Perspective on Planetary Entry, Descent, and Landing Research

Contributions and Lessons Learned

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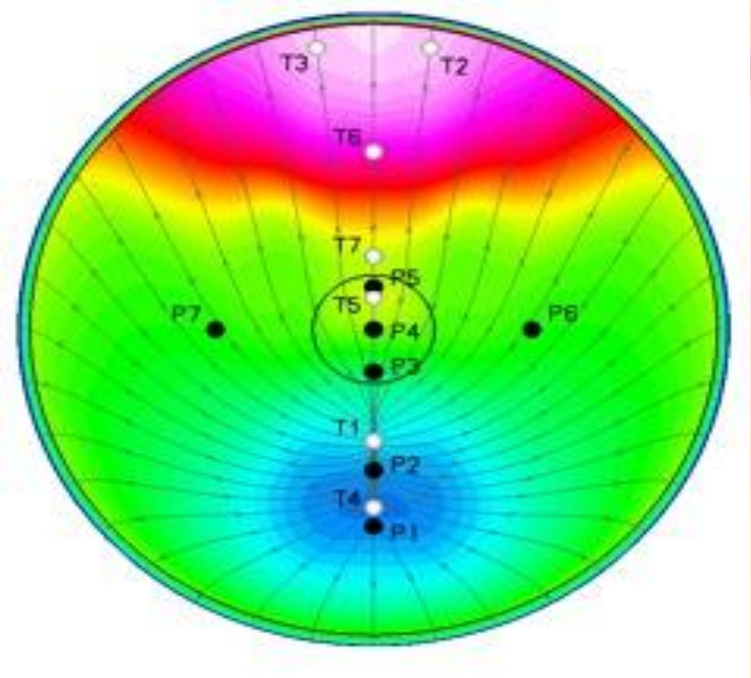
Introduction

- Entry, descent, and landing (EDL) is the phase of flight defined from atmospheric interface to touchdown on a planetary surface
- Future planetary missions strive to deliver larger payloads at higher altitudes with increased landing accuracy; currently driven by available EDL technologies
  - Nearing the limit with current technologies for Mars Science Laboratory (MSL); currently scheduled to launch Fall 2011
  - Stringent requirement for any manned missions; for Mars: two order of magnitude increase in landed payload mass, four order of magnitude increase in landing accuracy
- Current EDL systems are based on Viking-era technologies (1970's NASA Mars program) with minor modifications
  - Aeroshell geometry, thermal protection system (TPS) material, parachute design
- Development of newer, more robust EDL technologies rely on improving Earth-based modeling capabilities
  - Large uncertainties in computational simulations
  - Inadequate ground-based testing facilities
  - Sparse amount of flight data available

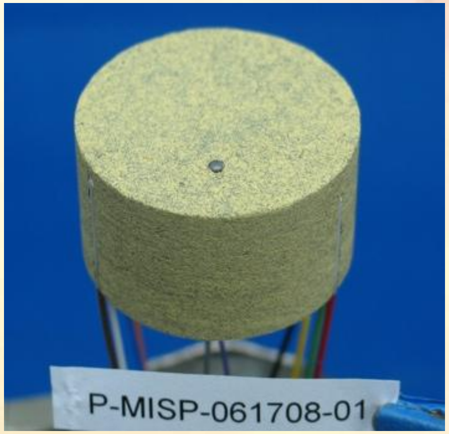
MEDLI Overview



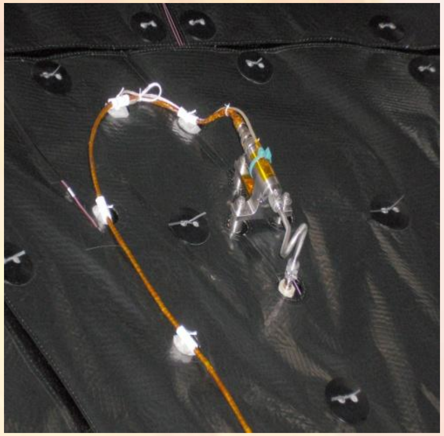
- The MSL Entry, Descent, and Landing Instrumentation (MEDLI) is a suite of sensors installed on the forebody heatshield of the MSL entry vehicle
  - Sensor locations determined by science team
  - Some similar components to previous entry instrumentation packages
- MEDLI operational from ten minutes prior to atmospheric interface to heatshield separation
- MEDLI proposed to address some of the challenges associated with development of newer, more robust EDL technologies
- MEDLI High-Level Objectives:
  - Provide more than an order of magnitude more data than all previous Mars entry missions combined
  - Answer fundamental questions relating to leeside turbulent heating levels, forebody flow transition, and TPS material response in a carbon dioxide atmosphere
  - Permit a more accurate post-flight trajectory reconstruction
  - Allow separation of aerodynamic and atmospheric uncertainties in the hypersonic and supersonic flow regimes.

