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Investigation and Technical Plan

1 - Scientific Goals and Objectives

1.1 – Scientific Goal

Derive atmospheric structure profiles (density, pressure, and temperature) from calibrated Inertial Measuring Unit (IMU) data during entry of the two landers for operational support, scientific analysis, and application to future Mars missions.

1.2 – Scientific Objectives

1 – To support the MER-B entry and the evaluation of thermal and mechanical stresses on both spacecraft during entry by providing the MER project with a preliminary analysis of the trajectory of both MERs and atmospheric structure profile during their entries within a week of receipt of the necessary data. This will address *environmental constraints and effects on spacecraft performance, quantify environmental effects which may impact system performance and survivability, characterize system performance and reliability* and *characterize environment state estimation capabilities* (AO, p5-6).
2 – To use calibrated and validated IMU data and the primary datasets discussed in Section 2 to derive entry trajectories, and atmospheric structure profiles (density, pressure, and temperature) along them, for each lander. This will *maximize the contribution of the Mars Exploration Rovers to future exploration and scientific understanding of Mars* (AO, p5).
3 – To deliver calibrated and validated IMU data (Level 1 data) to the Planetary Data System within six months of receipt of the data and to deliver the data products derived for Objective 2, all information necessary to derive them, and the software used to derive them (Level 2 data) to the Planetary Data System within six months after the Level 1 delivery. This will *maximize the contribution of the Mars Exploration Rovers to future exploration and scientific understanding of Mars* (AO, p5).
4 – To perform scientific analysis of the atmospheric structure profiles, as discussed in Section 1.3, and publish both preliminary and comprehensive versions in the peer-reviewed scientific literature in a manner consistent with the MER Science Team's schedule. This will *maximize the contribution of the Mars Exploration Rovers to future exploration and scientific understanding of Mars* and *calibrate orbital remote sensing data* (AO, p5).
5 – To improve the entry trajectories and atmospheric structure profiles by incorporating secondary datasets, as discussed in Section 2.3, into my analysis, if they are made available to me by other investigations, and then delivering the improved data products to the PDS. This will *maximize the contribution of the Mars Exploration Rovers to future exploration and scientific understanding of Mars.* (AO, p5).
6 – To advocate negotiation by the MER project for access to the Beagle 2 (Mars entry on 26 December 2003) accelerometer data with the aim of supporting the MER-A entry with Beagle 2 data just as the MER-B entry will be supported with the MER-A data. This will *quantify environmental effects which may impact system performance and survivability*, and *characterize environment state estimation capabilities*. (AO, p6).

This proposal *broadens participation* in the MER mission by giving a young scientist the opportunity for independent mission involvement and by involving a major planetary science institution with the MER mission (AO, p5). It *augments the existing MER science team* to include investigations not now represented (AO, p5), since *there are currently no selected scientists on the Athena Science Team who will derive atmospheric properties from the accelerometer profiles* (PIP FAQ#10).

1.3 – Importance of this Investigation

Current and foreseeable techniques for landing spacecraft on Mars all require accurate knowledge of its atmospheric density structure during atmospheric entry. This depends upon (at least) latitude, season, time of day, atmospheric dust loading, cloudiness, phase in the 11-yr solar cycle, and local topography, thermal inertia, and albedo (Zurek *et al*., 1992). The Viking and Pathfinder entries have provided three atmospheric structure profiles (Seiff and Kirk, 1977; Magalhaes *et al.*, 1999). Within a period of one month, Beagle 2, MER-A, and MER-B will double this number to six. Poor predictions of the atmospheric structure profile experienced during entry can lead to thermal or mechanical stresses of the spacecraft beyond its design limits. For example, higher than expected densities cause excessive heating and lower than expected densities cause excessive impact speeds and forces. The accuracy of the prediction is crucial to spacecraft performance and achievement of overall mission goals – even the spacecraft's survival upon entry. As an extreme example, Mars Climate Orbiter was destroyed, at a cost of around $100M, when it experienced higher than planned heating and aerodynamic forces during orbit insertion. Incorporation of these profiles into martian atmospheric models will lead to improved predictions of atmospheric profiles for future Mars missions. This will narrow the engineering margins required by landers, increasing performance, reducing cost, and reducing restrictions on landing site selection. This improved predictive ability is also required for future precision landing techniques and aerocapture.

