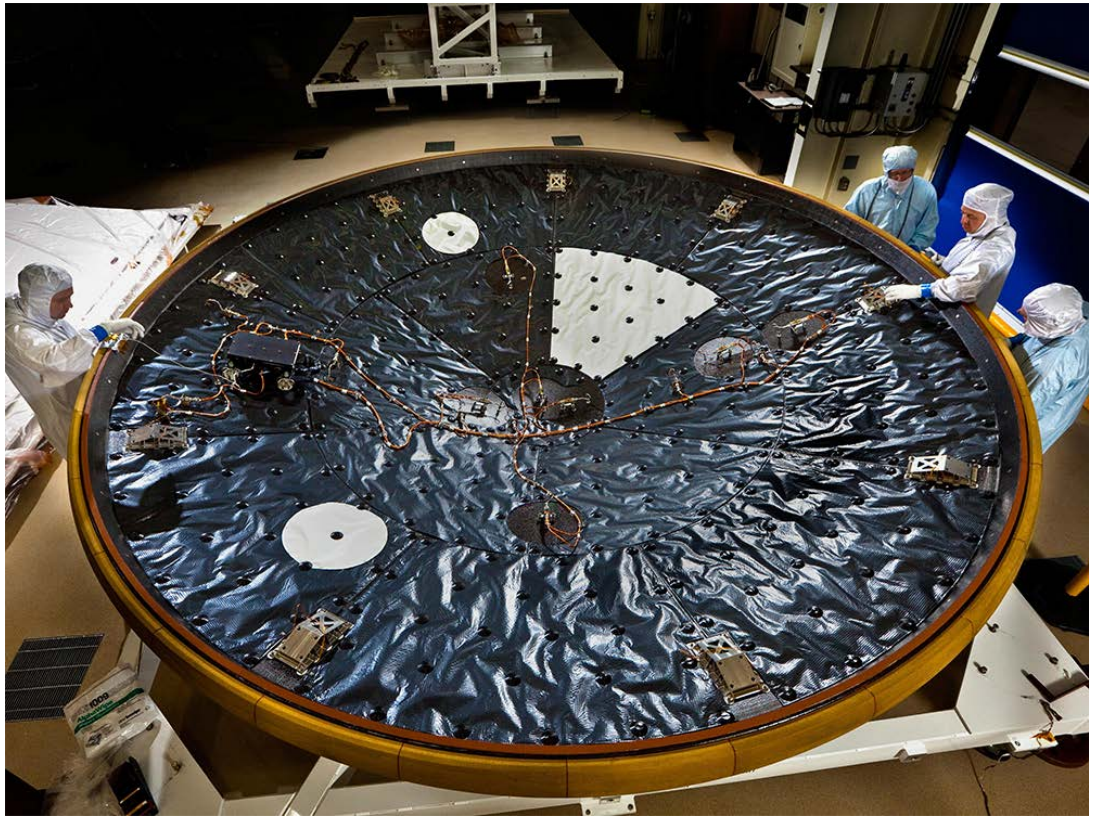
Atmospheric Reconstruction Method applied to MSL Heat Shield Pressure Data



instrumented MSL heat shield (NASA/Lockheed Martin)

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Köln, Germany
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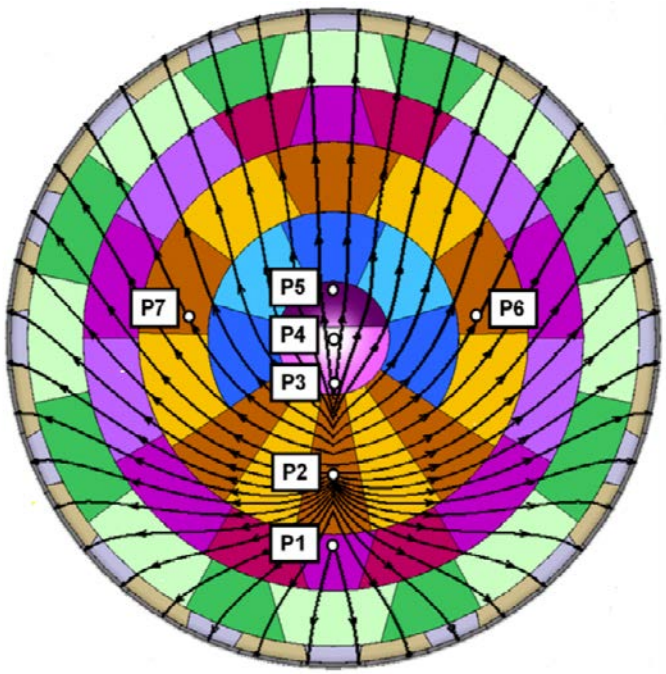
Past Work on MSL Forebody Pressure Data (MEADS)

- Successful reconstruction of atmospheric profiles [1,2,3] flow angles, and aerodynamic coefficients [4]
- Approximate wind estimation by blending pressure and IMU data [5]
- By fitting all 7 pressure measurements to forebody CFD predictions [6,7]



MSL heat shield pressure sensors [1]

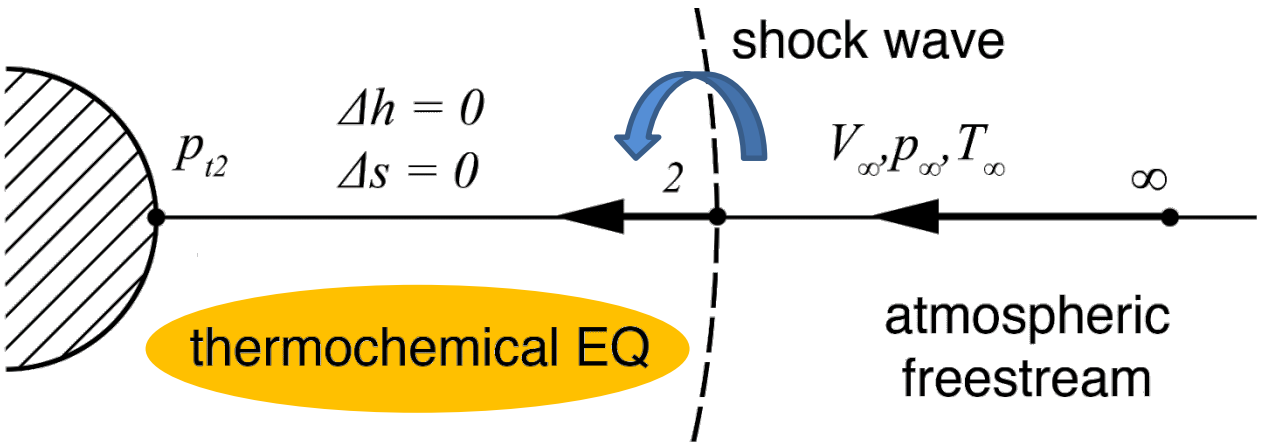
Pitot Reconstruction Method

- **Use only stagnation pressure** similarly to e.g. pitot probes in wind tunnel testing [8,9]

$$C_{pt2} = \frac{p_{t2} - p_\infty}{q_\infty} \quad \text{and} \quad \rho_\infty = \frac{2q_\infty}{V_\infty^2}$$

