



National Aeronautics and
Space Administration



Entry, Descent and Landing Flight Mechanics Predictions for Planetary Exploration

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Hypersonic Vehicle Flight Prediction Workshop

United States Air Force Academy

Colorado Springs, CO

20-22 June 2017



Objectives



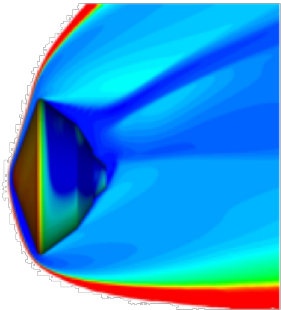
- **Hypersonic aerodynamic uncertainties can have a significant influence on the predicted performance of the Entry, Decent and Landing (EDL) phases for an atmospheric entry vehicle.**
 - Particularly for vehicles using a ballistic (un-guided) entry.
 - Clearly demonstrated by the effect some uncertainties can have on the location and size of the predicted landing footprint.
- **It is the job of the flight mechanics engineer is to consolidate all environmental and vehicle models (along with their uncertainties) at his/her disposal into a simulation to provide the best possible *estimate* of the vehicle performance.**
- **As is often the case, however, the prediction is only be as good as the models and inputs used to develop that prediction.**



Flight Mechanics End-to-End Simulation



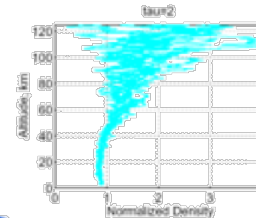
Aerodynamics &
Aerothermodynamics



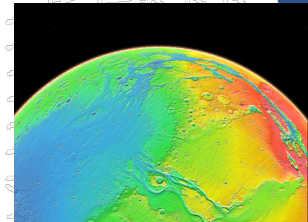
Mass Properties



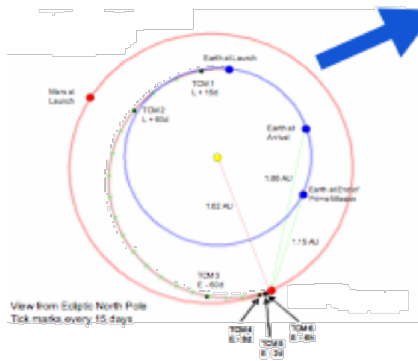
Atmosphere



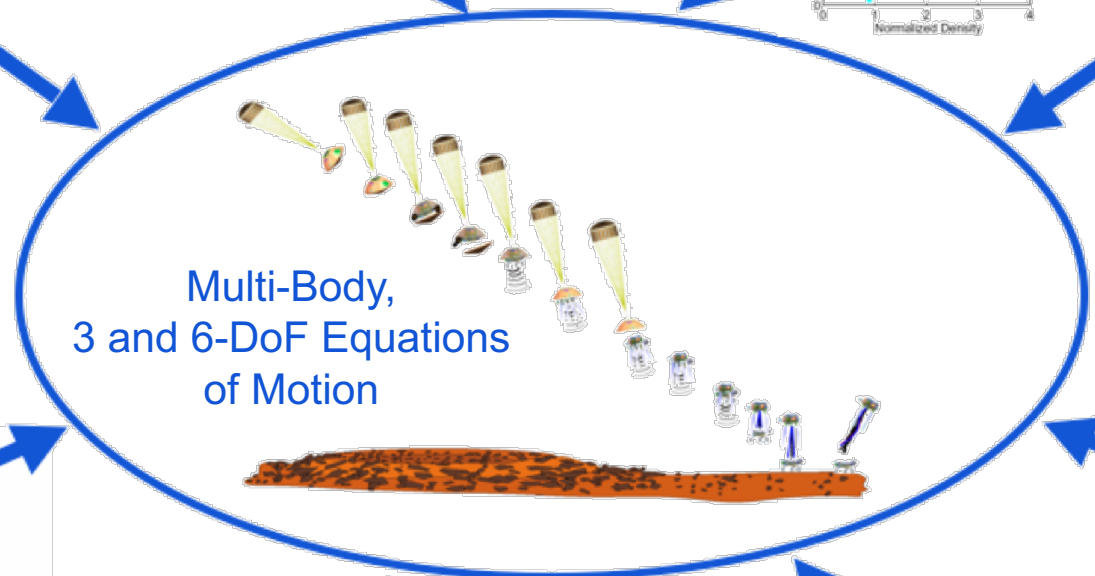
Planet



Entry Conditions
Approach Nav.