MEDLI Subsystems

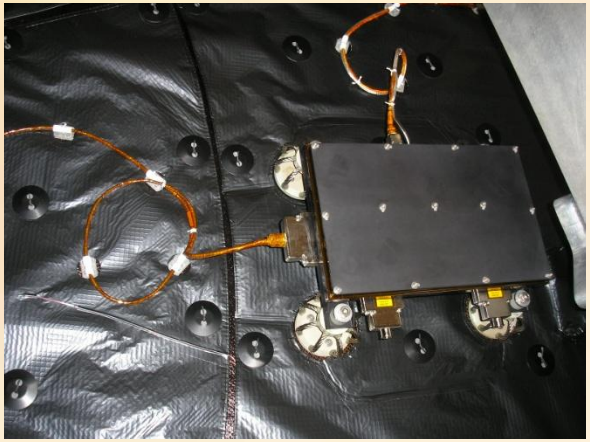
- MEDLI Integrated Sensor Plugs (MISP)
  - A plug consists of a 1.4” diameter heatshield TPS core with embedded thermocouples and recession sensors
  - Each plug consists of one (1) recession sensor and four (4) thermocouple sensors
  - Supports aerothermodynamic and TPS science objectives
- Mars Entry Atmospheric Data System (MEADS)
  - Series of through-holes, or ports, in the TPS that connect via tubing to pressure transducers
  - Based on Shuttle Entry Air Data System (SEADS)
  - Supports aerodynamic and atmospheric science objectives
- Sensor Support Electronics (SSE)
  - Electronics box that conditions sensor signals and provides power to MISP and MEADS



MISP



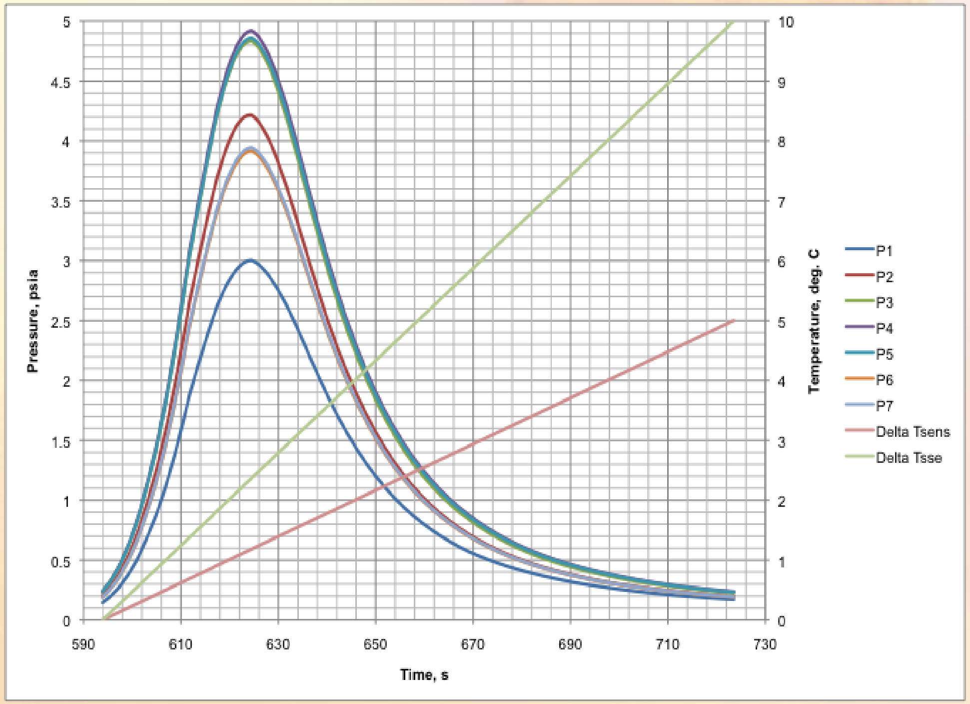
MEADS Pressure Transducer



SSE

Pressure Measurement System

- Components of the pressure measurement system: seven (7) MEADS pressure transducers, SSE
- <u>Pressure Measurement System Science Objectives:</u>
  - Estimate flight parameters from measured pressures
  - Improve atmospheric models (density) for Earth-based computational simulations
- Defendable uncertainty in estimated flight parameters rely on adequate measurement system characterization over extreme environmental conditions