- Estimate C_{pt2} with simple 1-D inviscid flow model
- Sufficiently accurate atmospheric reconstruction?
- Requires independent flight velocity V_∞ e.g. IMU

Stagnation Flow Model



$$C_{pt2} = \frac{p_{t2} - p_\infty}{q_\infty}$$

$$C_{pt2}\left(V_\infty, p_\infty, T_\infty\right)$$

shock conservation equations

$$\rho_2 V_2 = \rho_\infty V_\infty$$

$$\rho_2 V_2^2 + p_2 = \rho_\infty V_\infty^2 + p_\infty$$

$$\left(\rho_2 E_2 + p_2\right) V_2 = \left(\rho_\infty E_\infty + p_\infty\right) V_\infty$$

Newton solver

solve system for $CO_2/N_2/Ar$ gas mixture [10]

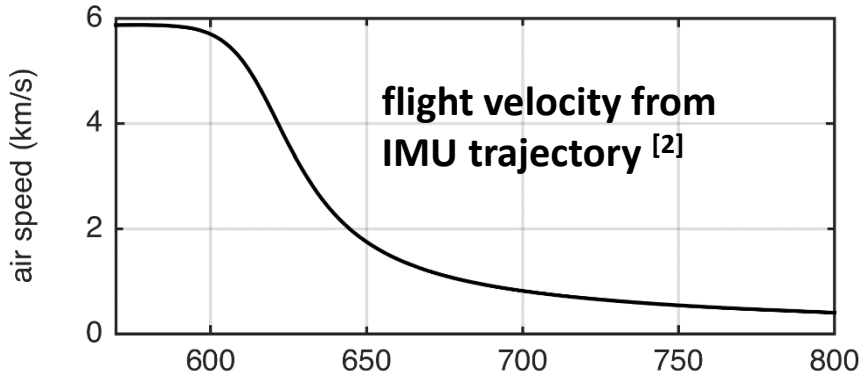
$$p(\rho, T) = \sum_i \frac{y_i}{M_i} \rho_i T R$$

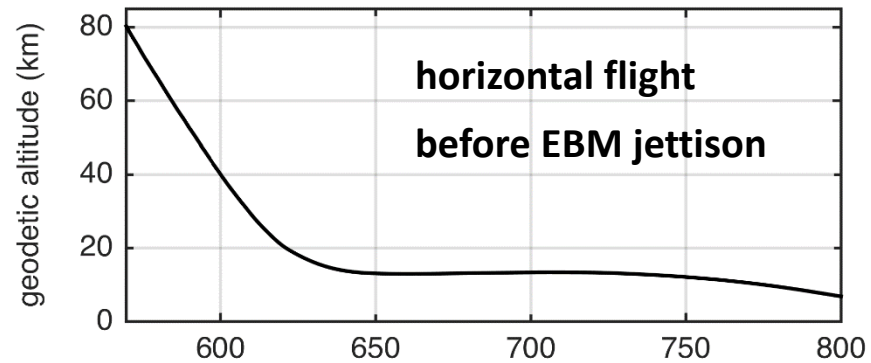
$$E(T) = \sum_i y_i e_i(T) + \frac{V^2}{2}$$

