

Results from the Phoenix Atmospheric Structure Experiment

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Context – Recent Scientific Discoveries at Mars

- MRO and MEX cameras give images and topographic maps with <1 m pixels for surface geology studies
- MRO and MEX radars probe sub-surface structure of volcanic terrains and polar caps
- MRO IR sounder continuing and improving climate monitoring begun by MGS
- Phoenix performed first landed studies of polar regions, including confirming Odyssey orbital detections of buried ice and controversial suggestion of liquid droplets
- Phoenix weather station gave millions of p/T data points and the first lidar studies of clouds and precipitation
- MAVEN will launch in 2013 to study upper atmosphere and escaping water – Aim is to understand history of climate on Mars

Context – Recent Cooperative Operations at Mars

- Communications
 - Orbiters like Odyssey and MRO relay large amount of housekeeping and science data from landers like Opportunity and Phoenix
 - Orbiters provide “eyes” and “ears” during EDL
- Navigation
 - Orbital remote sensing of landing sites support rover operations
- Planning
 - Orbital remote sensing assesses science and engineering characteristics of potential landing sites
 - Orbital and landed discoveries stimulate subsequent landed and orbital missions
- Scientific synergies
 - Orbiters provide global-scale context and regional-scale targeted mapping
 - Landers provide in situ ground truth at local and micro-scales

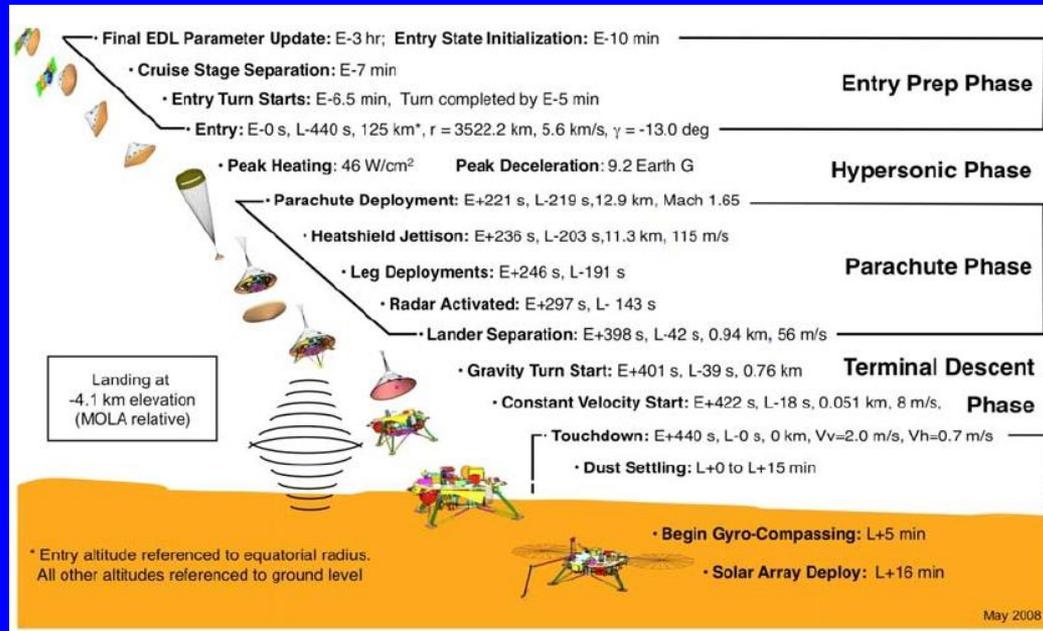
Outline

- Overview of trajectory and atmospheric structure reconstruction for Phoenix
- Highlight selected aspects of Phoenix reconstruction that offer lessons for future missions
- Demonstration of real-time reconstruction technique using direct-to-Earth radio link (Opportunity EDL)

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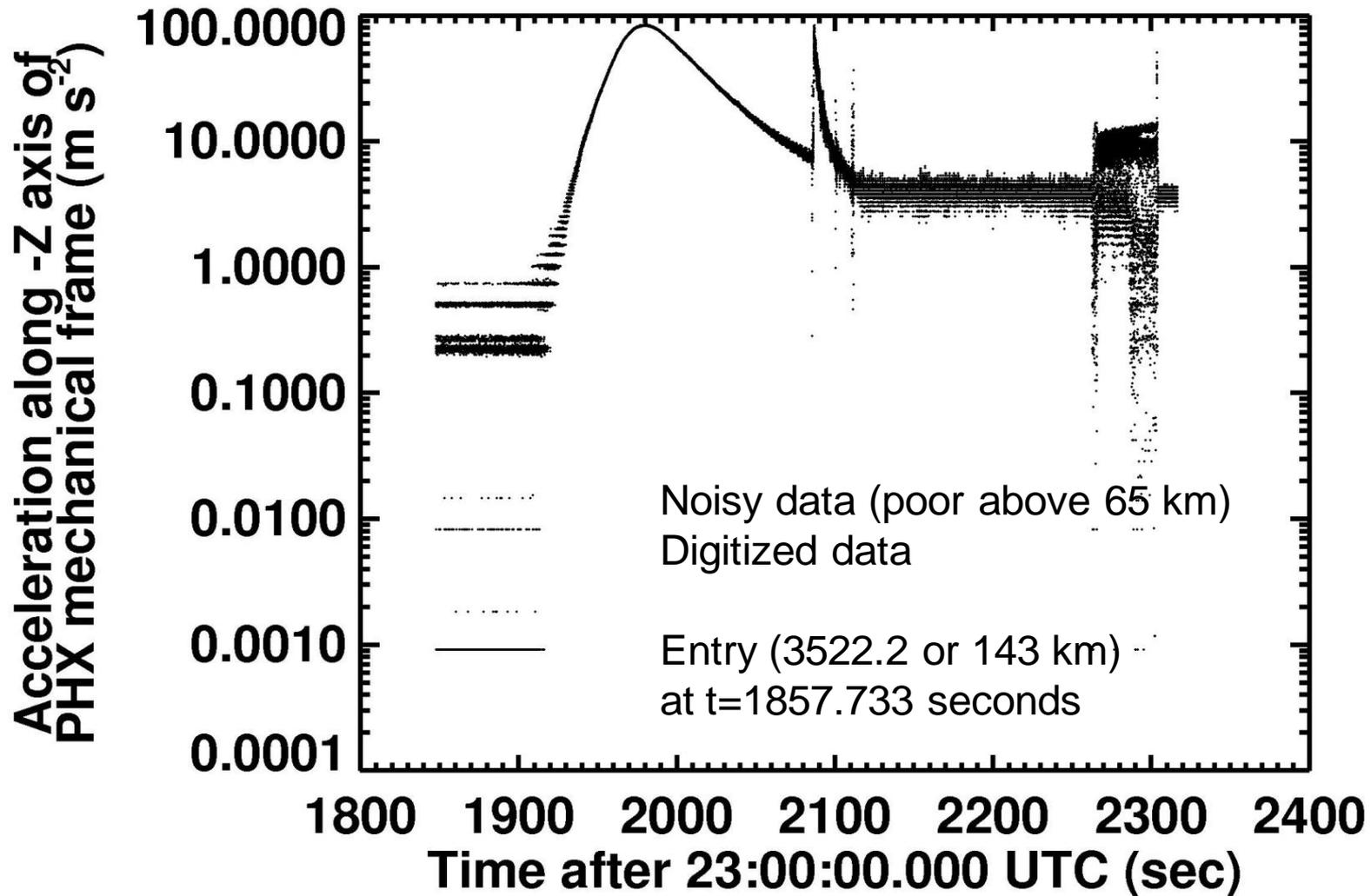
Phoenix atmospheric entry