A preliminary atmospheric structure profile which will be rapidly derived for MER-A entry and provided to the MER-B team will increase the probability of a safe entry for MER-B. If the MER-A atmospheric structure profile deviates significantly from predictions and the nominal entry for MER-B is now considered dangerous, the computer algorithm controlling events such as parachute deployment, rocket firing, and airbag inflation during MER-B entry could be modified. These are drastic options to be considered in the final three weeks prior to MER-B entry, but one can envision a crippled MER-A sending back enough data to save MER-B from a similar fate.

Atmospheric structure profiles, when archived for study by the wider scientific community, maximize *the contribution of the Mars Exploration Rovers to the future exploration and scientific understanding of Mars* (AO, p5). Such measurements of atmospheric density, pressure, and temperature are crucial in defining the internationally-accepted standard atmospheres for a given planet (Kliore, 1982; Seiff *et al.*, 1985; Keating, 2002). The published papers presenting the Viking entry profiles for the first time have been cited over 200 times; the corresponding Pathfinder papers have been cited over 50 times in only a few years (Nier *et al.*, 1976; Seiff and Kirk, 1976; Seiff and Kirk, 1977; Schofield *et al.*, 1997; Magalhaes *et al.*, 1999). Atmospheric structure profiles have better vertical resolution than any other technique for studying atmospheric properties. They also sample atmospheric regions inaccessible to any other technique. In Objective 4, I plan to compare and contrast the two MER profiles with each other, and to Viking, Pathfinder and Beagle 2 profiles; compare and contrast the two MER profiles with theoretical predictions, such as MGCM simulations; derive thermal tidal signatures from the profiles and hence identify the dominant tidal modes; compare the profiles to H_2O and CO_2 saturation curves to search for evidence of cloud condensation; compare near-surface pressures to theoretical models for seasonal atmospheric condensation onto the winter pole; compare the profiles with landed and orbital dust opacity measurements, compare the profiles with orbital remote sensing data (TES, MHSA, THEMIS) at the same location; and derive static stability profiles. I will be assisted in this data analysis by a to-be-determined graduate student assistant and, at a low level, by a to-be-determined atmospheric scientist. The main responsibility of the atmospheric scientist will be the comparison of the atmospheric structure profiles with large volumes of orbital remote sensing data from many different instruments.

The Beagle 2 and MER profiles will differ in one important respect from the Viking and Pathfinder profiles: they will be supplemented by many near-simultaneous local and Earth-based measurements. Mars Global Surveyor's TES and MOC, Mars Odyssey's THEMIS, many instruments onboard Mars Express and Nozomi, radio occultations by all four orbiters, instruments on Beagle 2 and the two MERs during landed operations, and earth- and earth-orbit based observations will all provide additional atmospheric data (Clancy *et al.*, 1996; Christensen *et al.*, 1999; Novak *et al.*, 1999; Sims *et al.*, 1999; Wolff *et al.*, 1999; Burgdorf *et al*, 2000; Jegou *et al.*, 2000; Sprague *et al.*, 2000; Chicarro, 2001; Christensen *et al.*, 2001; Encrenaz *et al.*, 2001; Malin and Edgett, 2001; Nozomi webpage, 2001; PIP; *etc.*). This set of synoptic measurements is an unparalleled opportunity to characterize the martian atmosphere from top to bottom at many different scales. The entry profiles will bridge the gap between the vertical regions accessed by the different instruments and provide localized high vertical resolution coverage to complement the global coverage at lower spatial resolution of the orbital instruments. They are the only in situ measurements made more than a metre above the ground (the landers) and less than hundreds of kilometres above the ground (energetic particle detectors and mass spectrometers on board Mars Express and Nozomi).

Without this proposal, atmospheric structure profiles will probably be derived by MER project engineers, similar to Spencer *et al.* (1999) for Pathfinder. They will be optimized for engineering analysis of the MER spacecraft and systems, not for scientific use. These profiles are unlikely to be made available for scientific use via the PDS and its peer-review panel. Hence, they will not be incorporated into future scientific models of martian climate, the models that will be used to *quantify environmental effects which WILL impact system performance and survivability* for future Mars landers and aerocaptured orbiters (AO, p6).