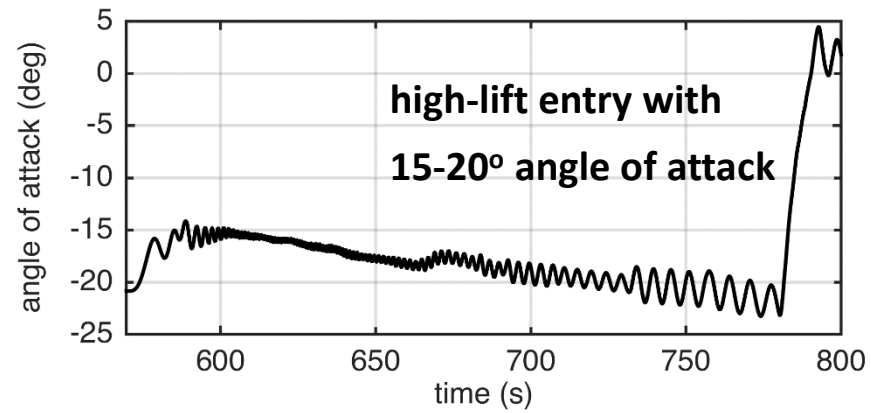
$$h(p, T) = \sum_i y_i h_i(T)$$

$$s(p, T) = \frac{1}{\rho} \sum_i \rho_i s_i(p, T)$$

MSL Entry Trajectory







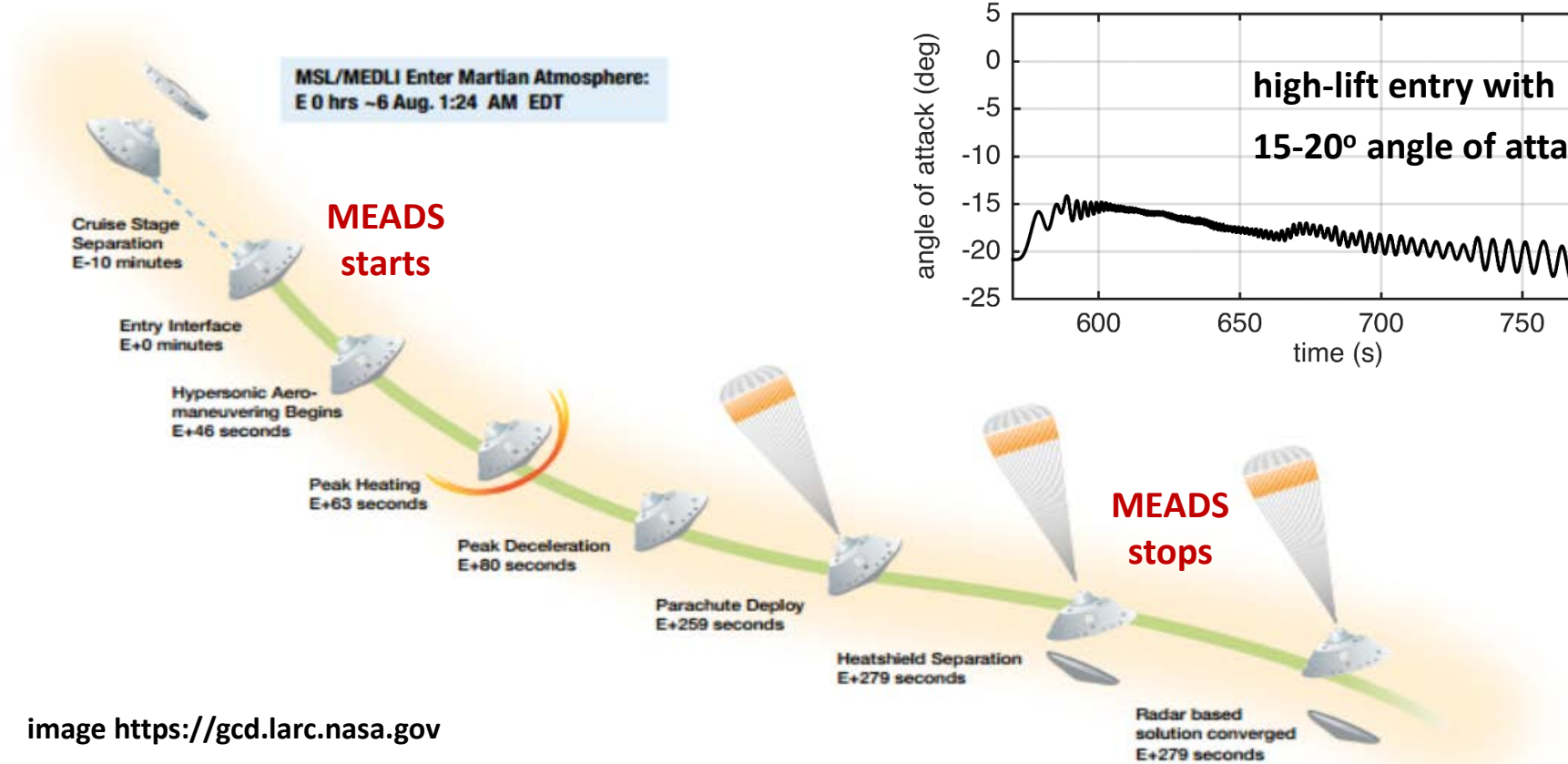
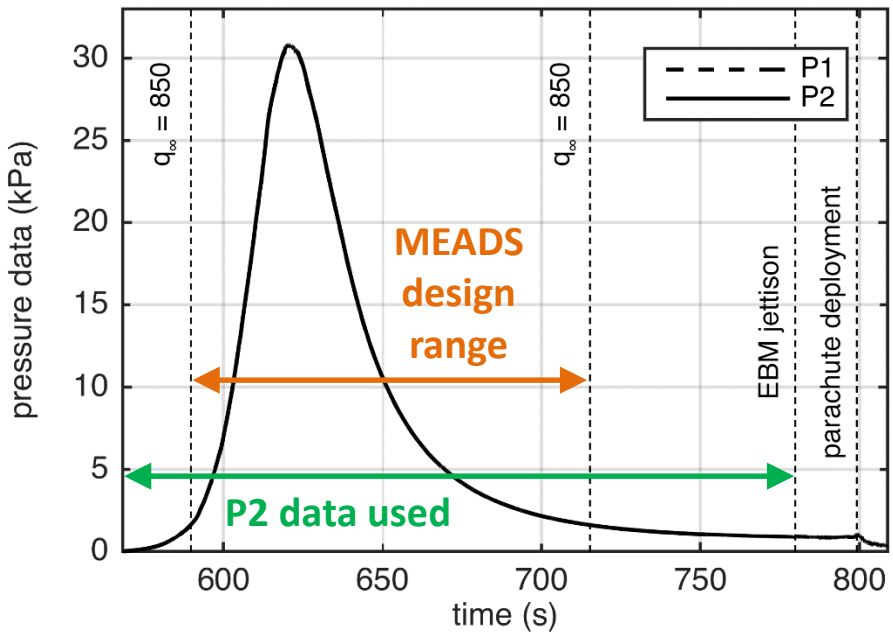
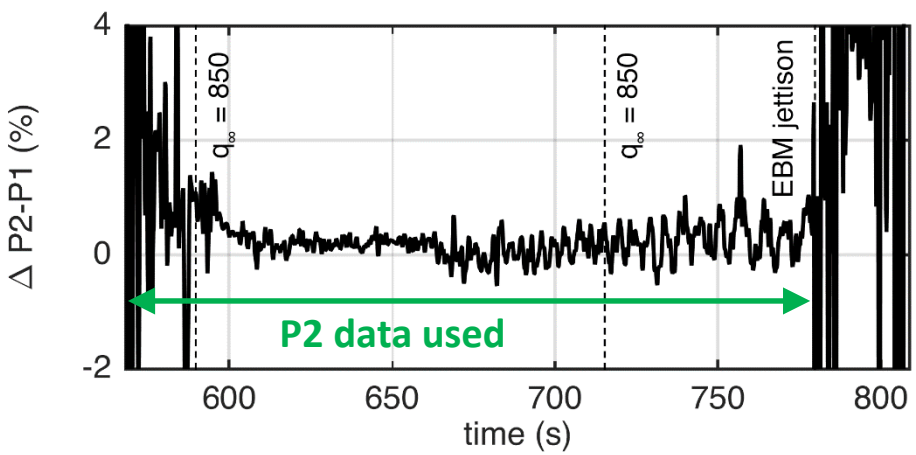


