Beagle 2 Entry Accelerometer

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Abstract's Abstract: We have tested techniques for turning Beagle 2's entry accelerometer data into a T(z) profile. We reproduced the PDS results for Pathfinder. The PDS trajectory for Pathfinder appears inconsistent with its entry state. Our code is available online.

Poster Layout

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  - ***Purpose of Accelerometers***
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  - ***Analyzing Accelerometer Data***
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Why Fly Accelerometers?

- During ***atmospheric entry***, spacecraft experience aerodynamic deceleration and heating dependent on the atmosphere.
- Accelerometers measure this aerodynamic deceleration. Combined with a gravity model and an initial position and velocity, the accelerations can be integrated to give the ***spacecraft trajectory*** from entry to surface impact.
- Essential for commanding safe landing – so ***won't be descoped*** off the spacecraft.
- Successfully flown on Viking, Pioneer Venus, Galileo, Mars Pathfinder, various Soviet landers; will fly on Huygens, Beagle 2, NASA's 2003 Mars landers

Science from Engineering

$$a = {(\rho C_D A V^2)}\big/{-2m}$$

- ρ is atmospheric density, C_D is a dimensionless drag coefficient, A is a specified reference area used as a scaling factor for C_D, V is the relative speed between the spacecraft and the atmosphere, m is the mass of the spacecraft, and a is the spacecraft's aerodynamic acceleration.
- Complicated parachute aerodynamics prevents use of this equation after its opening.
- From trajectory integration, all are known at each point along trajectory except ***atmospheric density***.
- Solve above equation for $\rho(z)$ along trajectory, integrate hydrostatic equation for pressure, $p(z)$, and solve equation of state for temperature, $T(z)$.
- Vertical resolution of ~100m, uncertainty in T(z) is ~few K, ***compare to predictions***.

Practical issues of the trajectory integration

- Accelerometer measurements are made in a ***spacecraft-fixed frame***, the integrations are easiest to do in an ***inertial frame***, and the results are best expressed in a ***rotating, planet-fixed*** frame.
- Rather than deal with the complications of integrating the equations of motion in a rotating frame, we performed each integration step in an inertial frame. This inertial frame was redefined at each timestep so that its axes coincided with those of a frame fixed with respect to the rotating planet.

Tracking Spacecraft Attitude

- This is essential for converting the accelerations measured in the spacecraft frame into an inertial or planet-fixed frame.
- **Drag-only**: assume that the aerodynamic accelerations are exactly opposed to the relative velocity between the spacecraft and the atmosphere.
  - ***Formally an oversimplification, but many spacecraft, including Pathfinder, are designed so that it is realistic (Magalhaes et al, 1999)***
- **Gyroscopes**: measure angular as well as linear accelerations and integrate these to track the spacecraft attitude.
  - ***requires additional instruments onboard***
- **Spacecraft xyz-axis acceleration ratios**: given these and the spacecraft's speed and aerodynamics, attitude is uniquely constrained.
  - ***requires detailed aerodynamic database***

Errors and Constraints

- Uncertainty in entry state – An error in the initial lat/lon propagates unchanged to the landing site, an error in the flight path angle below the horizontal causes large errors in the landing location
- Uncertainty in aerodynamic properties – Same relative error appears in solution for atmospheric density
- Instrument digitization – Same relative digitization appears in solution for atmospheric density
- Instrument sampling rate – Can be as low as 1 Hz
- Systematic offset in instrument response - ***Disastrous***
- Displacement of accelerometer from centre of mass – Introduces angular terms due to rotation of spacecraft
- Parachute aerodynamics – Not well known, prevents solution for atmospheric profiles after parachute has opened
- Numerical accuracy of the code itself
  - ***We are in the process of incorporating these uncertainties into our work***
- Well-known final landed position – Known from tracking of transmissions, move entry state within uncertainties to land at this position
- Post-landing gravity measurement to constrain the instrument accuracy – Check for systematic offsets
- Doppler-shifted telemetry during descent - Constraints on velocity
- Any radar altimetry during descent – Constraints on altitude
- Any direct pressure and temperature measurements during descent – Check on atmospheric profiles
  - ***Only the first two are likely for Beagle 2***