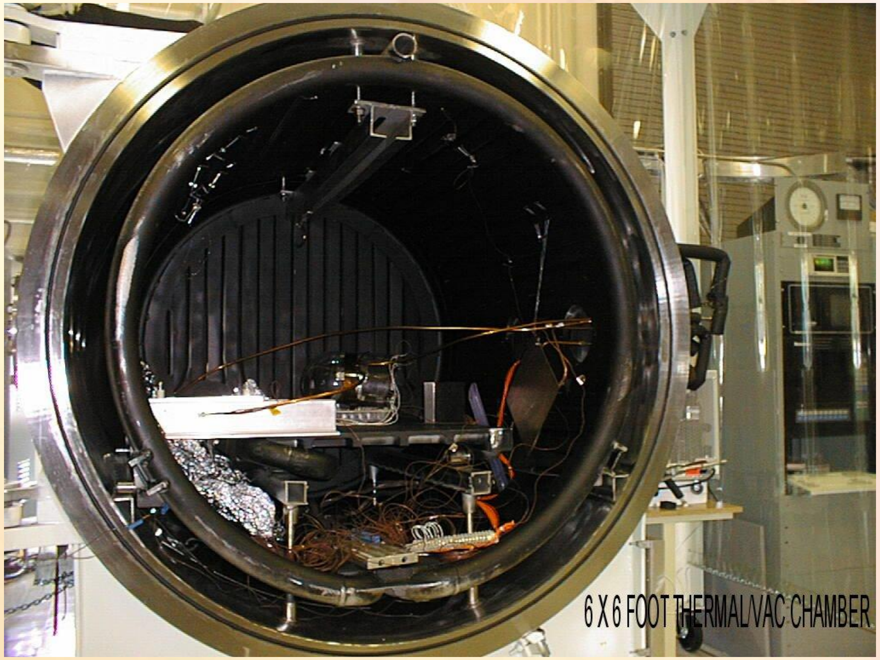
- <u>Pressure Measurement System Characterization Challenges:</u>
  - Pressure varies across port locations on the heatshield; temperatures vary between the SSE and pressure transducer locations; pressure and temperature vary with time during reentry
  - Possible Operational Ranges: 0.00 to 5.00 psia (Pressure), -120 to -60 deg. C (Transducer Temperature), -20 to 55 deg. C (SSE Temperature)
  - Large temperature ranges represent the uncertainty in the *start* temperatures (i.e. transducer temperature can start anywhere in the range of -120 to -60 deg. C with an expected change of 10 deg. C over the entry)

Pressure Measurement System Characterization - I

- Objective: Adequate measurement system characterization (calibration) over extreme environments; deliverables include
  - Mathematical model to estimate flight pressures
  - Uncertainty estimates throughout the flight trajectory
    - Total measurement uncertainty goal of 1 percent of reading through the range of 0.12 to 5.00 psia
- Utilized response surface techniques to provide a robust, defendable system characterization
  - RSM-based calibrations have been performed at NASA LaRC since 1999 (force balance applications)
  - Nontraditional use of RSM: not interested in system optimization; deliverables are measurement system knowledge (mathematical model and uncertainties)
  - Certain experimental design properties are important to providing a robust mathematical model that can be applied confidently to flight data
- Experimental Design Development
  - Mathematical model based on second-order Taylor series expansion of three factors
  - Replication included to estimate the pure experimental error in the measurement system (one metric for comparison of transducers)
  - Prediction variance properties of the design translate to total measurement uncertainty of the system

Pressure Measurement System Characterization - II

- NASA LaRC 6' x 6' Thermal Vacuum Facility
  - Provides the necessary testing conditions to characterize the pressure measurement system based on possible environmental conditions
  - Limitations of the Facility
    - The pressure measure system can stabilize with temperature within 2 hours and with pressure within 1 minute
    - Restrict the randomization of temperature to improve the experimental efficiency (split-plot)
      - Temperature combination is set and held constant while the pressure levels are varied



- Impact of Restricted Randomization
  - Since temperature is held constant while a pressure sequence is executed, there is a degree of correlation among the points; however different temperature combinations are independent
  - Require some advanced technique to perform the analysis which accounts for the restricted randomization
    - Restricted maximum likelihood (REML)
- Statistical calibration problem: develop forward regression model and invert to solve for estimated parameter