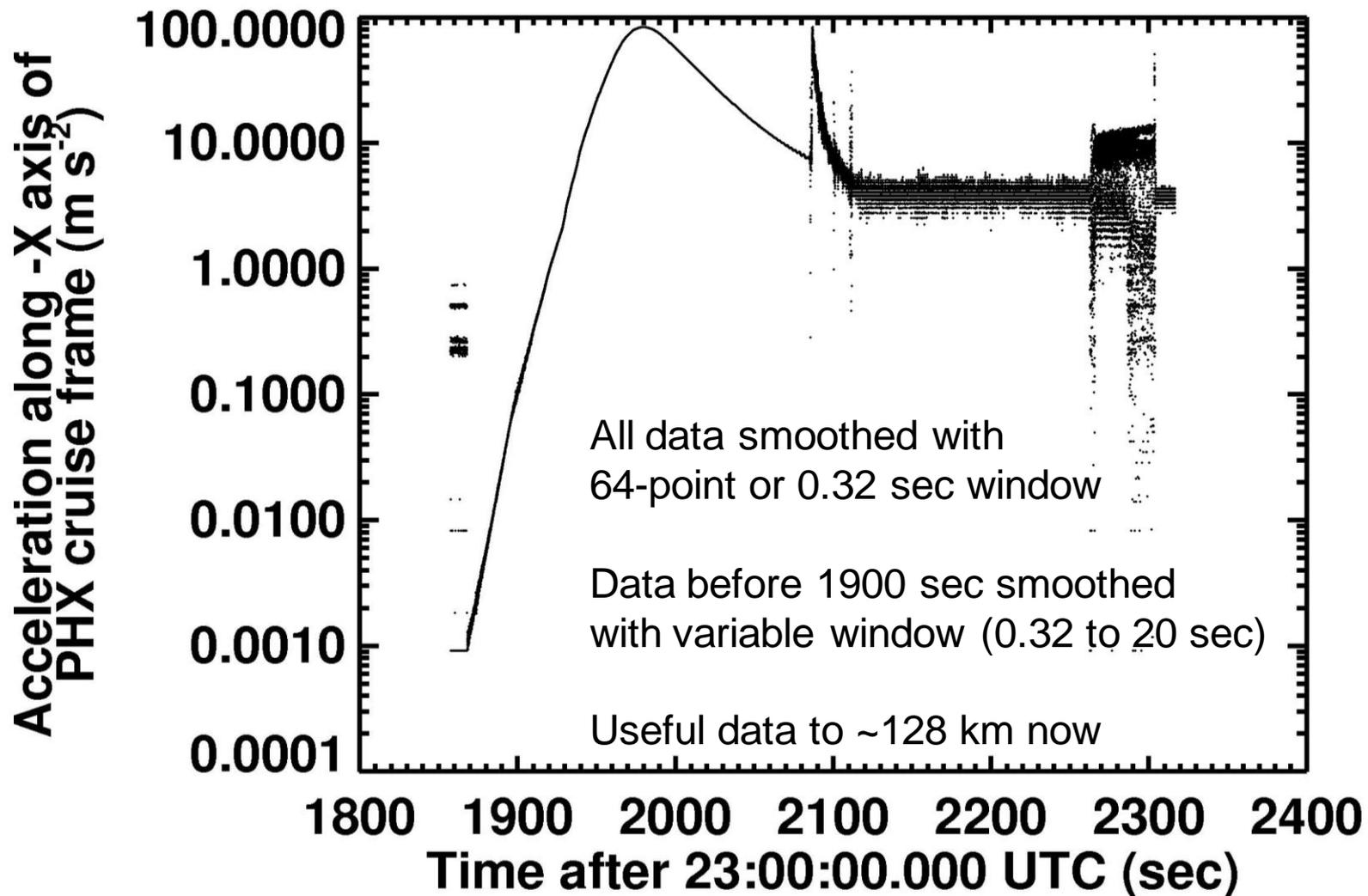
JPL figure

- 25 May 2008
- Landing site at
 - 68.2N, 234.3E
 - -4.1 km (MOLA)
- Ls=77, LST ~16:30
- Ballistic entry with many similarities to Pathfinder and MER
- Accelerometers and gyroscopes on board
- IMU specifications, location, etc, etc fixed without scientific input
- 200 Hz data (good), but noisy (bad)

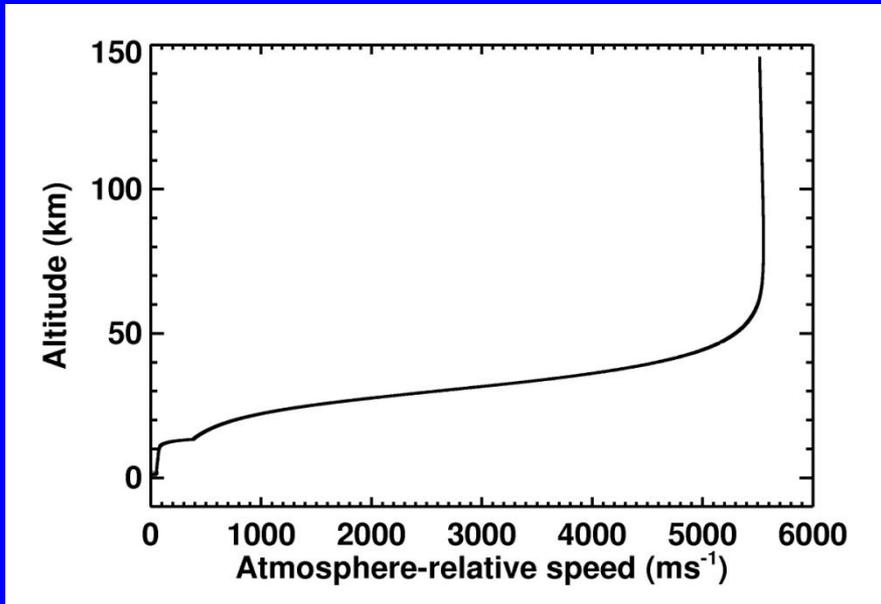
200 Hz accelerations



Smoothed accelerations



Reconstructed trajectory

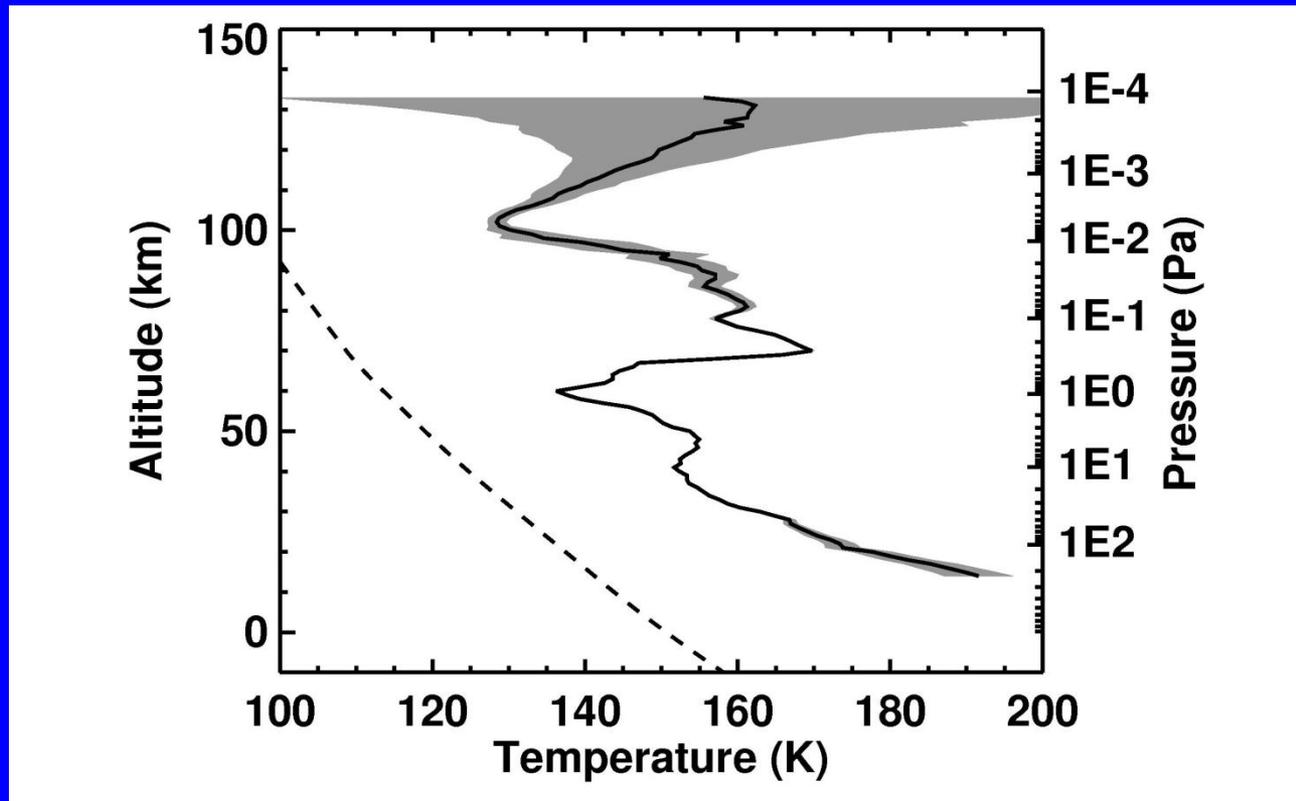


Reconstruction process essentially same as used for Spirit and Opportunity, with exception of gyroscope data

5600 m/s to 6.1+/-3.6 m/s
with design value of “few m/s”!