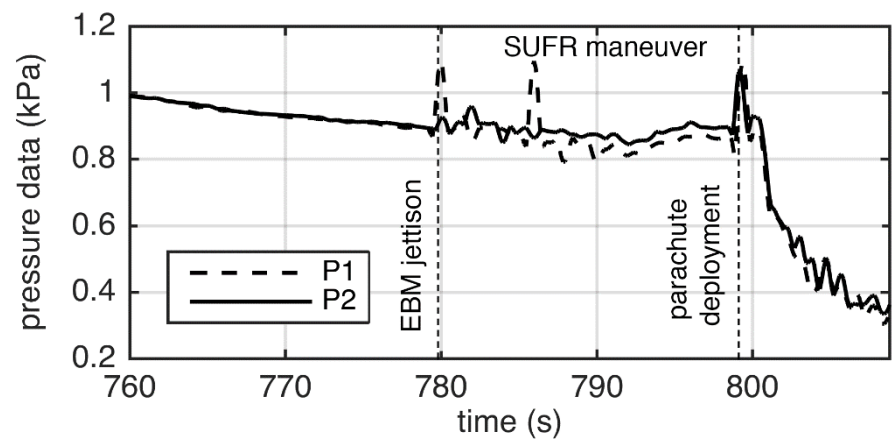
image https://gcd.larc.nasa.gov



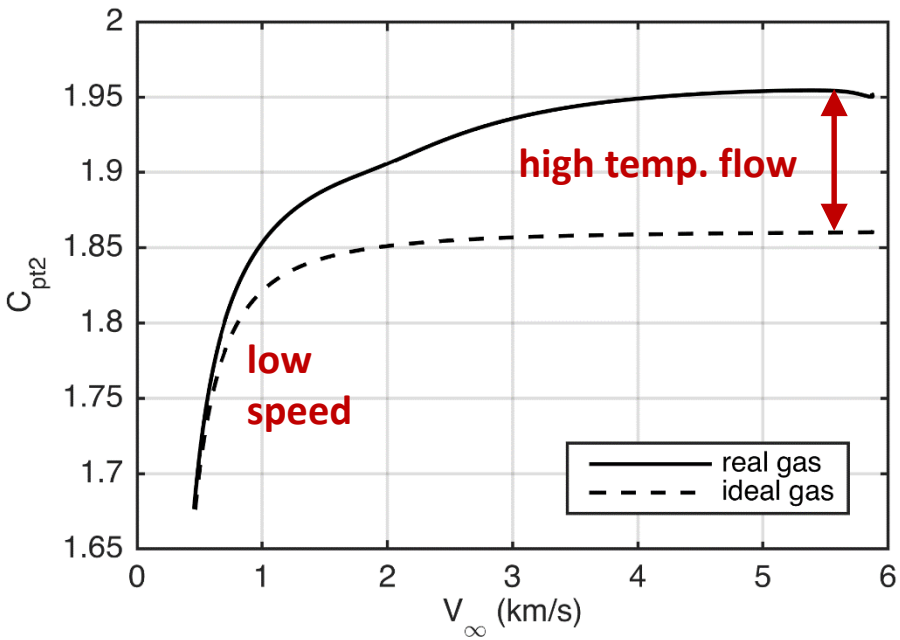
Stagnation pressure from port P2

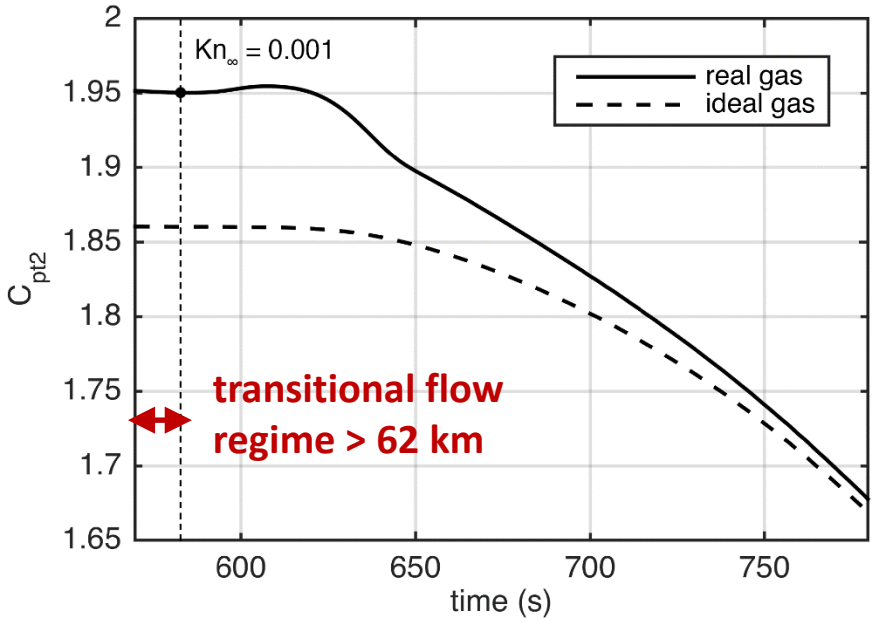
- tabulated pressure data [11]
- pressure P1 < P2 ≈ pt2 to ~ 0.3%
- use all P2 data up to EBM jettison
- scale factor correction [12]
- smoothed with 1.5 s window