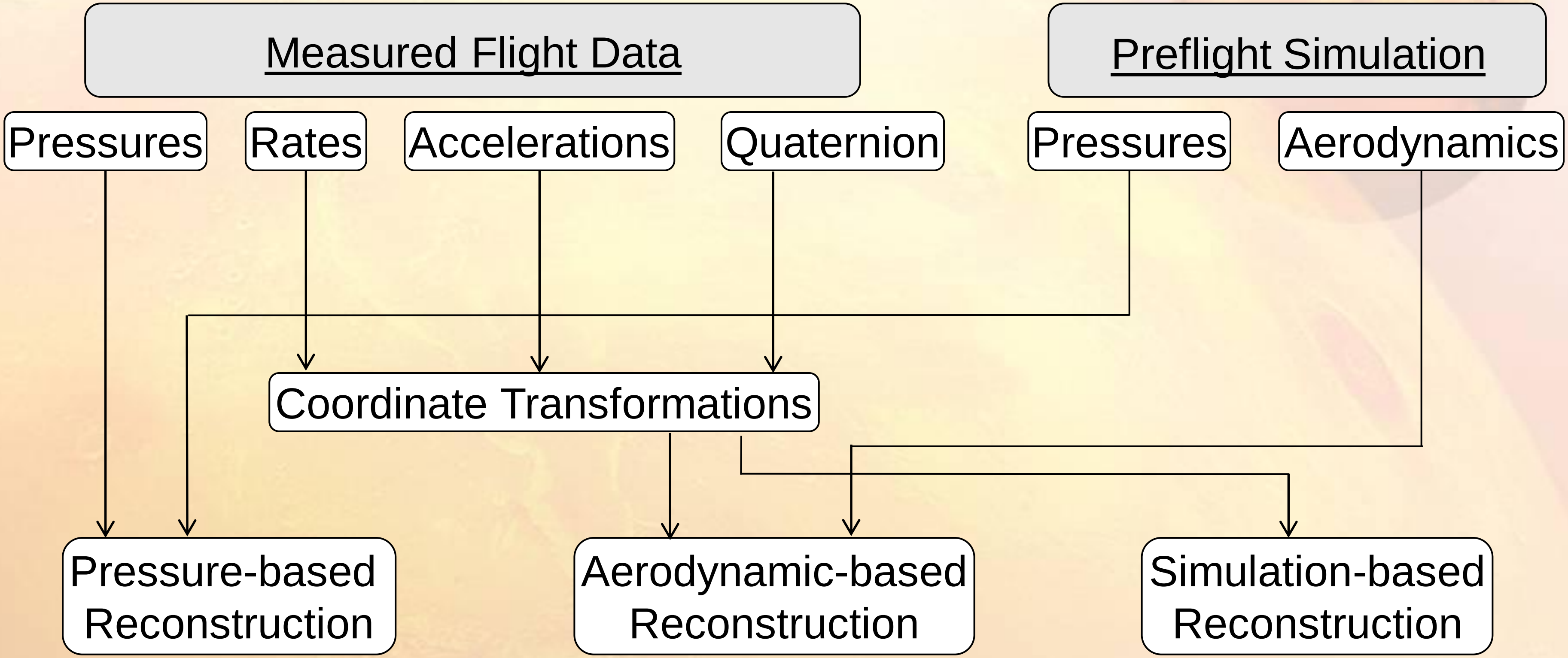
$$V = f\left(P, T_{\text{sens}}, T_{\text{SSE}}\right) \qquad \Rightarrow \qquad P = f\left(V, T_{\text{sens}}, T_{\text{SSE}}\right)$$

Pressure Measurement System Characterization Summary

<u>Methodology and Tools Overview:</u>

1. DOE/RSM:
   - Development of the experimental design to support objectives
   - Accommodate practical restrictions (restricted randomization)
   - Simulated entry trajectories: best attempt to simulate expected flight conditions on the ground
2. Transducer Repeatability:
   - Pure error estimation
3. Forward Regression Modeling:
   - REML: variance component estimation and model reduction
4. Model Inversion for Flight Data Reduction:
   - Estimate pressure from signal response and temperatures
   - Two (2) methods available: direct or iterative
5. Inverse Prediction Uncertainty:
   - Delta method used to calculate the variance in the estimated pressure
6. In-flight Zero Algorithm:
   - Exploit known, physical information prior to entry (hard vacuum in space)