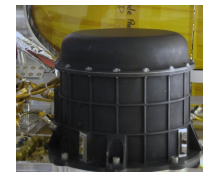
Multi-Body,
3 and 6-DoF Equations
of Motion



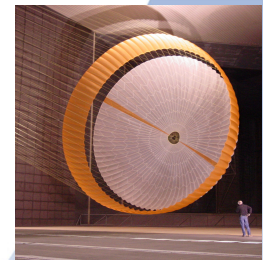
Propulsion



Guidance, Navigation, & Control



Parachute

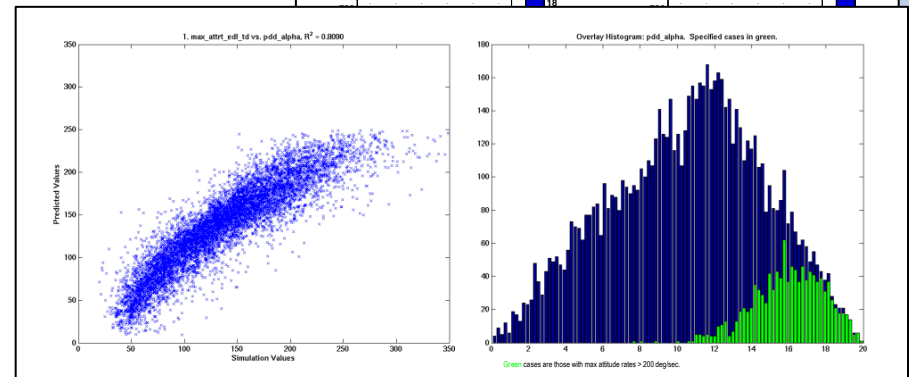
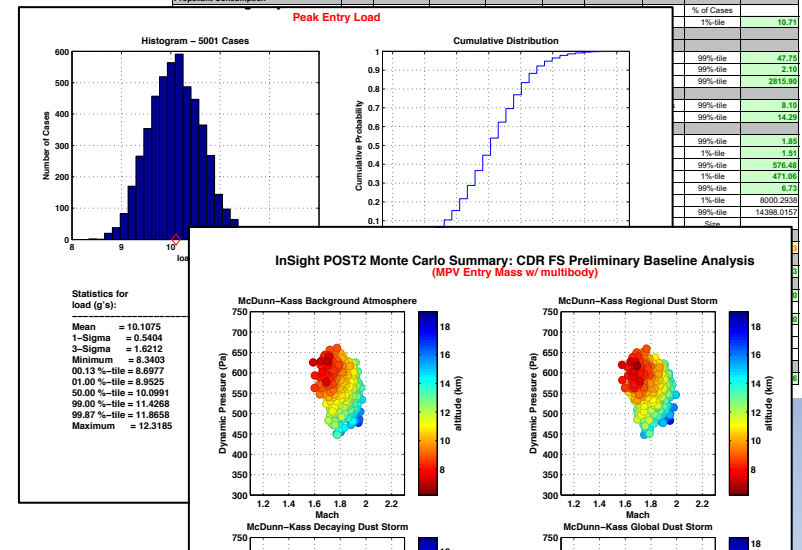


Images credit: NASA/JPL-Caltech

Monte Carlo Analyses

- By definition, all models are wrong!! (Although some can be useful...)
- The goal of any pre-flight analysis is to predict the limits of performance (i.e. encompassing all possible or most likely outcomes).
- Performance must be understood over all possible / likely range of conditions, both known (e.g. hardware specifications) and unknown (e.g. environmental factors).
- Monte Carlo Analyses are used to provide statistical understanding of EDL flight system margins against key mission requirements (e.g. landing footprint).
- These types of analyses also lend themselves to:
 - sensitivity studies: understanding which inputs and dispersions (or combination thereof) the system is most sensitive to
 - robustness studies: understanding where the system “breaks”