Stagnation Pressure Coefficients

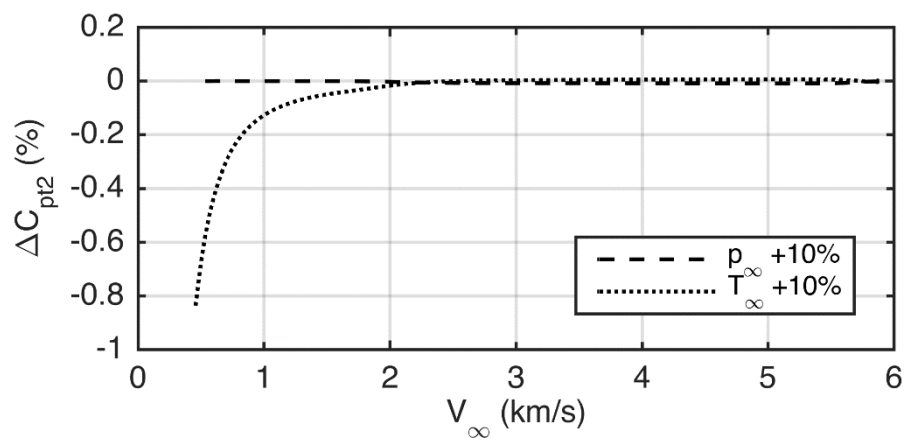




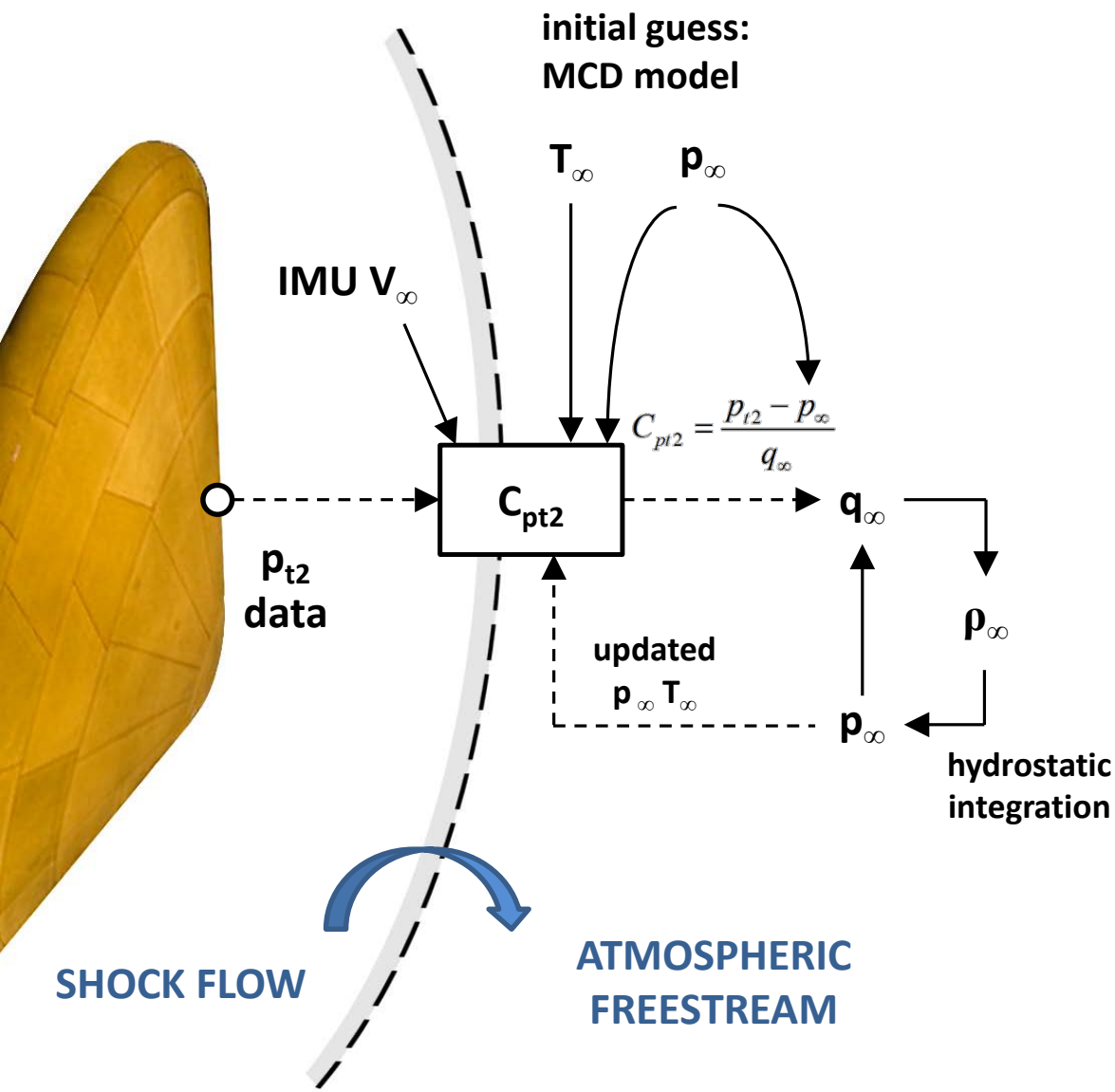
Pressure coefficient estimation:

$$C_{pt2}\left(V_\infty, p_\infty, T_\infty\right)$$

- V_∞ from IMU trajectory [2]
- p_∞ and T_∞ not known in advance: used Mars Climate Model (MCD) [13]
- Transitional flow above 60 km?
- C_{pt2} mainly depends on V_∞ also slightly sensitive to T_∞



Pitot Reconstruction Method



step 1:
initial MCD

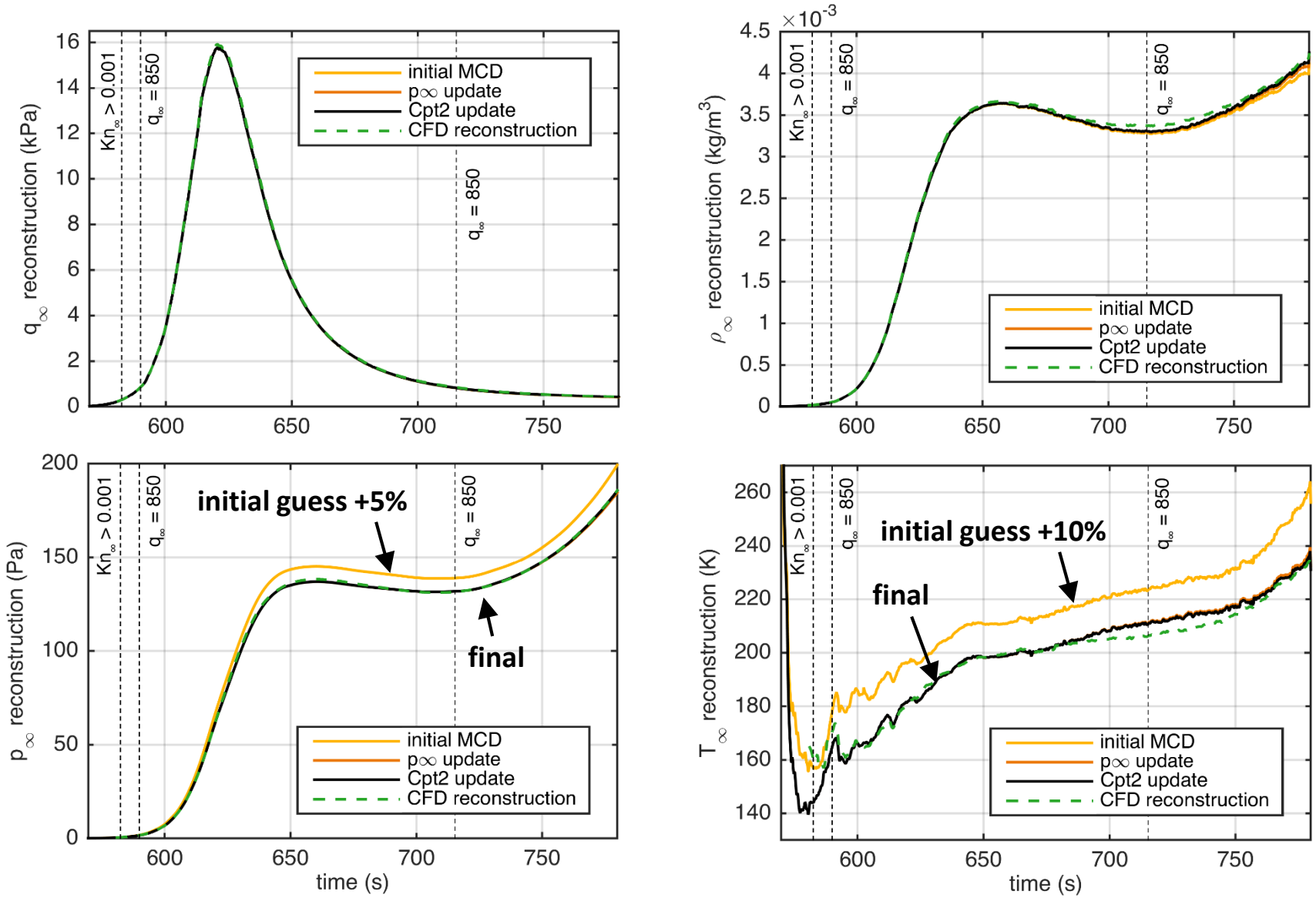
$$p_\infty = p_0 - \int g \rho_\infty dh$$