1.4 – Similar Investigations on Previous Missions

Atmospheric structure experiments have previously investigated the atmospheres of the Earth, Venus, Mars, and Jupiter (Seiff *et al.*, 1973; Kerzhanovich, 1977; Seiff and Kirk, 1977; Seiff *et al.*, 1980; Avduevskiy *et al.*, 1983; Blanchard *et al.*, 1989; Seiff *et al.*, 1996; Magalhaes *et al.*, 1999; Spencer *et al.*, 1999). One is currently en route to Titan on board Huygens (Fabris *et al.*, 1992). They have also flown as engineering instruments on Mars Global Surveyor and Mars Odyssey (and will fly as a fully fledged science instrument on Mars Reconnaissance Orbiter) to derive upper atmospheric profiles during the aerobraking phases of these missions (Keating *et al.*, 1998; Bougher *et al.*, 1999; Keating *et al.*, 1999, 2000). One will also enter the martian atmosphere one week prior to MER-A on the British Beagle 2 lander (Sims *et al.*, 1999; Towner *et al.*, 2000).

The scientific results from martian atmospheric structure experiments include defining a reference density, pressure, and temperature profile, defining its cloud structure, defining its tidal structure and, by comparison with model predictions, constraining dust opacity and seasonal atmospheric condensation onto the winter pole (Seiff and Kirk, 1977; Magalhaes *et al.*, 1999).

Since accelerometer measurements are necessary to control events such as parachute deployment during atmospheric entry, atmospheric structure experiments are likely to fly on almost every atmospheric-entering spacecraft launched in the next decade. The ability to derive atmospheric profiles for scientific use from such instruments is a strategic skill that NASA should maintain. NASA is currently in danger of losing this ability. Seiff's group at Ames, which pioneered this ability, has dispersed to the point that no-one from Ames is planning to propose to perform atmospheric structure derivation in response to this AO (Rich Young, personal communication).

A simplified theory for deriving atmospheric structure profiles from entry accelerometer measurements is outlined in the PIP and Magalhaes *et al*. (1999), and described in more detail in Withers (2001) and in Section 2.2 of this proposal.

I have worked with processed accelerometer data from the aerobraking of Mars Global Surveyor and Mars Odyssey through the involvement of my advisor, Steve Bougher, in Atmospheric Advisory Groups for both missions (Keating *et al.*, 1998, 2000; Bougher *et al.*, 1999; Withers *et al.*, 1999, 2000, 2001a, 2001b). I have already developed working techniques for the derivation of atmospheric structure profiles from entry accelerometer measurements (Withers, 2001; Withers *et al.*, 2001c; see also Resume section). I tested and verified my computer software using Pathfinder's EDL data. Figure 1 compares my results with those of Magalhaes *et al.* (1999 and archived in PDS volume MPAM_0001). I used the spacecraft entry state, mass, reference area, and accelerometer measurements archived in PDS volume MPAM_0001 and crude knowledge of the Pathfinder aerodynamic characteristics as inputs to my independently developed computational techniques. Figure 1 shows the difference between the temperature structure archived at the PDS (*PDS Atmosphere*) and my reconstruction (*Mine*) as a function of altitude. This should be compared with the absolute values of between 100 and 200 K in figure 7 of Magalhaes *et al.* (1999). The differences are only a few % and are primarily caused by my crude aerodynamic data for Pathfinder. My only knowledge of the aerodynamic characteristics of the spacecraft was Figure 3 of Magalhaes *et al.* (1999). A scanned copy of this figure was crudely digitized to serve as a proxy for accurate knowledge of the aerodynamic characteristics. The increased error seen in Figure 1 below 40 km corresponds to increased small-scale structure in Figure 3 of Magalhaes *et al.* (1999) which is not captured by my crude digitization. My results are described more fully in Section 3 of Withers (2001). A temperature profile of this quality as the result of the Mars Pathfinder Atmospheric Structure Experiment, though of a lower quality than that derived by the instrument team, would still have been a successful scientific result.