EDL Metric	>, <, =	Requirement Value	Desired Margin	Target Value	Units	POST2 Results	Units	Type	POST2 Confidence
Monte Carlo						7997.00	1	Size	
Number of Successful Cases	>	2001	1%	7920					
Landing Accuracy	<	150	0	150	km	109.83		Nominal	
99%-ile Landing Ellipse Major Axis	<	35	0	35	km	23.81		Nominal	
99%-ile Landing Ellipse Minor Axis	<								
Touchdown Conditions									
High Vertical Velocity	<	3.4	0.1	3.3	m/s	2.64		99%-ile	2.65
Low Vertical Velocity	>	1.4	0.1	1.5	m/s	1.72		1%-ile	1.70
Horizontal Velocity	<	1.4	0.1	1.3	m/s	0.73		99%-ile	0.76
Altitude Rate (RSS pitch/yaw)	<	11.3	1.7	9.6	deg/s	7.64		99%-ile	7.85
Max Altitude Rate During EDL	<	200	40	160	deg/s	168.20		99%-ile	172.35
Overall Probability of Safe Landing						99.25	%	Mean	
Propellant Consumption									





Typical Monte Carlo Dispersions



➤ Entry States

- delivery
- knowledge (FSW)

➤ Mass Properties

- propellant mass
- center of mass
- moments and products of inertia

➤ Attitude and Attitude Rates

- cruise stage tip-off
- separation events

➤ Aerodynamics (all configurations)

- free molecular
- hypersonic
- supersonic
- subsonic

➤ Atmosphere (profiles)

- density
- winds

➤ IMU

- alignment
- acceleration scale factor and bias
- gyro scale factor and drift

➤ Propulsion

- thruster location / direction
- specific impulse / thrust (incl. ramp up and ramp down)
- thruster leak rates

➤ Parachute

- mortar recoil
- size / diameter
- line lengths / inflation rate
- bridle stiffness
- deploy (apparate) angle

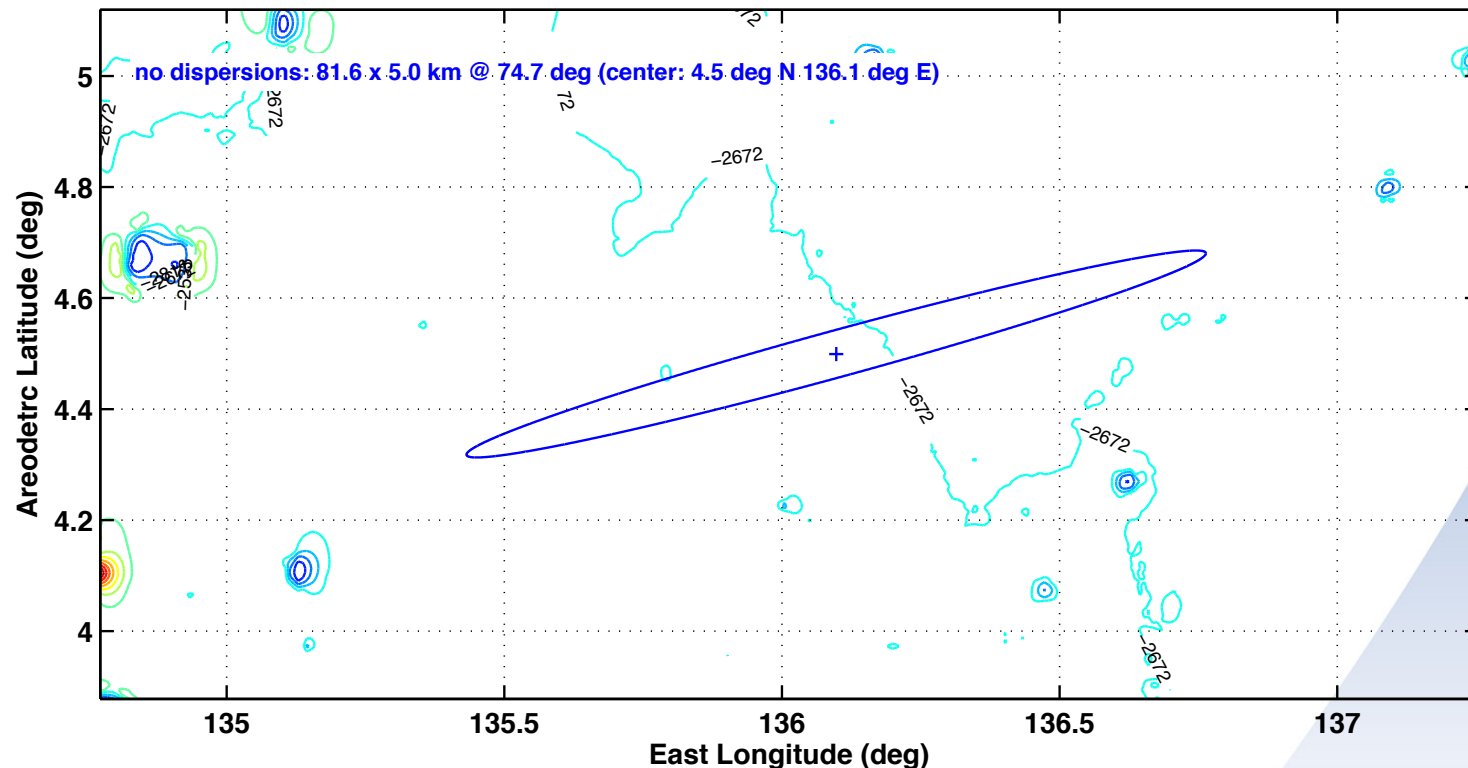
➤ Radar Performance...