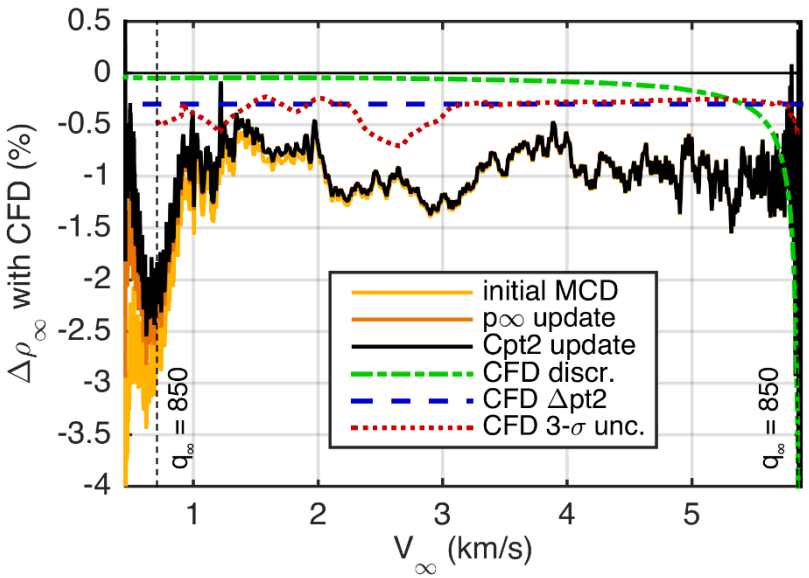
step 2:
p_∞ update

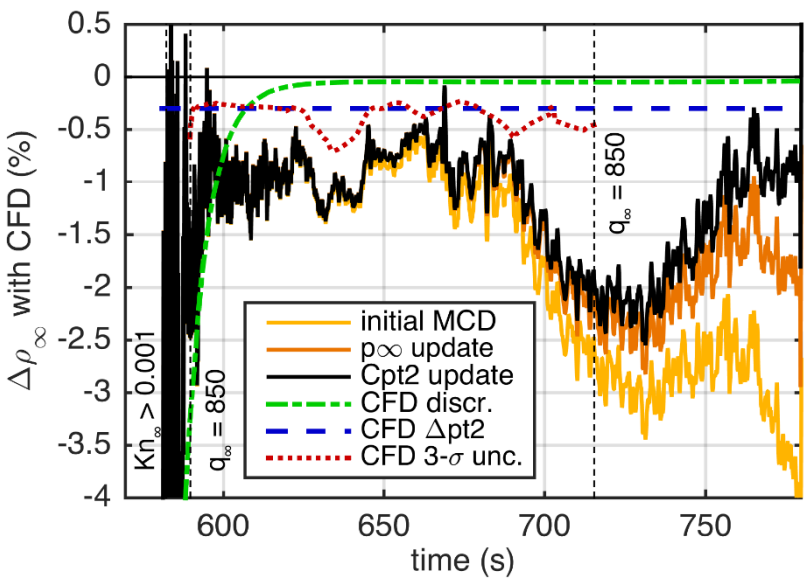
$$C_{pt2}(V_\infty, p_\infty, T_\infty)$$

step 3:
C_{pt2} update

Compare to independent results [1] that used CFD, all pressure ports, IMU velocity



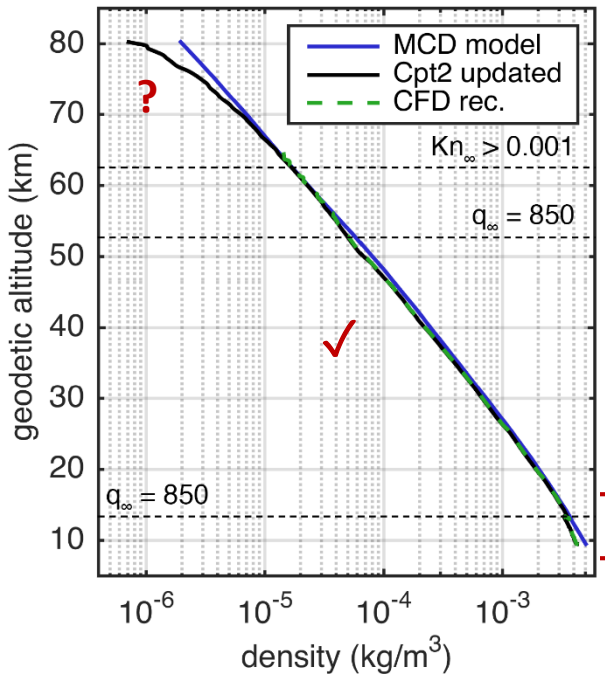


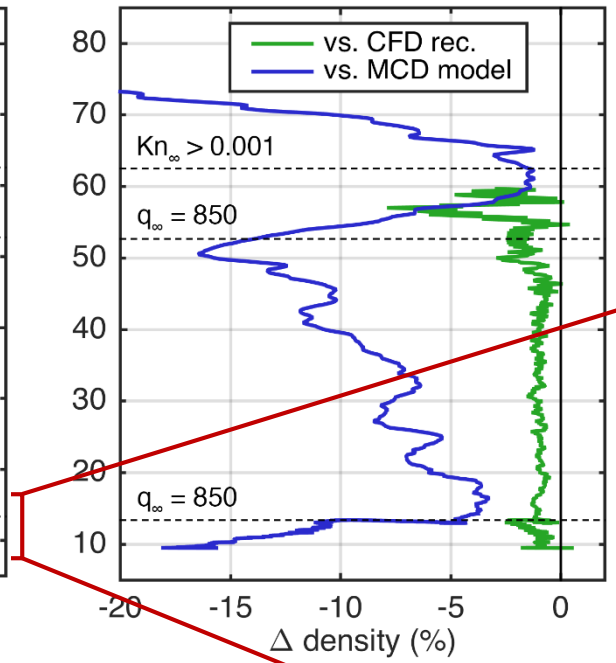


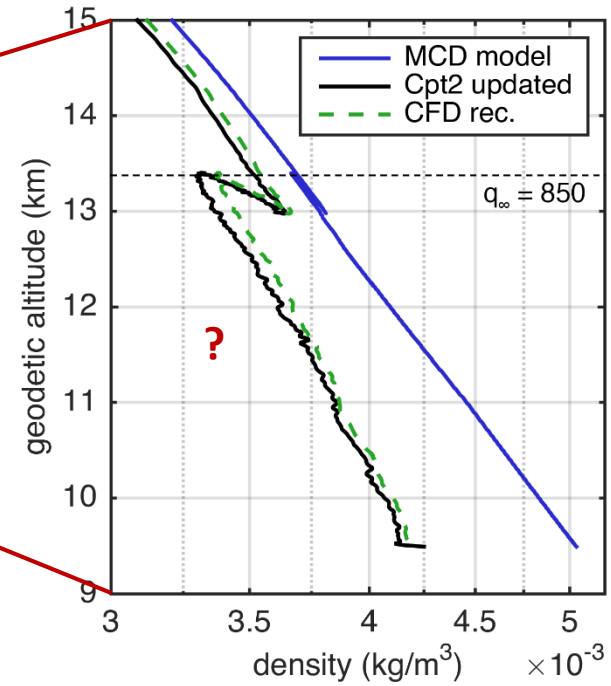
Comparison of reconstructed density

- CFD model uncertainty about 0.5% [14]
- Best match with CFD results ~ 1% in q_∞ > 850 Pa sensor design range
- Larger differences up to 2% for supersonic, horizontal flight
- Difficult to compare before 590 s or above 50 km altitude
- No comparison possible for transitional flow Kn_∞ 0.01-0.001