- Attitude found directly using gyroscopes, angle of attack is well behaved
- Parachute deployment at 13.5 km and 391 m/s (Mach 1.7)
- First ground contact at 1.10 +/- 1.49 km above ground level and 6.1 +/- 3.6 m/s

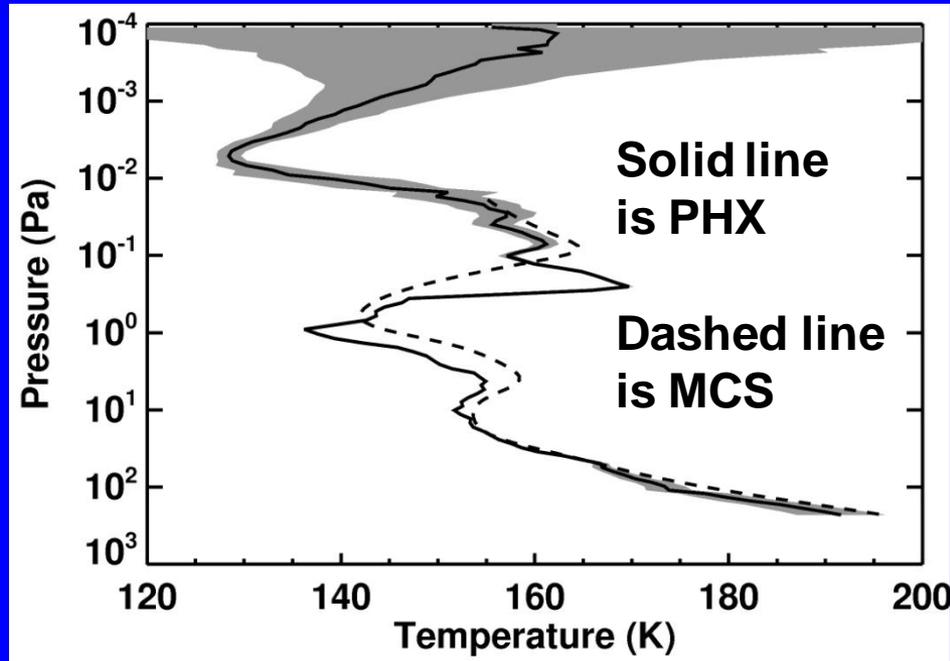
Reconstructed thermal structure



Reconstruction process essentially same as used for Spirit and Opportunity, but with updated aerodynamics and known attitude

- Much warmer than CO₂ condensation curve
- Mesopause
- Tides
- Gravity waves

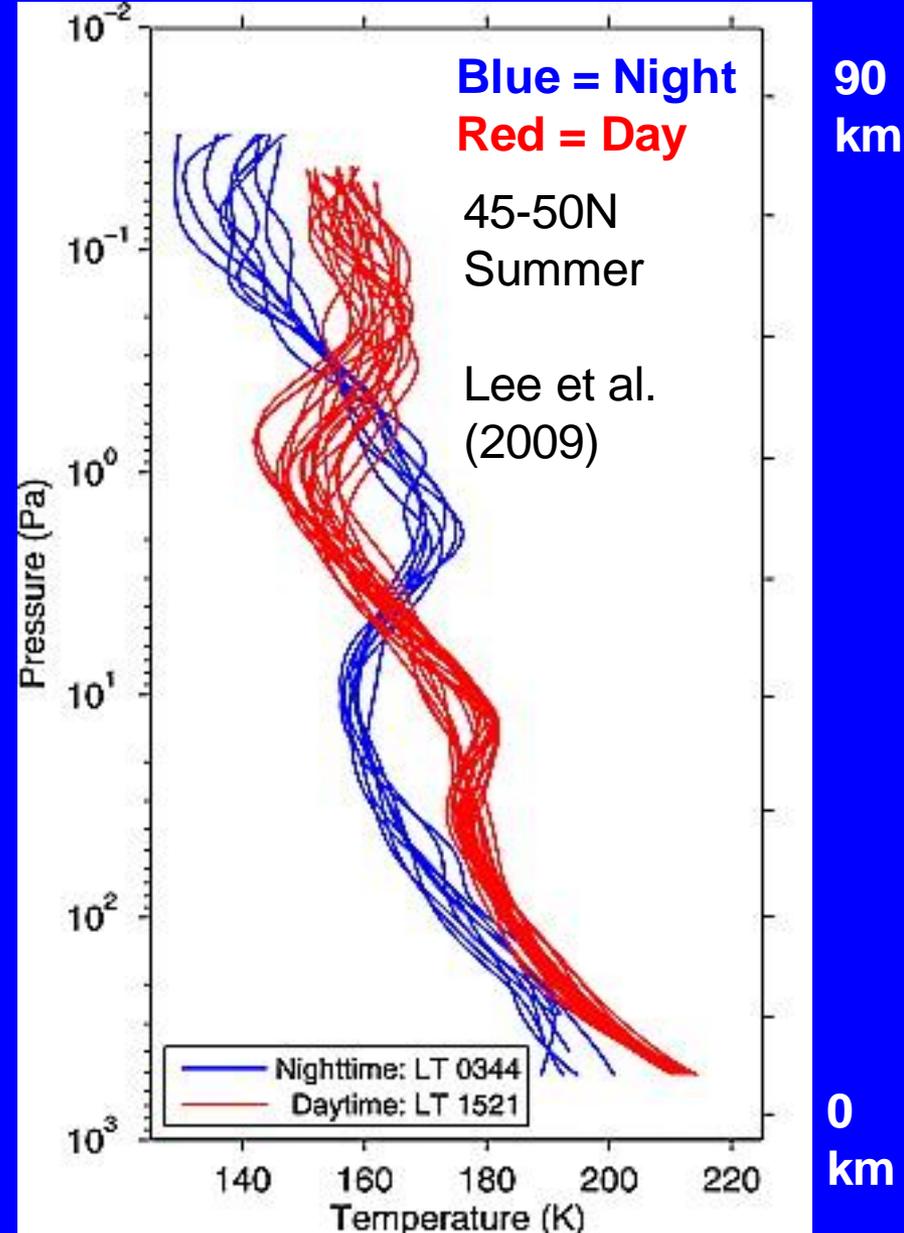
Comparison with MCS profiles



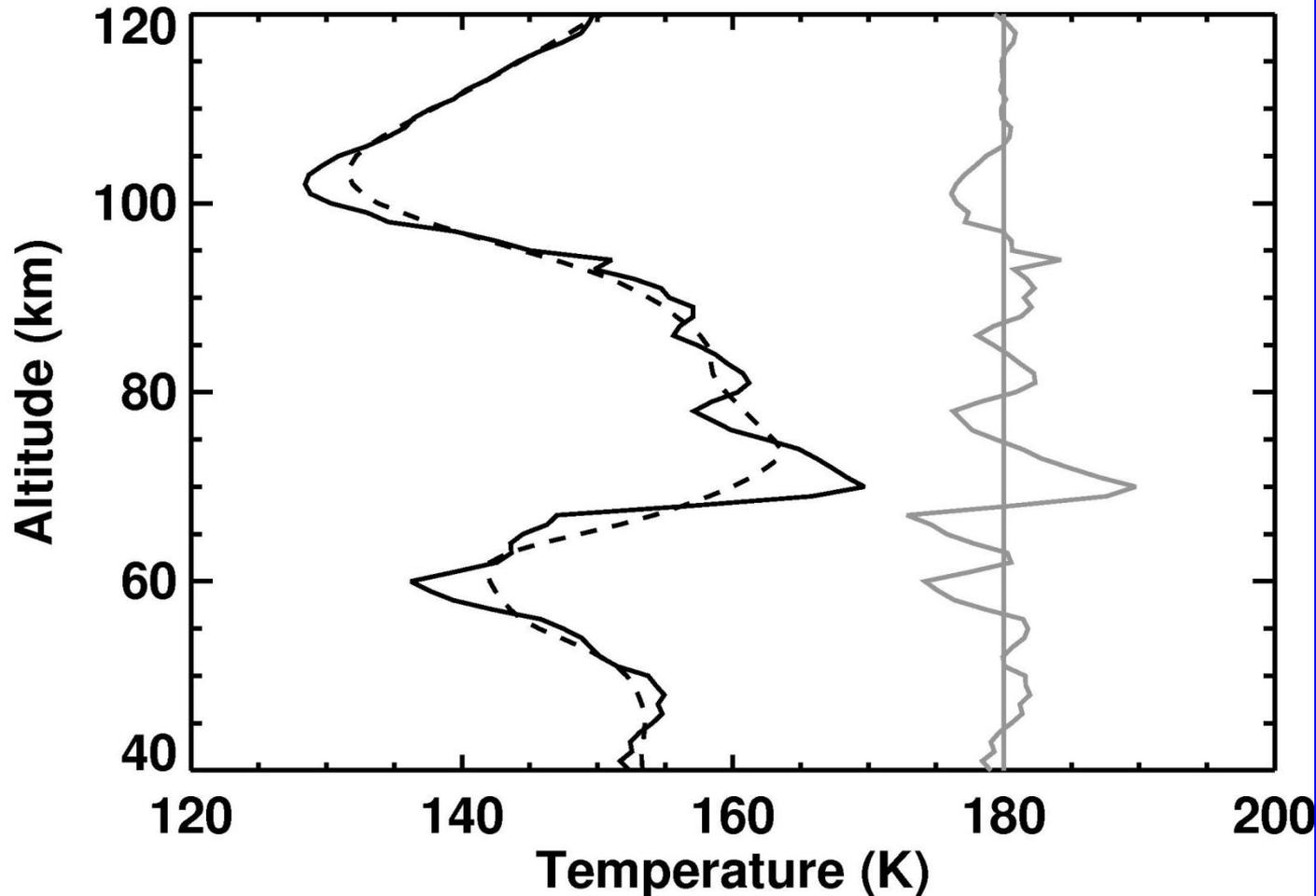
MCS = Mars Climate Sounder instrument on MRO