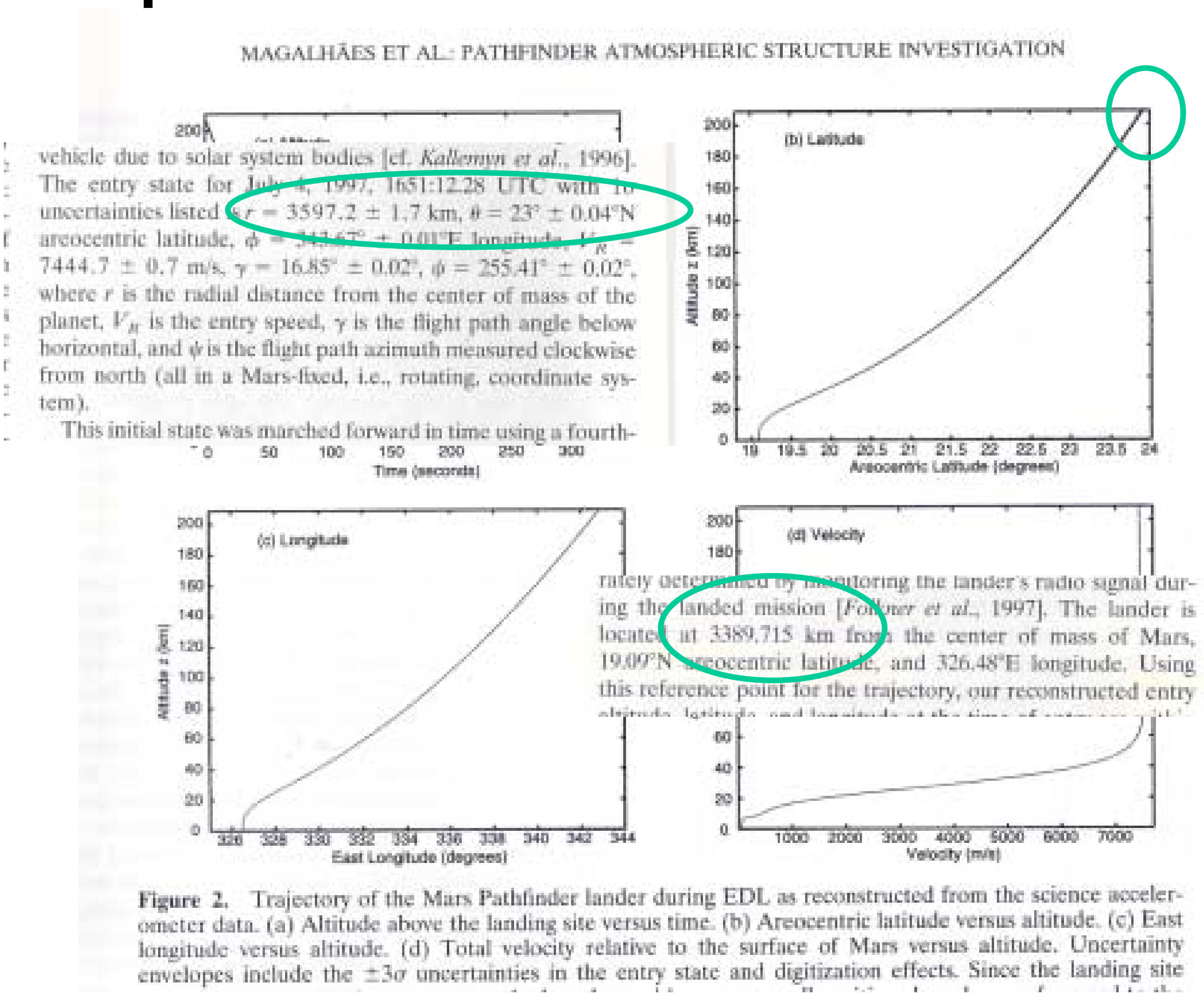
Details of Current Code

- Developed in preparation for Beagle 2 entry, it will ***analyse entry accelerometer data*** to obtain the trajectory to the landing site and profiles of atmospheric density, pressure, and temperature.
- When the Beagle 2 aerodynamic database is generated, we will ***constrain spacecraft attitude using the acceleration ratios***. In the current code, we have implemented the drag-only option.
- Includes J_2 in gravity field, ***fourth-order integration*** of equations of motion in inertial frame, and ***effects of planetary rotation***.
- Needs to have error analysis included.