Final Atmospheric Profiles



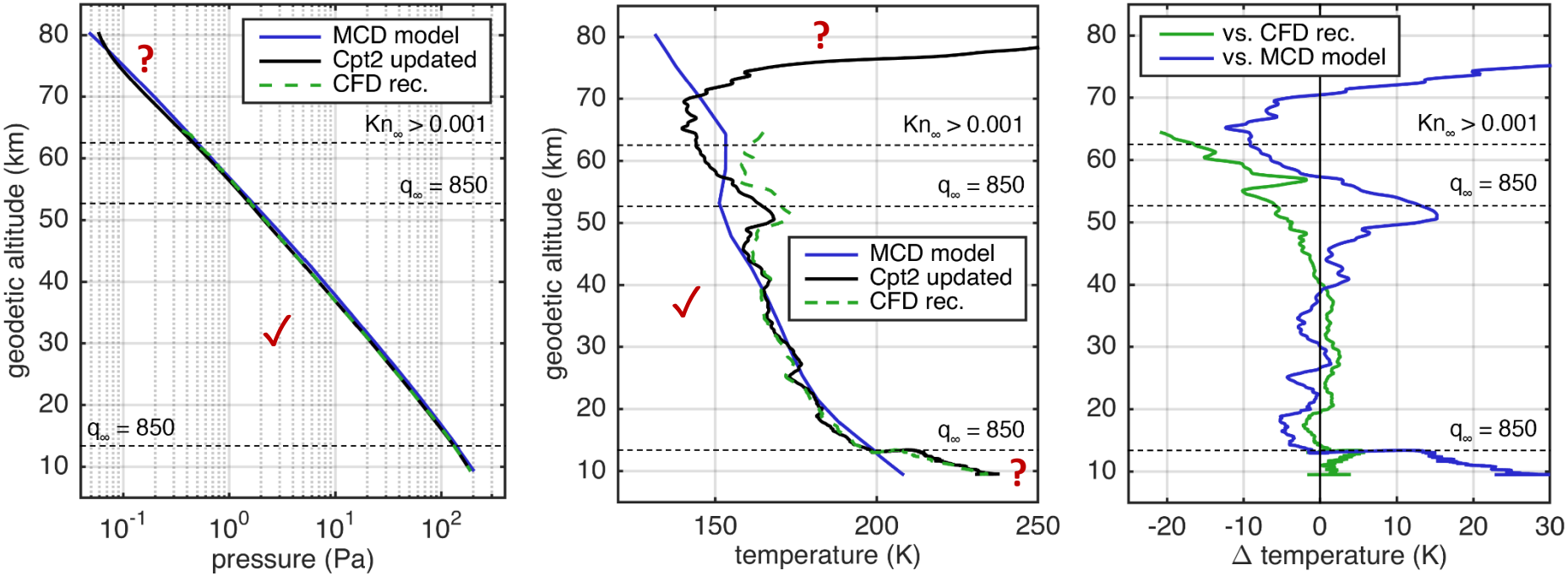




Density profile

- Match CFD 1-2% for altitudes below ~ 60 km
- Above 70 km: unrealistically low densities?
- Below 13 km: horizontal flight increases impact of unknown winds
  There was circumstantial evidence for tailwind ~20 m/s [1,2,3]

Final Atmospheric Profiles



Pressure & temperature profiles

- Match CFD below ~ 60 km
- Above 60 km: temperature too high → poor reconstruction temperature
- Below 13 km: unknown winds affect reconstruction

Conclusions

Pitot Reconstruction Method

- Simple inviscid equilibrium flow model (not vehicle specific)
- **Accurate reconstruction of ρ_∞, p_∞, and T_∞ between 60 and 13 km**
- Low velocity and horizontal flight increases sensitivity to winds [2,3]
- **Poor reconstruction above 60 km:**
  - Flow model incorrect near continuum flow limit?
  - Pressure sensors operating far below design range

  → **Directly compare flow model to CFD/DSMC (transitional to supersonic flow)**

Applications

- Efficient and accurate method for Mars EDL atmospheric reconstruction
- In-flight reconstruction with pre-calculated pressure coefficients
- ExoMars 2016 will measure stagnation pressure

References

[1] **2013, Karlgaard et al.**, “Mars Entry Atmospheric Data System Trajectory Reconstruction Algorithms and Flight Results”, AIAA 2013-0028.

[2] **2013, Karlgaard et al.**, “Mars Science Laboratory Entry, Descent, and Landing Trajectory and Atmosphere Reconstruction”, AAS 13-307.

[3] **2014, Chen et al.**, “Reconstruction of Atmospheric Properties from MSL Entry, Descent, and Landing”, J.S&R Vol.51/4, pp.1062-1075.

[4] **2014, Schoenenberger et al.**, “MEADS Trajectory and Atmosphere Reconstruction”, J.S&R Vol.51/4, pp.1076-1093.

[5] **2013, Dutta**, “Statistical Methods for Reconstruction of EDL Performance with Application to Vehicle Design”, PhD Thesis, Georgia Institute of Technology

[6] **2009, Schoenenberger et al.**, “Aerodynamic Challenges for the Mars Science Laboratory Entry, Descent and Landing”, AIAA Paper 2009-3914.

[7] **2012, Dyakonov et al.**, “Hypersonic and Supersonic Static Aerodynamics of Mars Science Laboratory Entry Vehicle”, AIAA Paper 2012-2999.

[8] **2007, zur Nieden & Olivier**, “Determination of Atmospheric Densities from Reentry Flight Data”, J.S&R Vol.44/2, pp.332-337.

[9] **2011, Van Hove**, “Free Stream Measurements and related Data Reduction Methods for the Longshot Hypersonic Wind Tunnel”, Report, von Karman Institute

[10] **2013, Scoggins**, “Development of MUTATION++: Multicomponent Thermodynamics And Transport properties for IONized gases library in C++”, Review of the VKI Doctoral Research, 2012-2013.