➤ Ground Effects...

➤ Other mission / spacecraft specific...

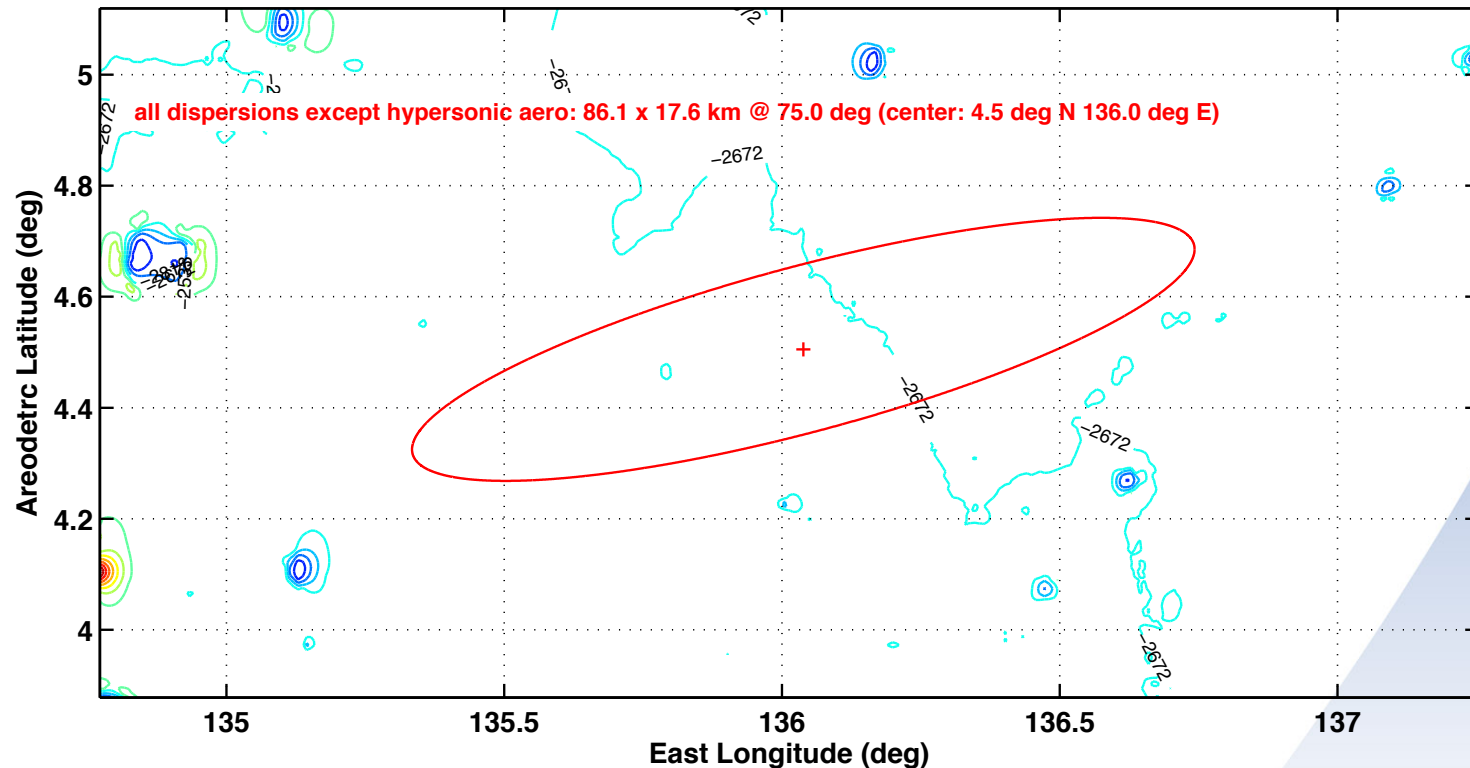
Effect of Dispersions on Landing Footprint