Comparison of Pathfinder Trajectories

- Using the ***entry state archived with the PDS by the Pathfinder Science Team*** (Magalhaes et al, 1999, JGR, v104, pp8943-8956), our trajectory reconstruction is ***systematically different*** to the PDS's by about a degree in both latitude and longitude.
- Using the ***entry state published by the Pathfinder engineers*** (Spencer et al, 1999, Journal of Spacecraft and Rockets, v36, pp357-366), it is systematically different by only hundredths of a degree.
- Is there a similar ***error*** in both our results and those of the Pathfinder engineers, or is there an ***error*** in the results archived with the PDS by the Pathfinder Science Team?

Inconsistency between publications and PDS?



vehicle due to solar system bodies [cf. *Kallemyn et al.*, 1996]. The entry state for July 4, 1997, 1651:12.28 UTC with 1σ uncertainties listed is r = 3597.2 ± 1.7 km, θ = 23° ± 0.04°N areocentric latitude, ϕ = 343.67° ± 0.01°E longitude, V_R = 7444.7 ± 0.7 m/s, γ = 16.85° ± 0.02°, ψ = 255.41° ± 0.02°, where r is the radial distance from the center of mass of the planet, V_R is the entry speed, γ is the flight path angle below horizontal, and ψ is the flight path azimuth measured clockwise from north (all in a Mars-fixed, i.e., rotating, coordinate system).

This initial state was marched forward in time using a fourth-

rately determined by monitoring the lander's radio signal during the landed mission [*Folkner et al.*, 1997]. The lander is located at 3389.715 km from the center of mass of Mars, 19.09°N areocentric latitude, and 326.48°E longitude. Using this reference point for the trajectory, our reconstructed entry

Figure 2. Trajectory of the Mars Pathfinder lander during EDL as reconstructed from the science accelerometer data. (a) Altitude above the landing site versus time. (b) Areocentric latitude versus altitude. (c) East longitude versus altitude. (d) Total velocity relative to the surface of Mars versus altitude. Uncertainty envelopes include the $\pm 3\sigma$ uncertainties in the entry state and digitization effects. Since the landing site

Text: Lat at 210 km altitude is 23.0°N

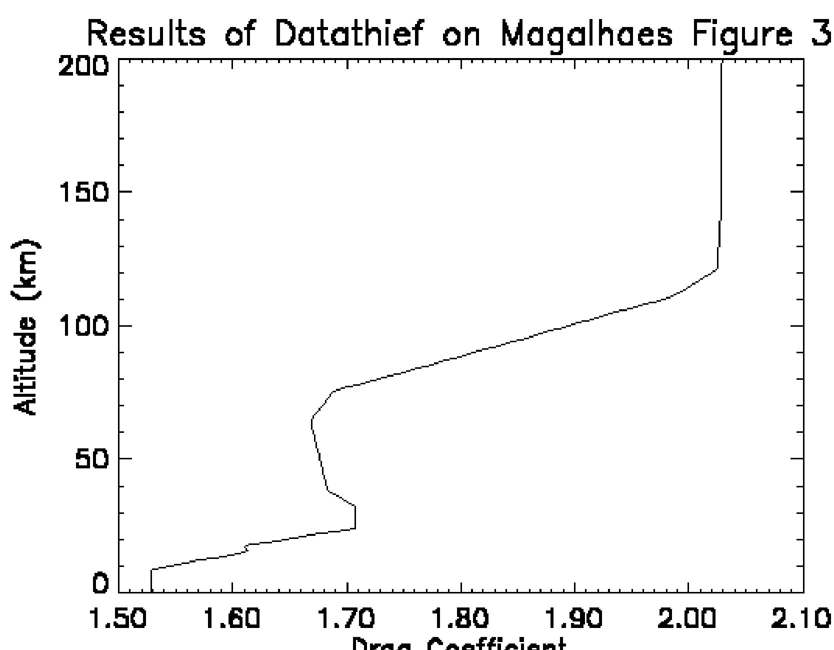
Figure: Lat at 210 km altitude is 24.0°N

Text and figures are inconsistent, so there is an error in either the quoted entry state or the trajectory. The error is identical to that between the PDS trajectory and our trajectory using the PDS entry state whereas the error is removed if we used the engineering entry state. Conclusion – ***the error is in the PDS entry state***.