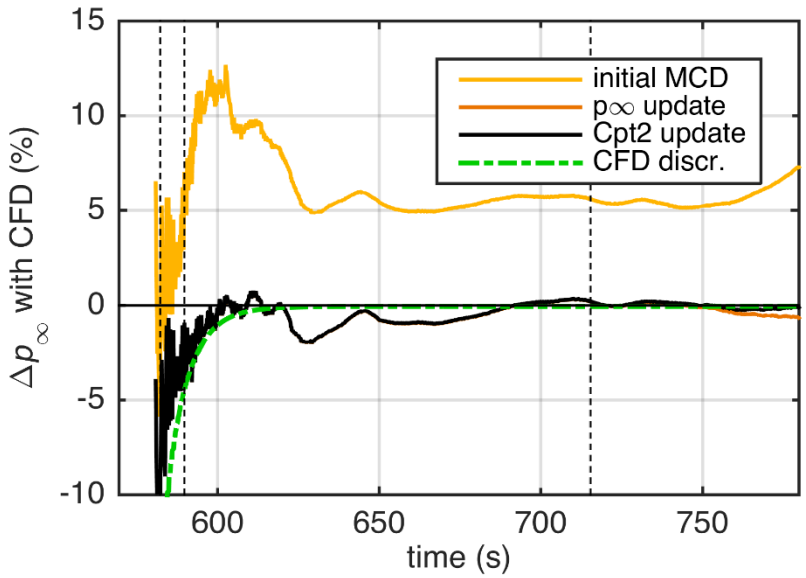
[11] **2014, Cheatwood et al.**, “Mars Science Laboratory (MSL) Entry, Descent, and Landing Instrumentation (MEDLI) - Complete Flight Data Set”, NASA/TM-2014-218533, Appendix A.

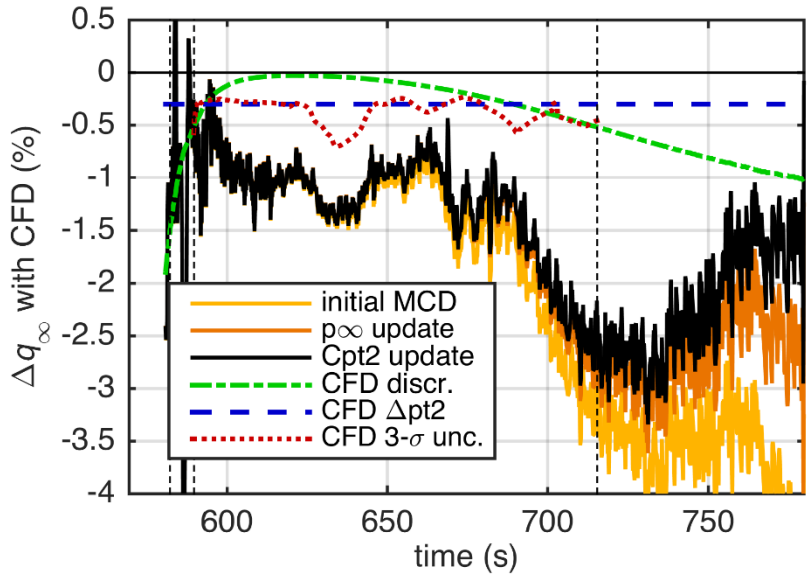
[12] **2014, Karlgaard & Kutty**, “MEADS Trajectory and Atmosphere Reconstruction”, J.S&R Vol.51/4, pp.1029-1047.

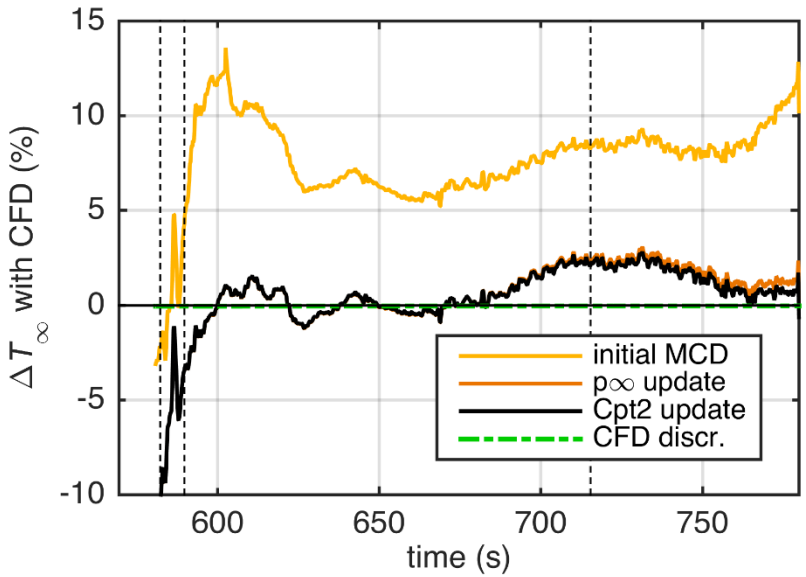
[13] **2008, F. Forget et al.**, “Modeling the Martian atmosphere with the LMD global climate model”, 3rd MOMA Workshop, Williamsburg, VA.

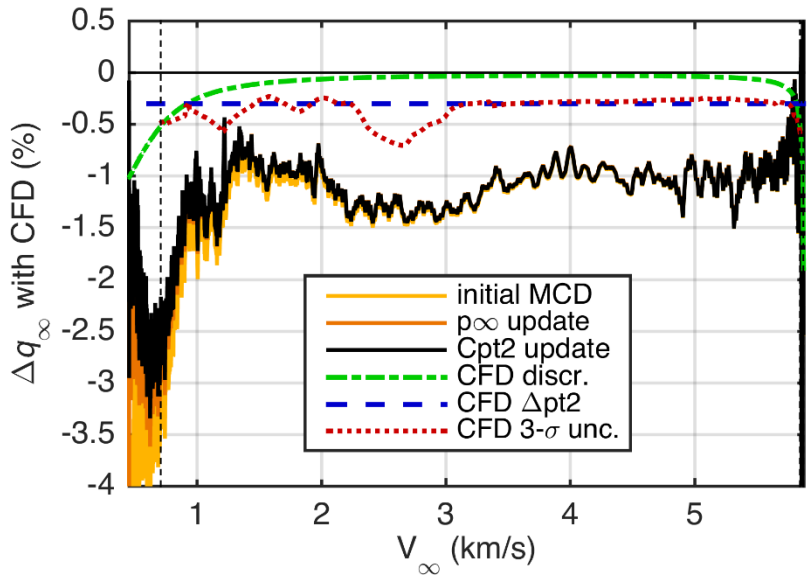
[14] **2014, Karlgaard et al.**, “Mars Entry Atmospheric Data System Modeling, Calibration, and Error Analysis”, NASA/TM-2014-218535

Appendix


initial MCD
p∞ update
Cpt2 update
CFD discr.
Δp∞ with CFD (%)
time (s)


initial MCD
p∞ update
Cpt2 update
CFD discr.
CFD Δpt2
CFD 3-σ unc.
Δq∞ with CFD (%)
time (s)


initial MCD
p∞ update
Cpt2 update
CFD discr.
ΔT∞ with CFD (%)
time (s)


initial MCD
p∞ update
Cpt2 update
CFD discr.
CFD Δpt2
CFD 3-σ unc.
Δq∞ with CFD (%)
V∞ (km/s)