Good agreement at low altitudes, gets worse as altitude increases

Strong signature of diurnal thermal tide



Gravity waves



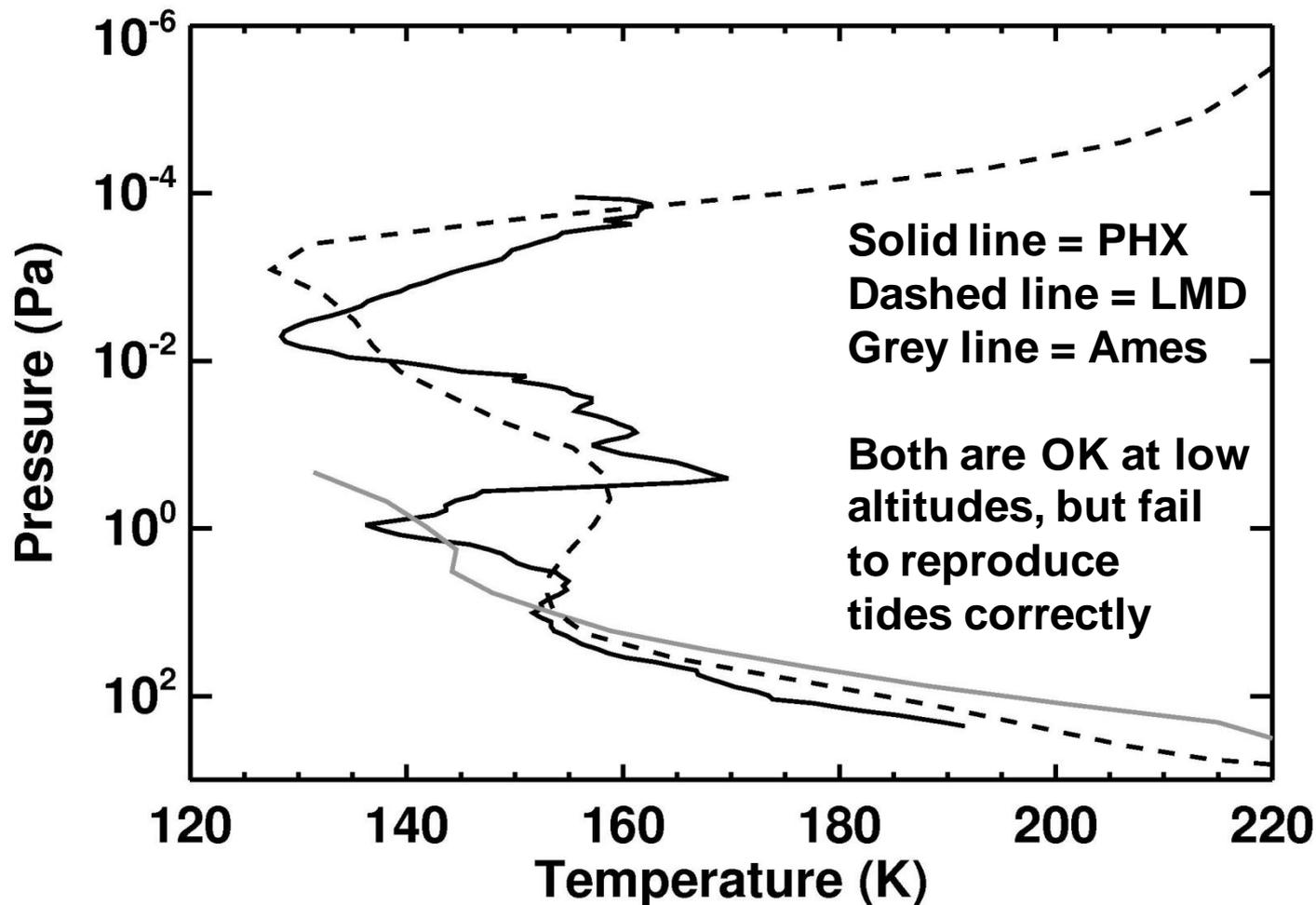
Black solid line
is PHX profile

Black dashed
line is 10 km
running mean

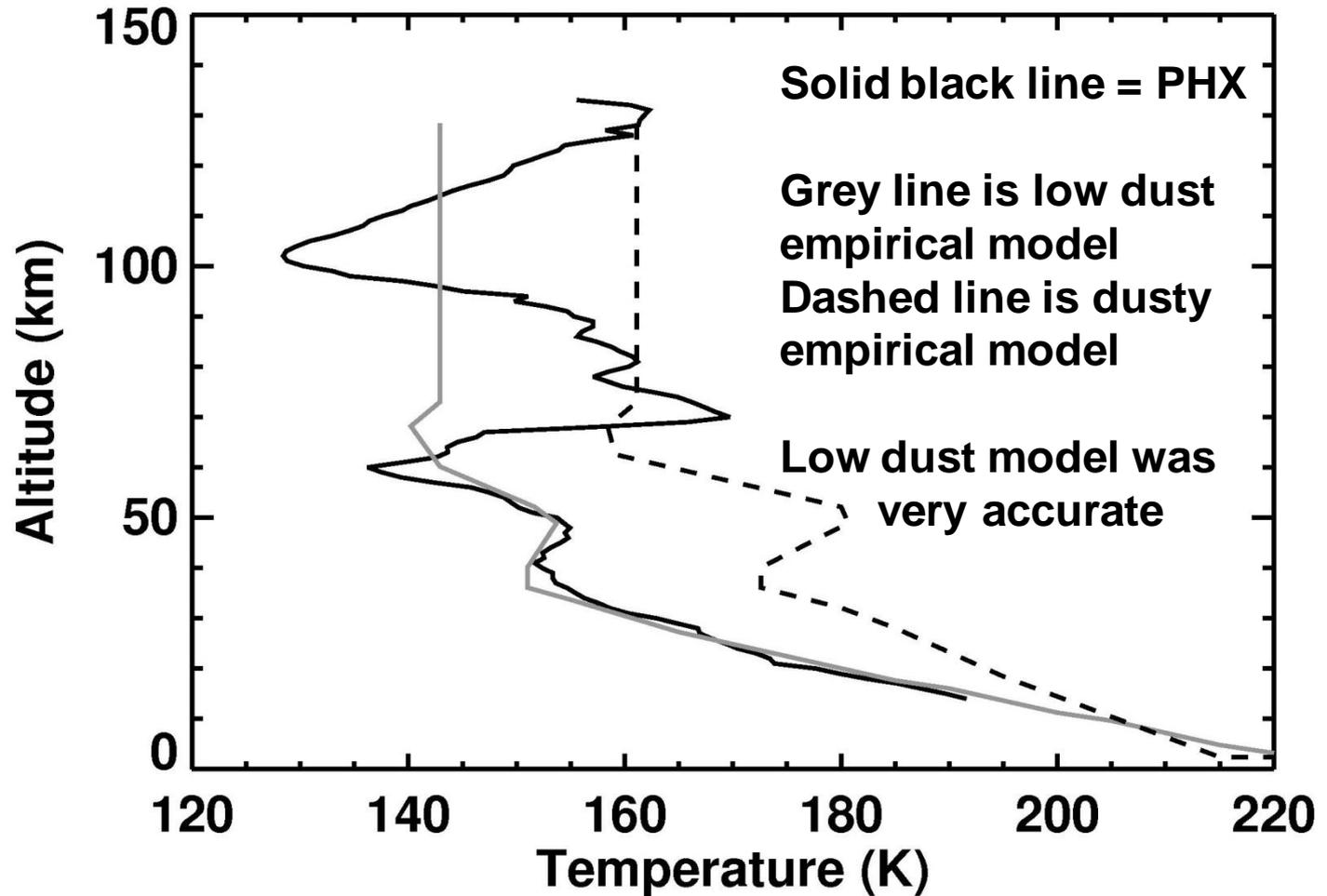
Grey lines show
temperature
difference, offset
by 180 K