We use the engineering entry state henceforth

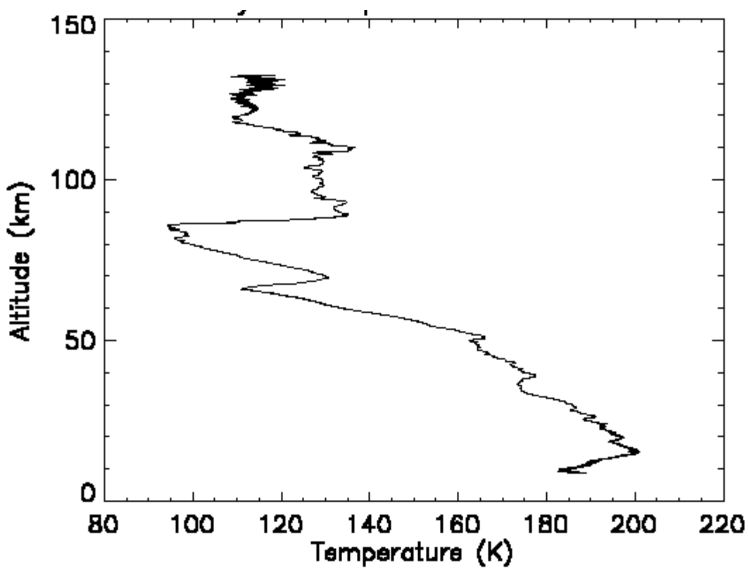
Pathfinder Aerodynamics

- Modelled for JPL on ***supercomputers*** and in ***fluid chambers*** as function of spacecraft speed and attitude, and atmospheric density and temperature.
- Results not available to us …
- … So we used the ***crudely scanned and digitized figure*** below as only aerodynamic database for deriving atmospheric profiles.

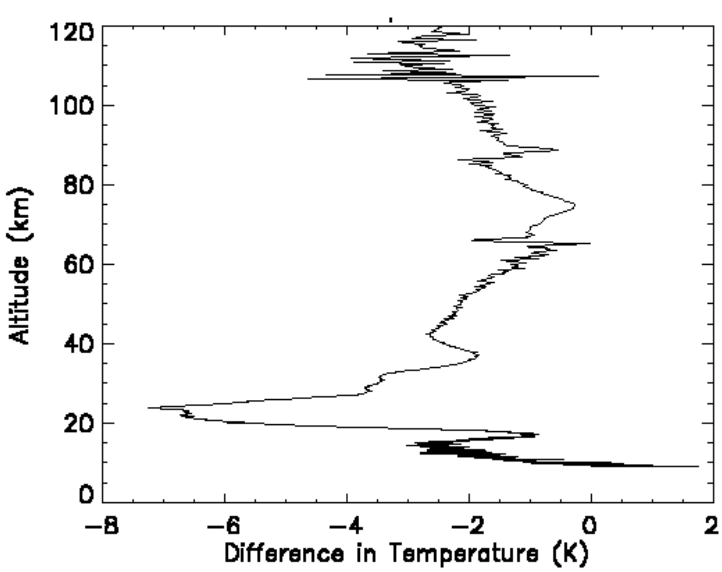


Independent derivation of Pathfinder T(z) profile

Our T(z) solution



Difference between our solution and PDS's



Our solution for the Pathfinder T(z) profile differs from the PDS profile by ***only a few K***. Larger differences in the lower atmosphere are caused by changes in the spacecraft aerodynamics that are not present in our crude database.

Our trajectory and atmospheric structure reconstruction code is working well, despite the simplicity of our aerodynamic database!

Free software to study atmospheric entry and accelerometer data

- http://www.lpl.arizona.edu/~withers/beagle2/
- Either specify spacecraft, planet, and entry state to derive trajectory using model atmosphere (traj.pro).
  - Output altitude, latitude, longitude, speed, atmospheric density, aerodynamic accelerations at each timestep along trajectory.
  - Does spacecraft impact surface or skim away?
  - What are the effects of changing entry speed or angle or spacecraft mass or area?
- Or specify spacecraft, planet, and entry state to derive trajectory and atmospheric profiles using an acceleration dataset (recon.pro).
  - Output all of the above and also profiles of atmospheric density, pressure, and temperature along the trajectory.
  - Use the supplied Pathfinder accelerometer dataset or results of your own experiment