- With perfect knowledge of all environmental factors and the spacecraft itself, the landing footprint is driven by delivery error at entry interface (particularly in entry flight path angle).



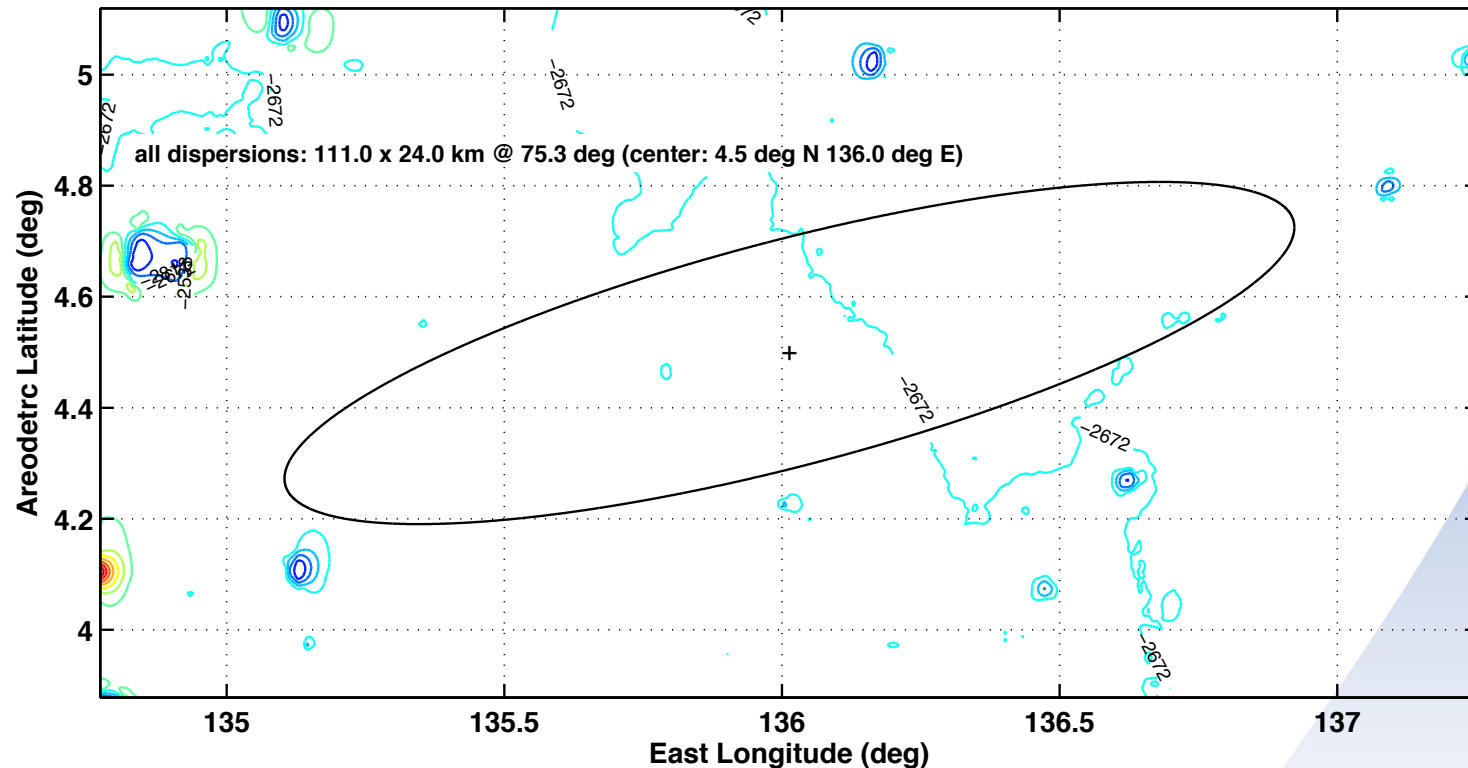
Effect of Dispersions on Landing Footprint

