increase in vehicle angle of attack away from the trim state. In each of these flight regimes, the vehicle is aerodynamically stable at higher angles of attack, such that the increase in vehicle angle of attack is bounded. The nominal attitude profile is shown in Figure 2. In general, this attitude motion is characterized by: (1) an increase in vehicle angle of attack just prior to peak heating; (2) flight with a lower angle of attack, but higher oscillation frequency through peak dynamic pressure; (3) a second increase in vehicle angle of attack just prior to peak Reynolds number, which is quickly damped, and (4) a final increase in vehicle angle of attack as parachute deployment is reached.

At roughly 150 seconds past entry, a parachute will be deployed, followed by the release of the heatshield 10 seconds later. The lander will be deployed below the backshell along a 20 m bridle. At an altitude of 1.5 km above ground level (AGL), a radar altimeter will acquire the ground. Altimeter data will be used by the flight software to inflate an airbag system and fire a set of three solid rockets (mounted on the backshell) at an altitude of 50 m AGL. At an altitude of 15 m, the bridle will be cut, and the lander will fall directly, buffered at ground impact by the airbag system. Sufficient impulse will remain in the solid rockets to carry the backshell and parachute to a safe distance away from the lander.

The Pathfinder entry trajectory is designed to meet a number of requirements. For the Pathfinder mass and entry velocity, the limiting flight path angle for skipout from the Mars atmosphere is -11.2° (i.e., if the spacecraft inertial velocity vector is less than 11.2° below the local horizontal at the time of entry, skipout may occur). The Pathfinder Project has required that the entry trajectory be designed so that the worst-case inertial flight path angle at entry is at least 2° steeper than the skipout angle.

The EDL system will employ a Dacron supersonic parachute. The required parachute deployment conditions are as follows: dynamic pressure no greater than 703 Pa, Mach number greater than 1.2, and time from parachute deployment to 1.5 km AGL (earliest possible ground acquisition by the altimeter) greater than 75 s. This 75 s allows sufficient time, including margin, for the parachute to stabilize, release of the heatshield, and lander deployment along the 20 m bridle.

Arcjet testing at NASA Ames Research Center has demonstrated that the aeroshell ablative material (SLA-561 V) can maintain its physical integrity at stagnation point pressures of 25.332 kPa (0.25 Earth atm) or less. At stagnation point pressures of greater than 25.332 kPa, surface spallation of the aeroshell ablative material can occur, effectively changing the aerodynamic characteristics of the aeroshell and creating uncertain heating conditions. The Pathfinder entry trajectory is designed to have a peak stagnation point pressure of less than 25.332 kPa.

The nominal Pathfinder entry trajectory has been designed for an inertial flight path angle of -14.8°. This design is contingent upon an entry mass of 556 kg, resulting in a ballistic coefficient of 60 kg/m^2 at peak heating. A parachute deployment algorithm has been developed, in which accelerometer readings and a predetermined acceleration profile are used to deploy the parachute at a nominal dynamic pressure of 600 Pa, Mach number of 1.8, and altitude of 8.6 km above the reference ellipsoid. A plot of altitude versus time during entry for the nominal entry trajectory is shown in Figure 3.

Monte Carlo simulations have been used extensively in the design of the Pathfinder entry trajectory. Simulations have been performed independently at the Jet Propulsion Laboratory (3 DOF), and NASA Langley Research Center (6 DOF). Table 1 shows the 3 DOF Monte Carlo analysis variables and their associated uncertainties. Figure 4 shows a scatter plot of output from a 3 DOF Monte Carlo simulation containing 2000 cases. The data points show the dynamic pressure at the time of parachute deployment, plotted against the descent time from parachute deployment to the time of earliest possible ground acquisition by the altimeter (at 1.5 km AGL). The 3 DOF Monte Carlo analysis results, as seen in Table 2, indicate that the required conditions at parachute deployment are met by the 3σ range of trajectories. The 3σ high dynamic pressure at the time of parachute deployment is 662 Pa, and the 3σ low Mach number is 1.617. The EDL System requirement of 75 seconds from parachute deployment to 1,5 ktn AGL is met in 2.4σ (98%) of the

Monte Carlo trajectories. This is an acceptable risk level to the project, as recent design improvements in the bridle subsystem have increased the margin in the terminal descent timeline. The range of total integrated heating through the time of heatshield release was used in sizing the aeroshell thermal protection system, designed to have a uniform thickness of 1.905 cm (0.75 in).