Vertical wind speeds of ~ 5 m/s associated with these 5 K oscillations with 7 km wavelength

Comparison with general circulation models



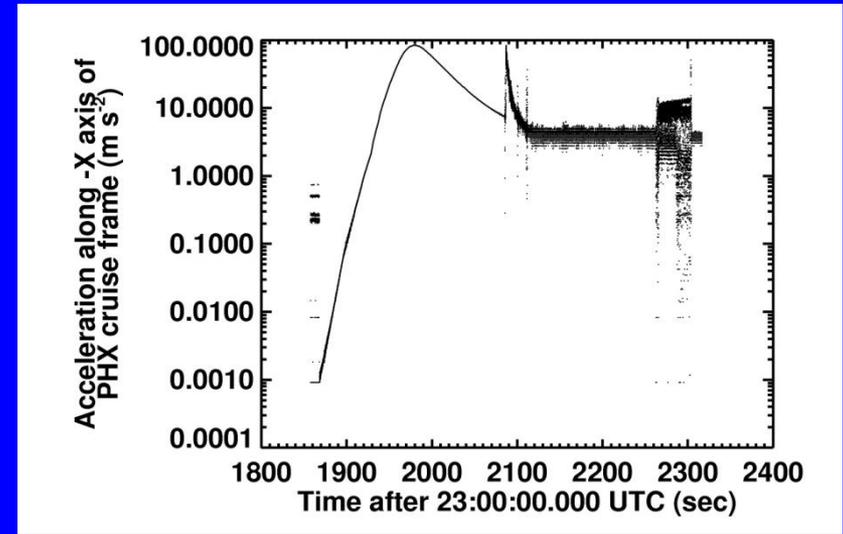
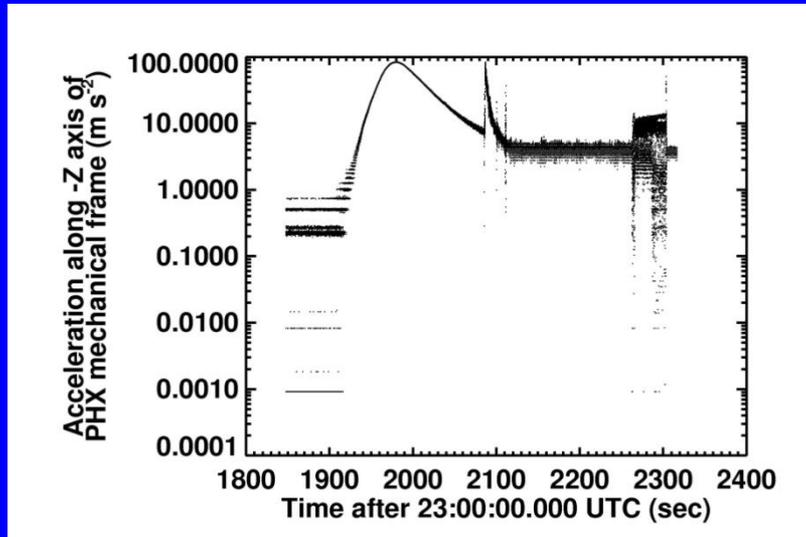
Success of project's empirical model



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Challenges for smoothing accelerations



Exponential increase at high altitudes

$$a = a_0 \exp \frac{t}{\tau}$$

Discontinuities appear when width of averaging window is changed

- Mean of an exponential function does not equal desired central value
- Can't use mean of $\log(a)$ because noisy data varies sign

Solution – Use two averages

$$a_{mean} = \frac{1}{2t_X} \int_{t=-t_X}^{t=t_X} a_0 \exp\left(\frac{t}{\tau}\right) dt$$

$$a_{mean} = \frac{a_0 \tau}{2t_X} \left[\exp \frac{t_X}{\tau} - \exp \frac{-t_X}{\tau} \right]$$

$$a_{mean} = a_0 \frac{\tau}{t_X} \sinh\left(\frac{t_X}{\tau}\right)$$

$$a_L = a_0 \frac{\tau}{2t_S} \sinh\left(\frac{2t_S}{\tau}\right)$$

$$a_S = a_0 \frac{\tau}{t_S} \sinh\left(\frac{t_S}{\tau}\right)$$

$$\frac{a_L}{a_S} = \frac{1}{2} \frac{\sinh\left(\frac{2t_S}{\tau}\right)}{\sinh\left(\frac{t_S}{\tau}\right)}$$

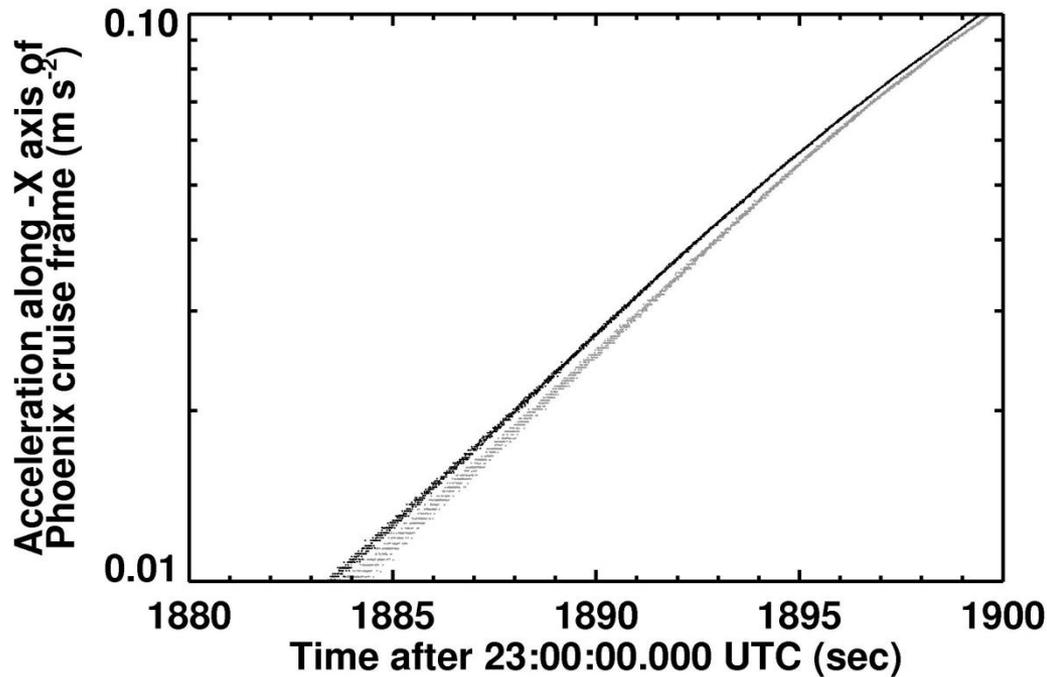
$$\frac{a_L}{a_S} = \cosh\left(\frac{t_S}{\tau}\right)$$