Parameters for free software

- Select a ***planet*** from Venus, Earth, Mars, Jupiter, Titan, or define your own planetary rotation rate, mass, radius, atmospheric surface density, scale height, and mean molecular mass. The atmospheric properties are only used to derive a trajectory using a model atmosphere.
- Select a ***spacecraft*** from Pathfinder, the Galileo probe, the Pioneer Venus sounder/large probe, Beagle 2, Huygens, or define your own spacecraft mass and area.
- Select ***entry states*** for any of the above spacecraft or define your own initial position and velocity.
- Specify the size of the timesteps when deriving a trajectory using a model atmosphere.
- Specify a ***constant drag coefficient***.
- Use the ***Pathfinder accelerations dataset*** or supply your own.
- Online version of code assumes a spherically symmetric planet and gravity field and uses a first-order integration routine.

Very Crude Aerodynamics

C_D varies between about 1.5 and 2.1 depending on the density and temperature of the atmosphere and the speed and attitude of the spacecraft; 2 is a nominal value.

During a planetary entry, C_D changes significantly only over altitude ranges significantly greater than a scale height.

Can useful results be obtained using the simplistic C_D = 2?

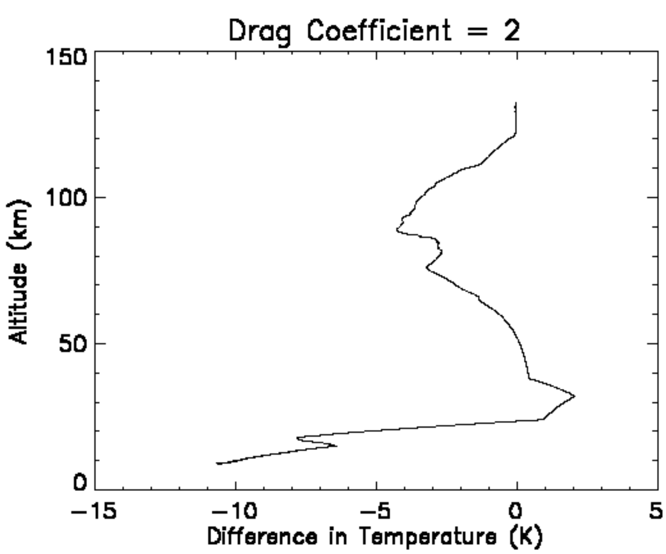
$$a = (\rho C_D A V^2) \big/ -2m$$

The pointwise solution for the density along the trajectory is in error by on the order of tens of percent.

C_D = 2 results

$$p(z) = -\int \rho g dz$$

- The solution for the pressure at a given altitude is dominated by the solution for the density at and just above that altitude. Since the drag coefficient is relatively constant over this range, the pressure profile is in error by roughly the same varying factor as is the density profile.
- $T(z) \propto \rho(z) \big/ p(z)$ The errors cancel out when ratioing the density and the pressure to obtain the temperature. The temperature profile is relatively insensitive to errors in the drag coefficient.



The temperature profile is only in error by a few K with no spacecraft aerodynamic data used at all.

Beagle 2 Mars Lander

- ***Lands in Isidis on Dec 26, 2003***, a few days before NASA's two Mars landers.
- Beagle 2 will analyse its environment for traces of organic compounds, the building blocks of life. It will measure carbon isotopic ratios, to distinguish biotic and abiotic samples, and perform the ***first radiometric (K-Ar) dating*** experiments beyond Earth
- It is equipped with a robot sampling arm and a small "mole" which can be deployed by the arm and is capable of subsurface sampling. It is equipped with instruments for gas chromatography and mass spectroscopy, a microscope, panoramic and wide-angle cameras, Mossbauer and X-ray spectrometers and environmental sensors (including the accelerometer!)

Future Work

- Analyse the effects of errors on the results.
- Obtain a realistic aerodynamic database for blunted cones and implement more sophisticated aerodynamic model.
- Apply additional constraints to solution procedure.
- See if Withers's proposal to perform the trajectory and atmospheric structure reconstruction for the NASA 2003 Mars Landers Science Team is successful.

Can you help us obtain the Pathfinder aerodynamic database for further development of this code?

Magalhaes et al, 1999, JGR, v104, pp 8943-8956
Spencer et al, 1999, Journal of Spacecraft and Rockets, v36, pp 357-366
http://www.lpl.arizona.edu/~withers/pppp/pdf/oureport.pdf
(Discusses development of this work in detail)