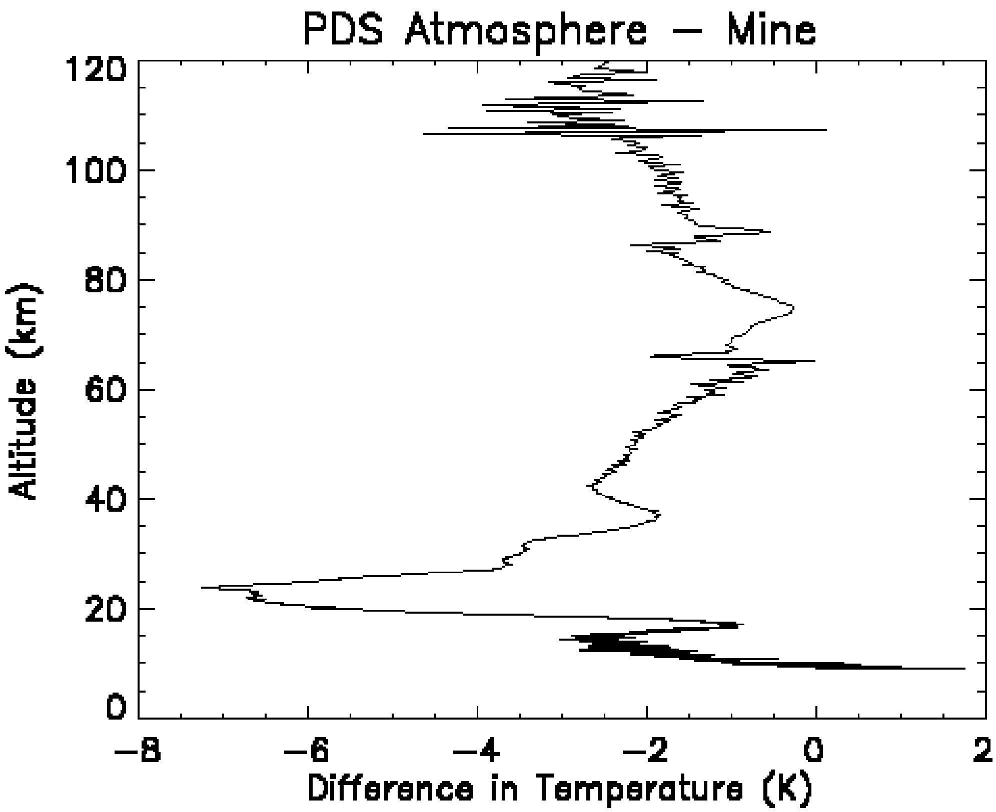

Figure 1

2 – Data Requirements

2.1 – Primary Data

The primary data required for this proposal are:

A Aerodynamic characteristics of the spacecraft with uncertainties of 10% or less (Braun *et al.*, 1995; PIP FAQ #7).

B Entry state of the spacecraft with uncertainties comparable to those of Pathfinder (Magalhaes *et al.*, 1999)

C 3-axis accelerometer and 3-axis rate gyro measurements from both rover and backshell IMUs sampled at 8 Hz prior to and during EDL with the specifications in the PIP FAQ #7 and the Litton website referenced by the PIP FAQ.

D Measurements of IMU or spacecraft internal temperature during entry for calibration (PIP, p49)

E Occasional measurements during cruise to study offset drifts with temperature and time (PIP, p49)

F Post-landing measurements at known martian surface gravity for calibration (PIP, p49)

A must be provided to me by the MER project, most probably by the Langley aerothermodynamics group who have performed this work in the past (PIP FAQ #7). This information will have been generated prior to landing for designing the entry trajectory.

B must be provided to me by the MER project, most probably by the JPL NAV team who have performed this work in the past (PIP, p49). This information will have been generated prior to landing for a final landing ellipse estimate.