Calculate “long average” a_L from $t = -2t_S$ to $t = +2t_S$

Calculate “short average” a_S from $t = -t_S$ to $t = +t_S$

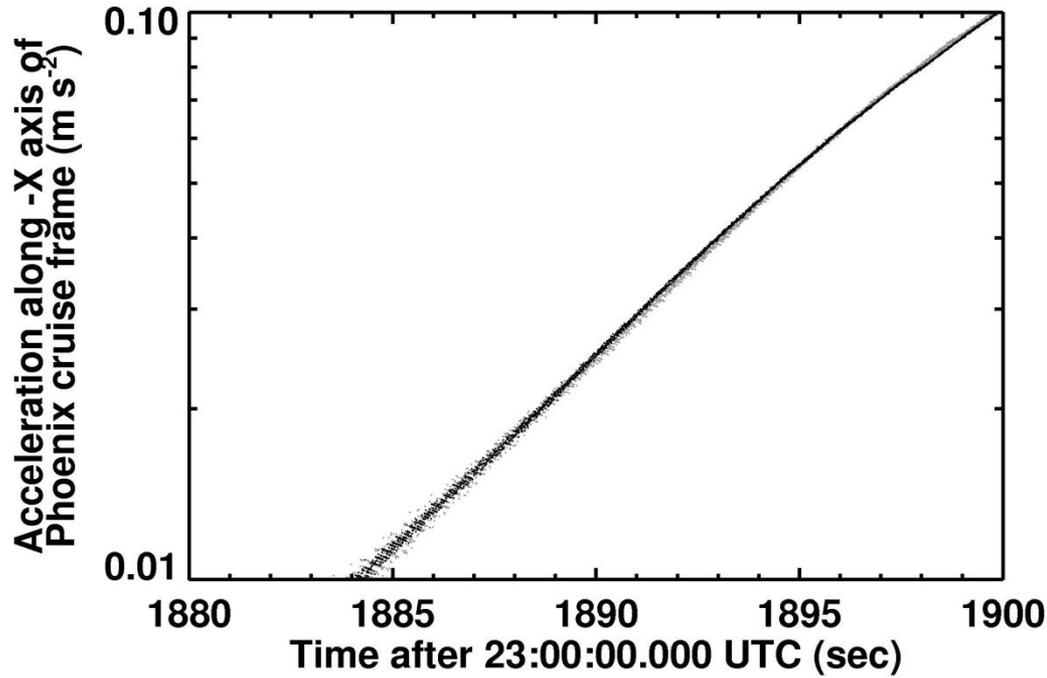
Ratio gives desired tau

$$\frac{t_S}{\tau} = \ln\left(\frac{a_L}{a_S} + \sqrt{\left(\frac{a_L}{a_S}\right)^2 - 1}\right)$$



Grey dots are normal smoothing with 1024 point running mean
 Black dots are normal smoothing with 2048 point running mean

Difference indicates the problem
 How do you transition from one averaging window to another?



Grey dots are 1024 point running mean corrected using ratio to 2048 point running mean
 Black dots are 2048 point running mean corrected using ratio to 4096 point running mean

Overlap of two series enables easy transition from one averaging window to the next

Transformation from IMU frame into spacecraft frame

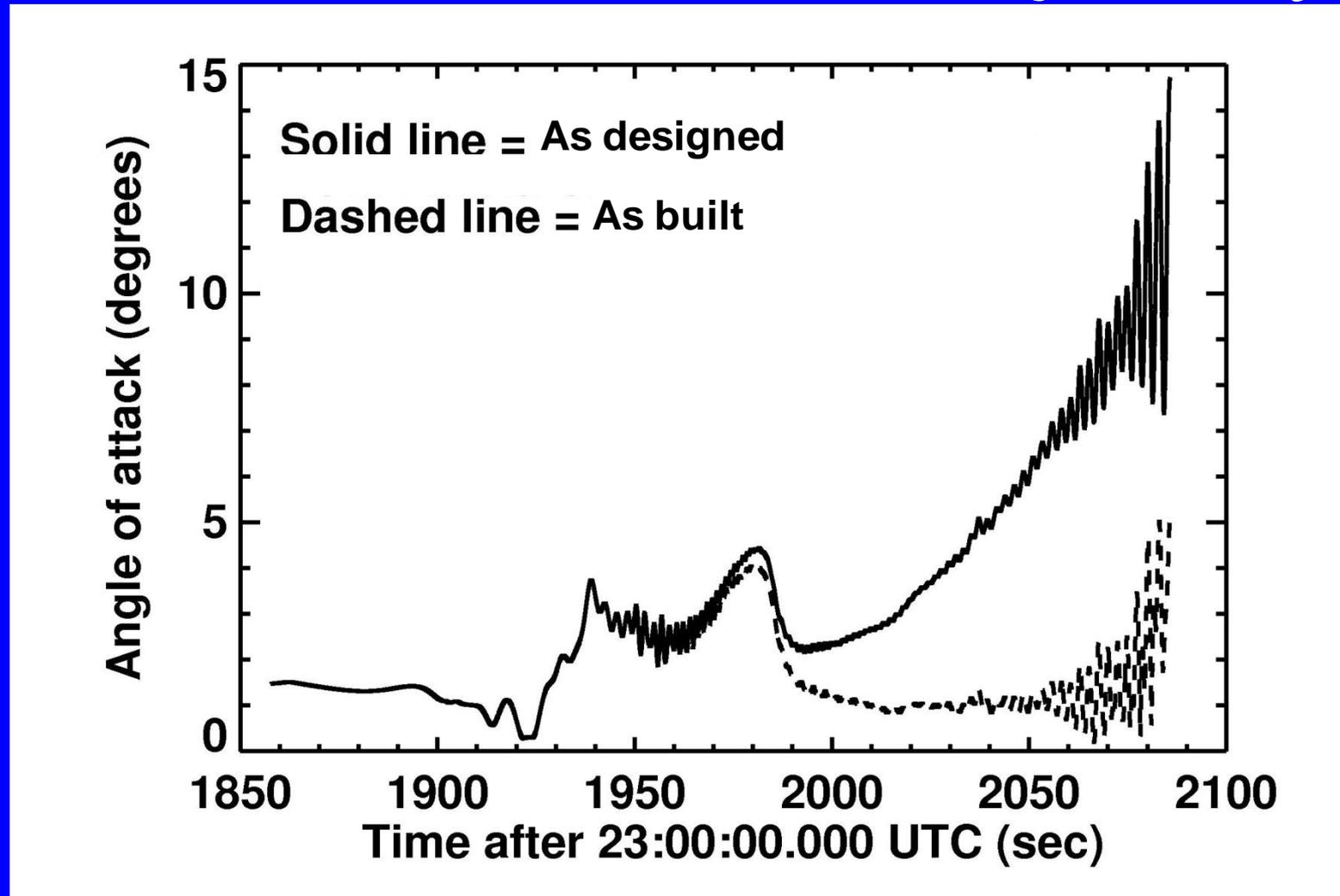
$$\underline{\underline{M}}_{IMU}^C = \begin{pmatrix} 0.001658000000000 & 0.434532000000000 & 0.900655000000000 \\ 0.865583671733631 & -0.451637796435926 & 0.216304845776395 \\ 0.500761102355330 & 0.779233610045474 & -0.37687298280806 \end{pmatrix}$$

- One source, as built

$$M = \begin{bmatrix} 0 & 0.4226 & 0.9063 \\ 0.8660 & -0.4532 & 0.2113 \\ 0.5 & 0.7849 & -0.3660 \end{bmatrix}$$

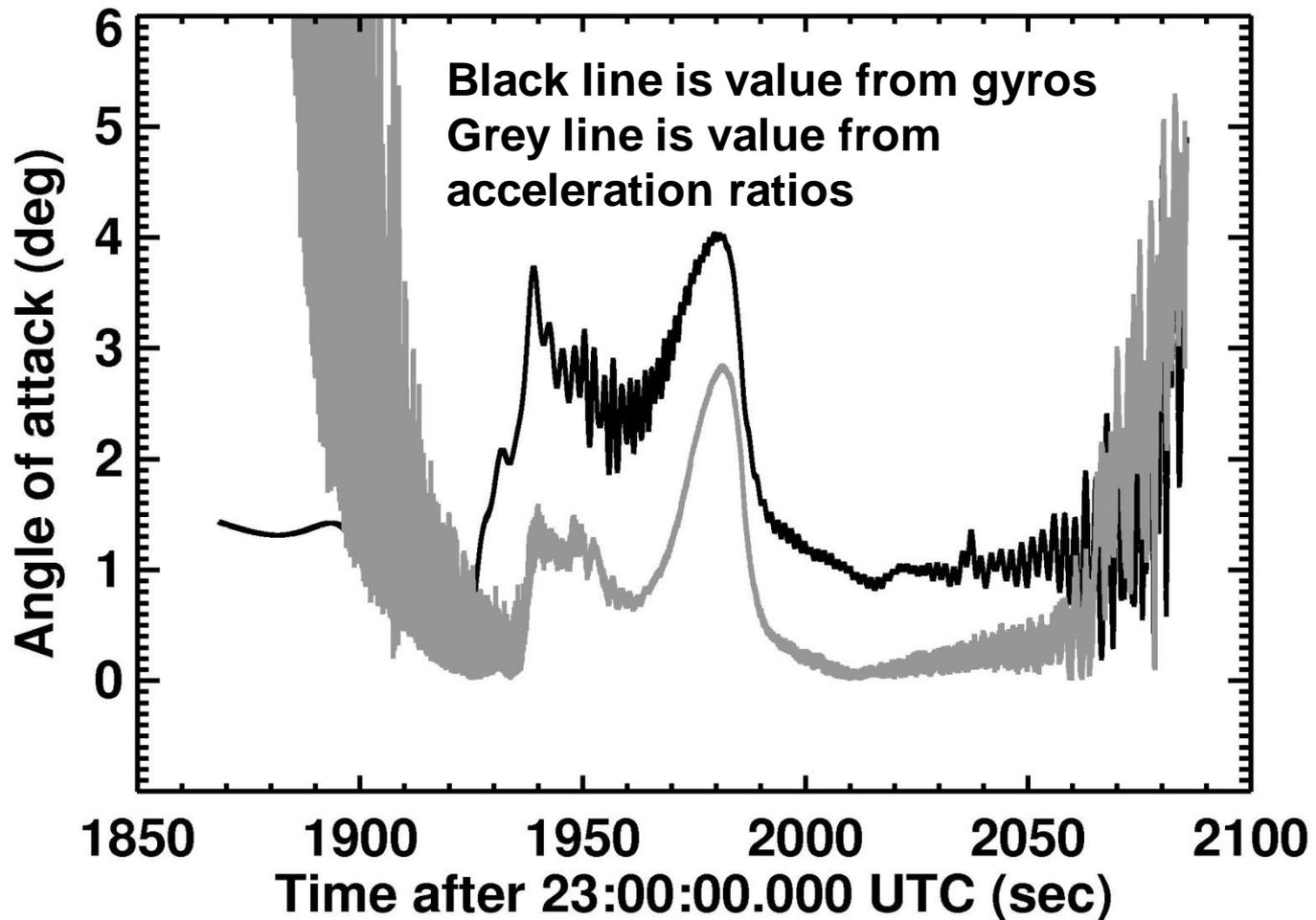
- Another source, as designed
- Differences seem small, but effects are not