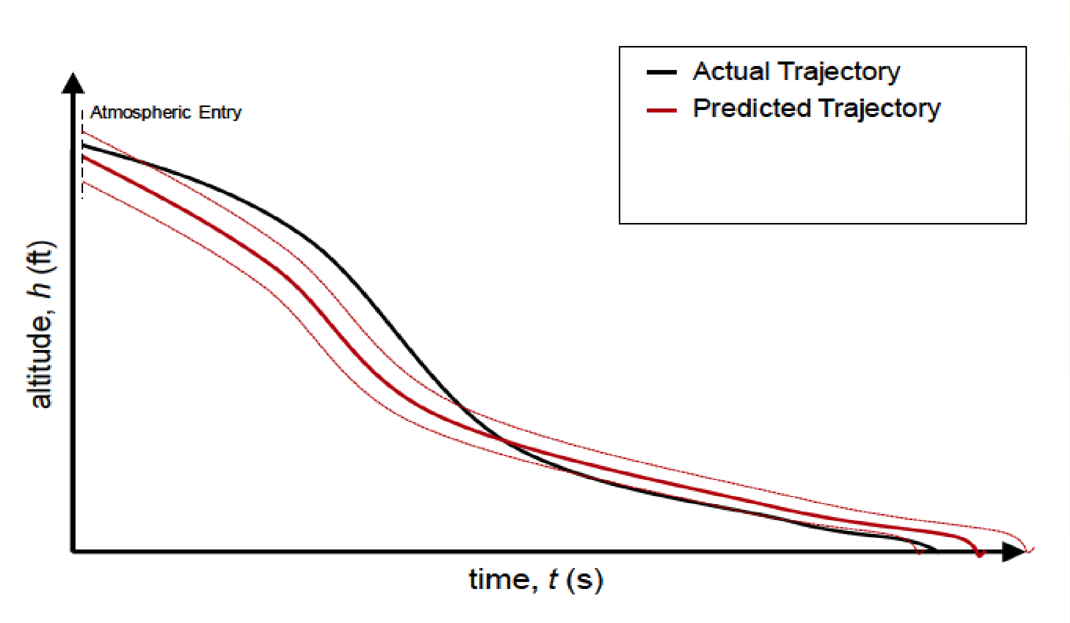
Post-Flight Trajectory Reconstruction



- Three (3) quasi-independent methods to reconstruct the entry trajectory
  - Ideally all the reconstructed trajectories match
  - Historically discrepancies have existed in the reconstructed trajectories which have not been systematically resolved
- System-level approach to quantifying uncertainties has not been emphasized for previous reconstruction efforts
- Emphasize more strategic approach to help meet objectives: Monte Carlo vs. Designed Experiment

Reconstruction Reconciliation

- Research effort with Georgia Tech (Jason Corman and Brian German) under the funding auspices of the NASA Graduate Student Research Program (GSRP)
- Focused on the development of a general approach to determine the causes in differences between various trajectory reconstruction methods
  - Reconstructed trajectories do not need to match exactly
  - Uncertainty intervals of the trajectories to overlap
- Developed a simplified, 2 degree-of-freedom (DOF) simulation tool to study trends and sensitivities
  - Identified and tested techniques to help mitigate discrepancies in basic reconstruction methods
  - Apply the approach to the actual 6 DOF simulation tool used during reconstruction



Pressure-based Trajectory Reconstruction

- Combines actual flight pressure data and preflight simulation data to estimate vehicle orientation, freestream dynamic pressure, and Mach number
- Preflight simulation data based on computational fluid dynamics (CFD) with limited anchoring to experimental data
  - Experimental facilities available are not relevant to expected flight environment
  - Higher confidence in computational results in certain regions of the trajectory
- Uncertainty requirements for estimated flight parameters (angle of attack, angle of sideslip, Mach number, dynamic pressure) specified at project's inception
- Uncertainty requirements were determined assuming perfect (no uncertainty) preflight simulation data
  - Investment of resources focused on minimizing the uncertainty in the pressure measurement uncertainty
- Total uncertainty is the root sum squared (RSS) of the pressure measurement system uncertainty and the preflight simulation uncertainty
  - Pressure Measurement System Uncertainty ~ ± 0.25 percent (actual)
  - Preflight Simulation Uncertainty ~ ± 5 percent

$$\text{Total Uncertainty} = \sqrt{(0.25)^2 + (5)^2} \approx 5$$

Summary

- Development of more robust EDL technologies rely on capabilities of Earth-based modeling capabilities
- Contributions to MEDLI:
  - Pressure Measurement System Characterization
    - Mathematical modeling of the pressure measurement system
    - Defendable uncertainty quantification of the system
  - System-level Approach to Preflight Trajectory Reconstruction
    - Subsystem uncertainty quantification
    - General approach to reconstruction reconciliation
- Lessons Learned from MEDLI:
  - Traceable objectives to support future missions
    - Development of technologies
    - Decision-making process
  - Investment of resources to support objectives
    - Division between computational and physical experiments
  - Focus on knowledge and learning rather than what needs to be done or built
    - De-emphasizes data quantity

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