The 6 DOF Monte Carlo results show a similar set of mean values, but a larger variance than that shown in Table 2. Six DOF effects which could impact the magnitude of these dispersions include the lift and side forces generated at non zero angles of attack, and the drag degradation which results as vehicle angle of attack increases. The final paper will compare the 3 DOF and 6 DOF Monte Carlo results.

Design of the Pathfinder entry trajectory, and identification of the likely aerodynamic dispersions during critical events, have been essential for the development of the various EDL subsystems. The Pathfinder entry trajectory design currently meets all EDL requirements with a significant amount of margin, providing a high level of confidence that Pathfinder's 300 seconds of flight through the Mars atmosphere will result in a successful landing.

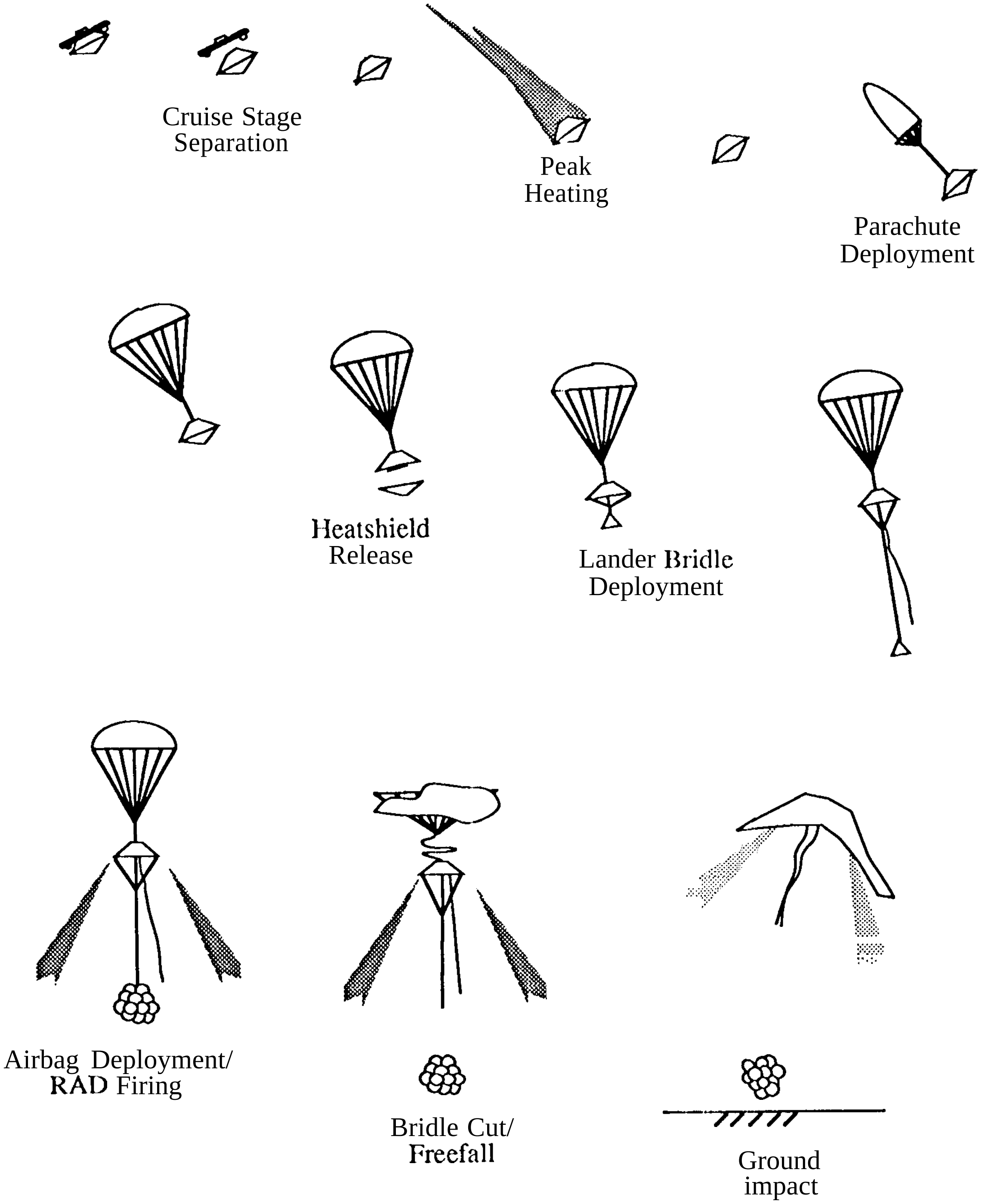


Figure 1. Entry, Descent, and Landing Sequence of Events

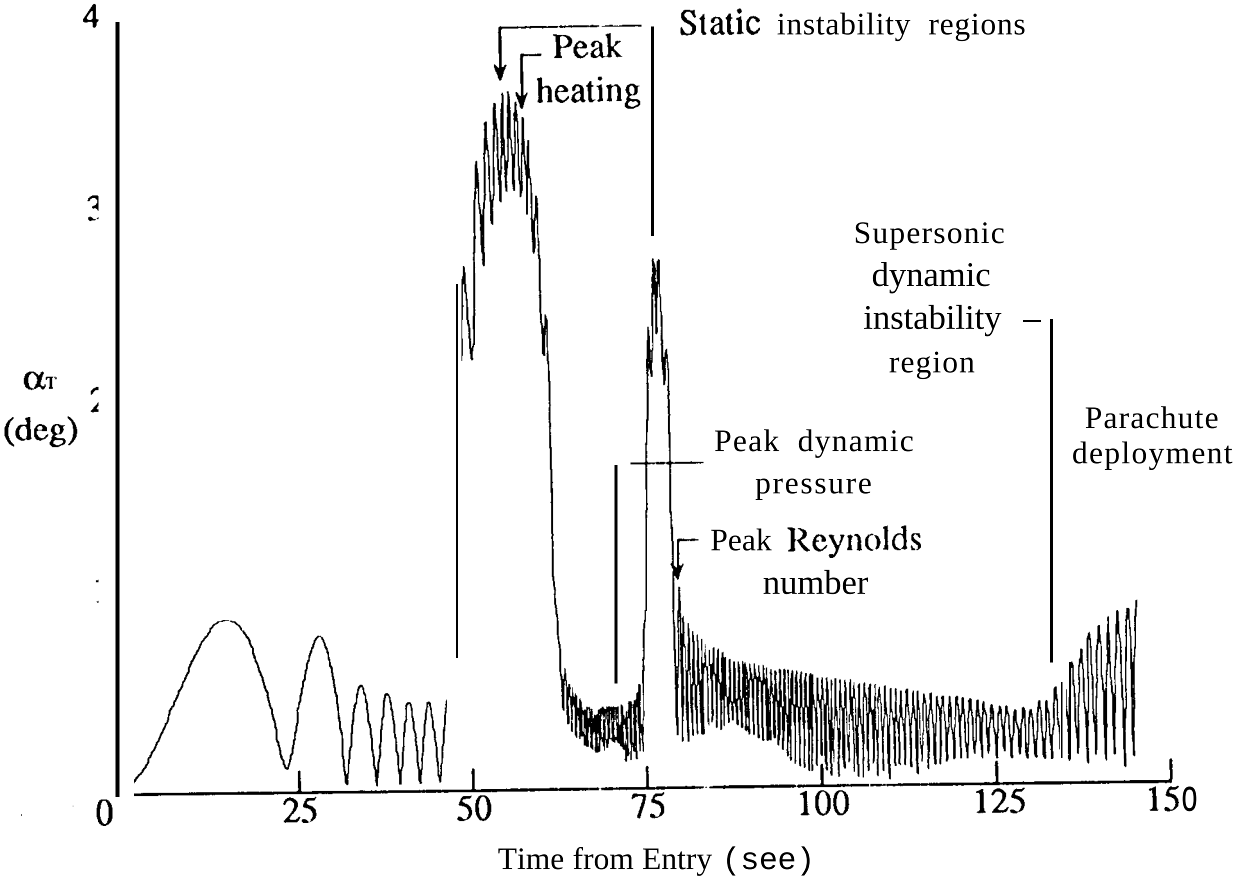
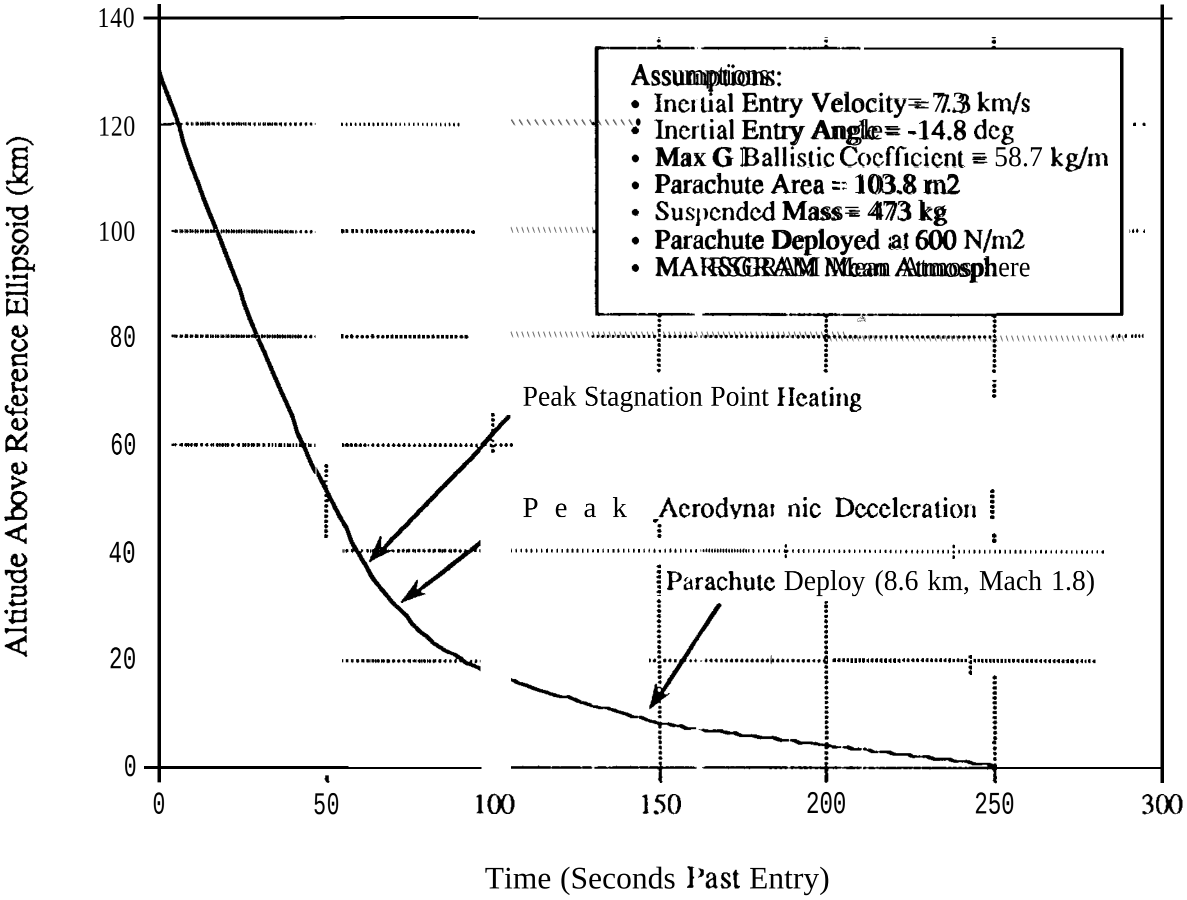