Effects of frames on trajectory



Differences of a few km in altitude at parachute deployment and landing, differences of tens of m/s in speed at landing

Angle of attack



Results of two different methods for finding the angle of attack are inconsistent by 1-2 degrees.

This is SEPARATE issue from predicted/reconstructed differences

Outline

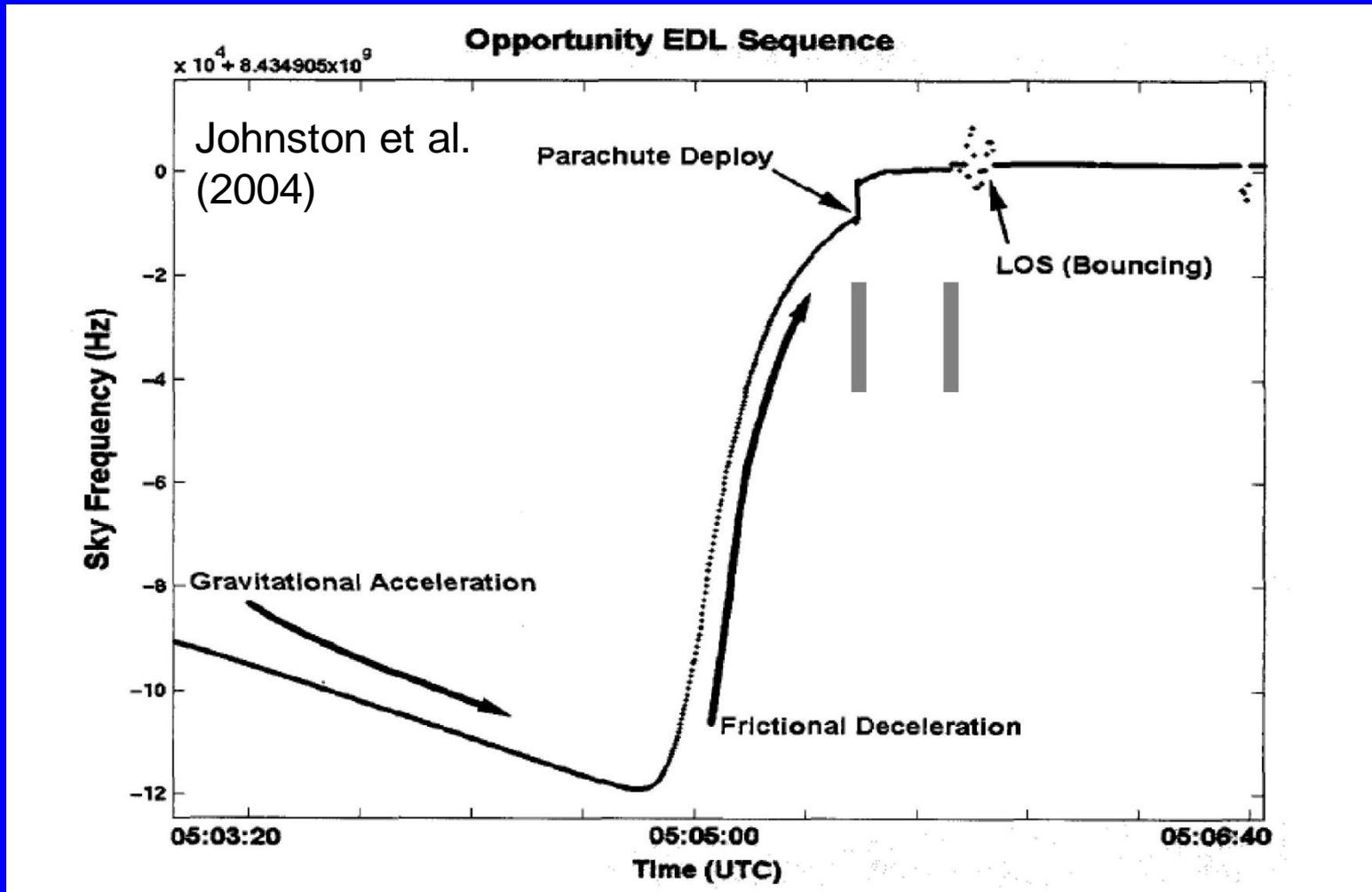
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Entry reconstructions – What if done in “real time”?

- Rapid estimate of landing site location
- Rapid assessment of accuracy of predicted environmental conditions
- Engage public during “EDL event”
- Don’t need mission to survive after EDL for subsequent data transmission

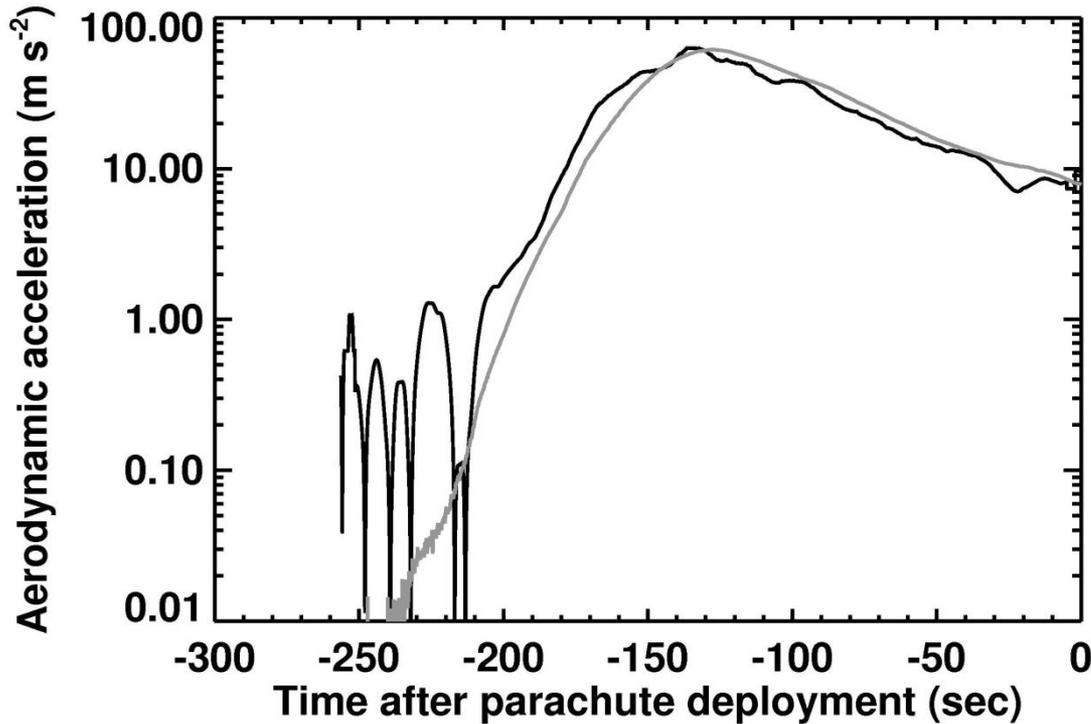
- Direct-to-Earth radio link offers alternative approach