- With perfect knowledge of hypersonic aerodynamics only, the landing ellipse grows significantly.



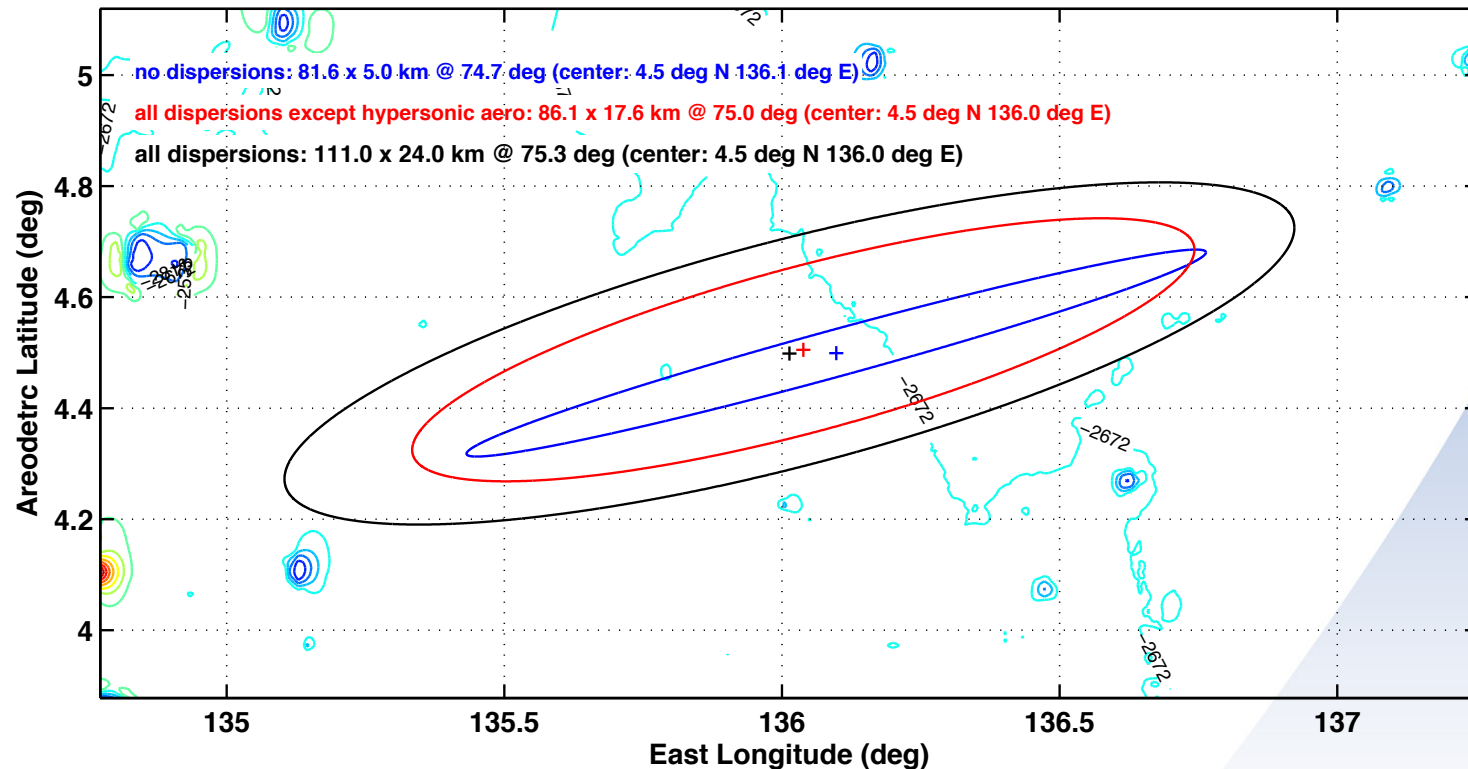
Effect of Dispersions on Landing Footprint