Figure 2. Nominal 6 DOF Entry Attitude Profile



Assumptions:
- Inertial Entry Velocity = 7.3 km/s
- Inertial Entry Angle = -14.8 deg
- Max G Ballistic Coefficient = 58.7 kg/m
- Parachute Area = 103.8 m2
- Suspended Mass = 473 kg
- Parachute Deployed at 600 N/m2
- MARSGRAM Mean Atmosphere

Peak Stagnation Point Heating

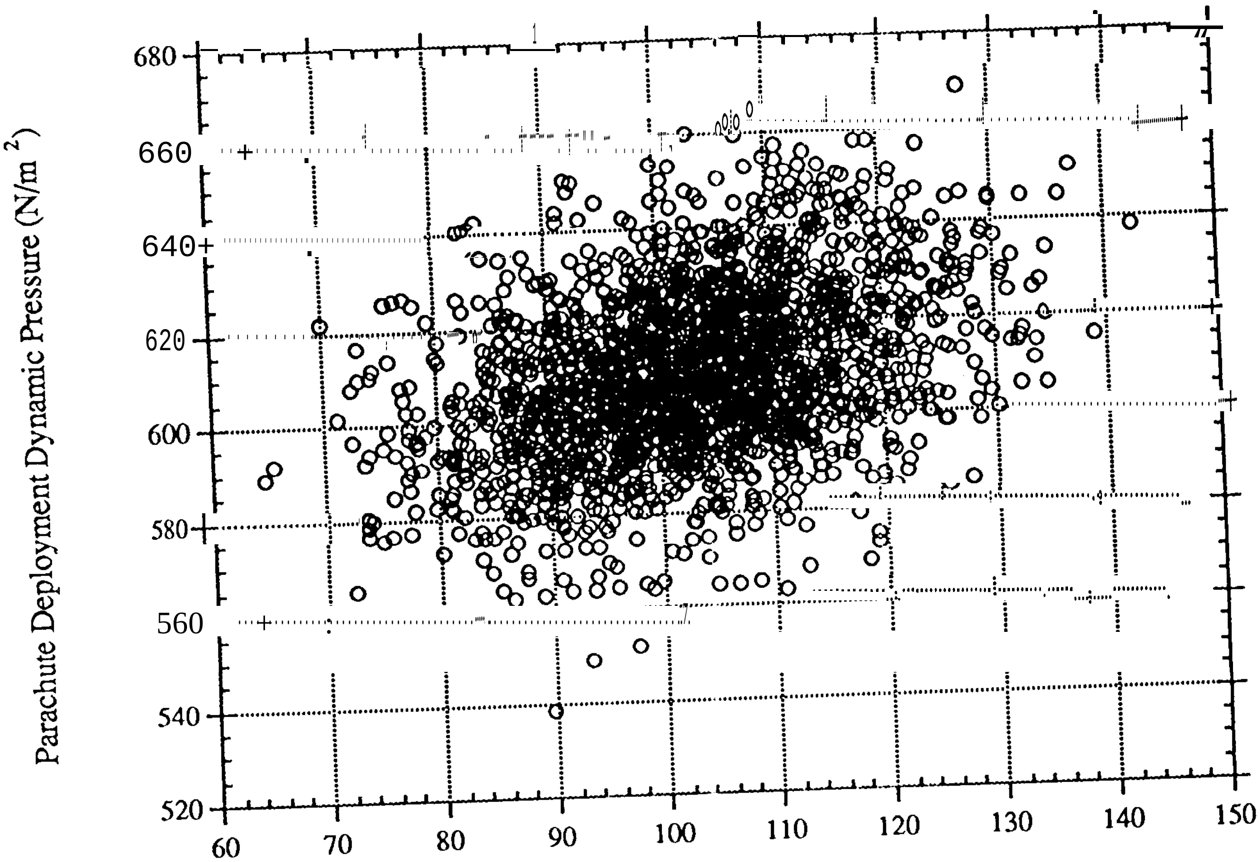
Peak Aerodynamic Deceleration

Parachute Deploy (8.6 km, Mach 1.8)

Figure 3. Nominal Entry Trajectory Altitude vs. Time

Table 1. Monte Carlo Entry Simulation

Input Variable	**Distribution**	**Variation**
Entry State	Normal	±1° Flight Path Angle (3σ
Atmospheric Density	Normal	MARSGRAM ±6σ Below 75 km MARSGRAM ±1σ Above 100 km
Entry Body Drag Coefficient	Normal (1-Sided)	-6% (3σ
Parachute Drag Coefficient	Normal	±13% (3σ
Accelerometer Readings	Normal	±0.5 g (3σ
Event Timing	Normal	±0.25 sec (3σ
Landing Site Elevation	Normal	±1 km (3σ)



Time from Parachute Deployment to Earliest Ground Acquisition (s)

Figure 4. Dynamic Pressure at Parachute Deployment
vs. Parachute Descent Time
Monte Carlo Simulation (2000 Cases)

Table 2. Atmospheric Entry Monte Carlo Sinulation Results (3 DOF)

Event	Mean Value	Standard Deviation	3σ Range
Parachute Deployment			
Time Past Entry (s)	147.06	7.56	124.39—169.74
Altitude (km)	8.52	0.78	6.18—10.86
V_a (km/s)	0.403	0.013	0.364-0.442
γ (deg)	24.10	0.67	22.08-26.12
Deceleration (g's)	0.687	0.033	0.587-0.787
Mach Number	1.80	0.06	1.617—1.993
Dynamic Pressure (Pa)	609.6	17.6	556.7-662.5
Heatshield Release			
Time Past Entry (s)	167.06	7.56	144.39—189.74
Altitude (km)	6.52	0.75	4.27—8.78
V_a (km/s)	0.107	0.006	0.091-0.125
γ (deg)	44.36	1.31	40,43—48.28
Deceleration (g's	0.721	0.029	0.634--0.809
Mach Number	0.48	0.03	0.40-0.56
Dynamic Pressure (Pa)	52,2	3.9	40.42-63.96
Total Integrated Heating (J/cm^2)	3363	80	312>3603
Ground Acquisition			
Time from Chute Deploy (s)	103.01	11.83	67.50-138.51
RAD Firing			
Time Past Entry (s)	274.94	11.83	227.12—322.78