Doppler shift during Opportunity EDL



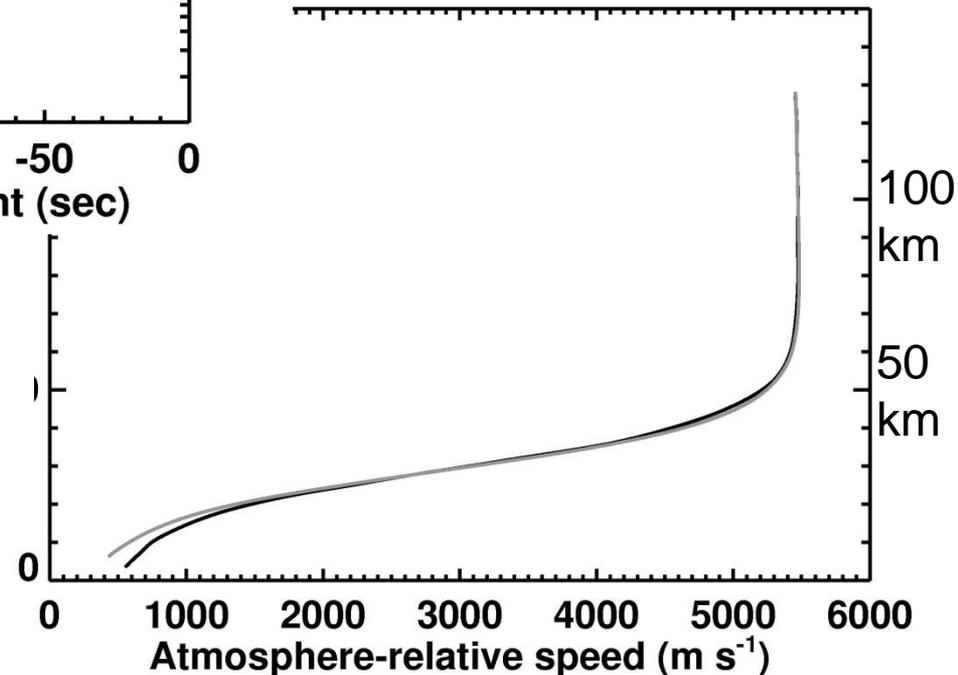
This only gives one component of velocity. Assuming that the aerodynamic deceleration is parallel to velocity gives 3D velocity. Demonstrate using scanned version of this figure (not real data).

Reconstructed trajectory

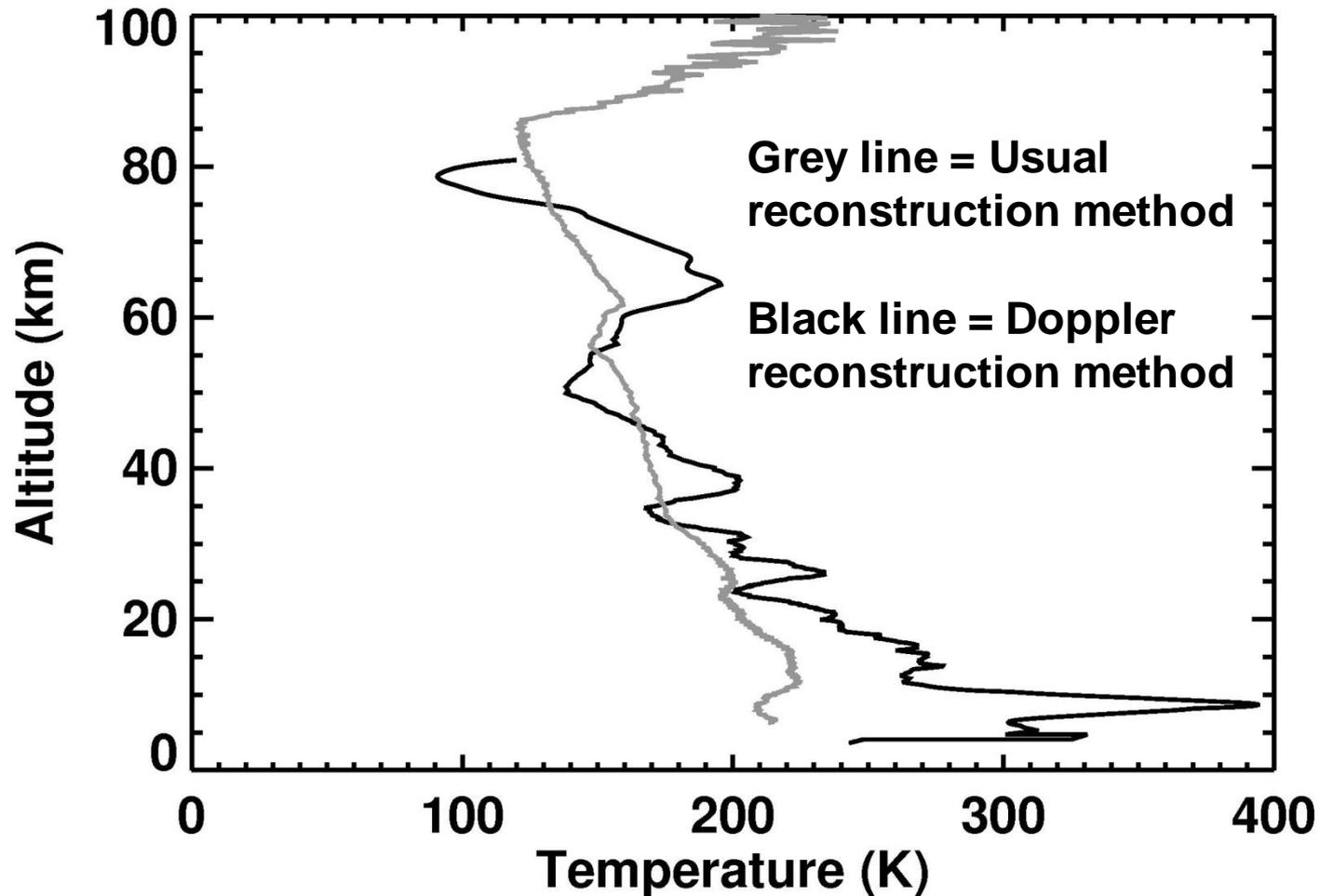


Grey line = Usual reconstruction method
Black line = Doppler reconstruction method

Time discrepancy of about 10 seconds, but results look acceptable



Reconstructed temperature



Plausible temperatures between 20 km and 60 km.

This technique works, but should be validated using real data.

Uncertainty analysis also needed to estimate expected accuracy.

Conclusions

- Trajectory and atmospheric structure reconstruction for Phoenix successful
 - Results available in PDS
- Future atmospheric entry probes might consider:
 - Reduction of noise by smoothing
 - Sensitivity to mundane engineering details, like relationships between reference frames
 - Why two different angles of attack?
 - Potential of rapid reconstruction using radio link

Backup Material

Why bother?

- Independent reconstruction of trajectory
- Rapid results for:
 - Engineers (Where did we land? Nominal?)
 - Public (See results immediately)
 - Science (What are atmospheric conditions?)
- Get results even if lander explodes when reaching ground

Detailed approach

Measured: $\underline{v} \cdot \underline{l}_0$

Obvious: $\underline{v}_1 = \underline{v}_0 + \underline{a} dt$

$$\underline{a} = \underline{a}_{aero} + \underline{g}$$

Re-arrange:

$$\underline{v}_1 \cdot \underline{l}_0 = \underline{v}_0 \cdot \underline{l}_0 + \underline{a} \cdot \underline{l}_0 dt$$

Re-arrange:

$$\underline{a}_{aero} \cdot \underline{l}_0 = \frac{1}{dt} (\underline{v}_1 \cdot \underline{l}_0 - \underline{v}_0 \cdot \underline{l}_0) - \underline{g} \cdot \underline{l}_0$$

Big assumption:

$$\underline{a}_{aero} = -k \underline{v}_0$$

Outcome is expression for a-aero using known quantities

$$\underline{a}_{aero} = \frac{-\underline{v}_0}{\underline{v}_0 \cdot \underline{l}_0} \left[\frac{1}{dt} (\underline{v}_1 \cdot \underline{l}_0 - \underline{v}_0 \cdot \underline{l}_0) - \underline{g} \cdot \underline{l}_0 \right]$$