- Dispersing hypersonic aerodynamics as well, the landing ellipse size grows further to what is typically expected for Mars ballistic entry.



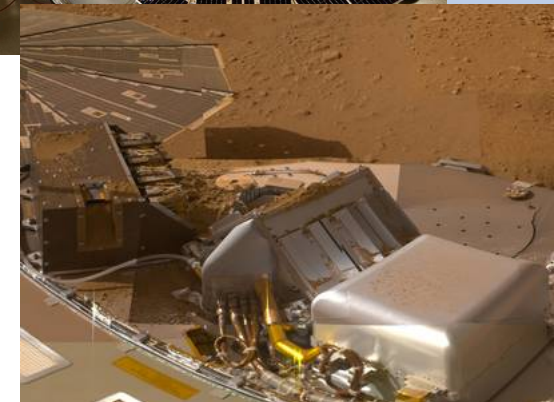
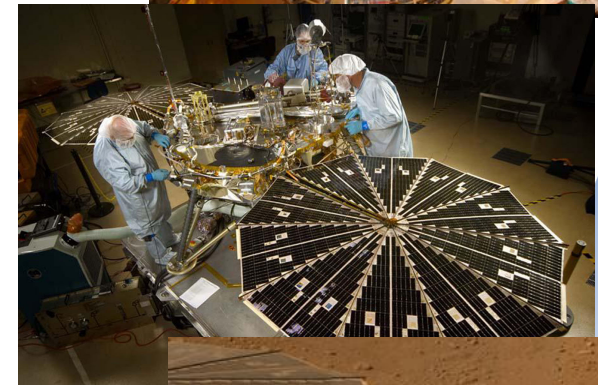
Effect of Dispersions on Landing Footprint

- The size and location of the landing footprint needs to be predicted to the best possible accuracy in order to insure mission requirements can be met.
- range to science target
 - landing safety (hazards and terrain)



Phoenix Case Study

- On 25 May 2008, the Phoenix Lander successfully touched down on Mars.
- At the time of landing, the EDL analyses were predicting a landing footprint of approximately 55.1 x 19.2 km.
- Phoenix landed 21.2 km downtrack and 5.1 km crosstrack from the center of the predicted footprint.
 - This has come to be known as a “ $\sim 2.5\sigma$ landing”
 - EDL reconstruction also showed a larger-than-expected trim angle of attack during the hypersonic phase of flight, which was quickly identified as a major contributor to the “long landing”.
- It was later discovered that approximately 6 months prior to landing, the EDL flight mechanics simulation reduced the adder component of the hypersonic pitching coefficient (C_m) dispersion from the original $\pm 3\sigma$ value to a (effectively) $\pm 2\sigma$ value.
 - Maintaining the original dispersions, the predicted landing footprint prior to EDL would have been larger, resulting in a landing closer to $\sim 1.5\sigma$.





Summary



- Hypersonic flight predictions are critical to entry, descent and landing performance assessments for planetary entry systems.
- Although the time spent in hypersonic flight may be relatively short, it occurs early in the entry / descent phase and sets up the initial conditions for subsequent supersonic and subsonic flight phases.
- Monte Carlo analyses can be used to predict flight system performance over a wide range of possible (or likely) conditions.
- Dispersions to hypersonic aerodynamics must be conservative given the lack of test data available for blunt body vehicles.
- As seen with Phoenix, understanding of what the dispersions are (and how large they should be) is not only critical in pre-flight predictions of the landed footprint, but also in properly evaluating post flight reconstruction performance.