The required data volume, **C**, is small. The EDL IMU data covers two minutes of pre-entry data for final offset calibration, six minutes of entry, and two minutes of post-landing data (PIP, p6 and p49). A sampling rate of 8 Hz (PIP, p49) requires 4800 sets of measurements. Both the rover and the backshell carry an IMU (PIP, p49). Each IMU consists of a 3-axis accelerometer and a 3-axis rate gyro (PIP, p49). This requires a total of 57600 individual measurements. With a sampling rate of 8 Hz and a delta-v resolution of 6.1E-5 m s^{-1}, the accelerometer resolution is 4.88E-4 m s^{-2} (PIP FAQ #7). With a range of 81.6 G, which is 1.7E6 times greater than the resolution, this requires 21 bit data, since 2^{21} is 2.1E6 (PIP FAQ #7). Unlike the digitization of one of the three Pathfinder gain states, -16 mg to +16 mg with 14 bit digitization to give a digital resolution of 2 μg, this digitization does not give an exact power-of-2 relationship between resolution and range. Also, 21 bit analogue to digital converters are rare. I suspect that the specifications in the PIP FAQ are incomplete. The PIP mentions *all gain settings* on p49, yet the specifications give only one range and one resolution. I suspect that, like most previous atmospheric structure experiments, digitization to a specified number of bits is applied to several gain states and the gain state switched several times during entry. However, for the purposes of this proposal, I shall use the specifications in the PIP FAQ and hence 21 bit digitization. I assume an identical number of bits and sampling rate for the gyros. This gives a data requirement of 1.2 Mbits to be recorded during EDL and later transmitted. The total transmission time required is less than 10 s using the 128 kbits s^{-1} nominal link to Mars Odyssey (PIP, p60). This data volume is approximately 1% of that required for a single PC/MT 360 Panorama (PIP, p68). Once recorded, this data can be transmitted at any time during landed operations, but Objective 1 is best served with transmission in the first sols. The PIP implies that the MER project is already committed to returning this data to Earth (PIP, p49).

D must be provided to me by the MER project, most probably by engineers studying the thermal state of the spacecraft during entry. This information will be recorded during entry and returned to Earth for engineering purposes.

For **E**, two minutes of calibration during every one of the seven months of cruise requires a similar total data volume. The PIP implies that the MER project is already committed to returning this data to Earth (PIP, p49).

For **F**, a post-landing set of IMU measurements, detecting martian surface gravity for calibration purposes, will require an even smaller amount of data. The backshell IMU will have been discarded and a high sampling rate is not needed. 1 min of 1 Hz data from the accelerometer only gives 3780 bits. The PIP implies that the MER project is already committed to returning this data to Earth (PIP, p49)

2.2 – Data Processing

With the primary data I have requested, I will derive entry trajectories and atmospheric structure profiles in the following way:
Step 1 - The calibration data will be used to transform each IMU output into linear and angular accelerations with known uncertainties.
Step 2 - The two independent IMU datasets and their known locations and directions relative to the spacecraft reference frame will be merged to yield centre of mass linear accelerations and angular accelerations about the spacecraft axes and uncertainties.
Step 3 - Using the specified entry state and its uncertainty, the known martian gravitional field and its uncertainty, the linear and angular accelerations and their uncertainties, the equations of motion will be integrated to obtain spacecraft position, velocity, attitude, and rotation state and associated uncertainties as a function of time.
Step 4 – Each of the three linear and three angular acceleration measurements at a given time and their uncertainties can be substituted into an aerodynamic equation similar to equation 1 (Peterson, 1965a, 1965b).

$$\rho C_D A V^2 = -2ma \qquad (1)$$

Spacecraft mass, m, and reference area, A, and their uncertainties are known. The relevant velocity, V, and linear acceleration, a, and their uncertainties are known from Step 3. The relevant aerodynamic coefficient, such as C_D, and its uncertainty can be obtained from the aerodynamic database using the spacecraft attitude and velocity solution and *either* an estimate for the atmospheric density and pressure at this point *or* a solution for the atmospheric density and pressure from a previous iteration (Magalhaes *et al.*, 1999). The six independent density estimates, ρ, should be consistent and the one with the lowest uncertainty can be carried forward. This will be the linear acceleration along the spacecraft symmetry axis, since it will have the best signal to noise ratio.
Step 5 – Calculate the atmospheric density scale height as high as the uncertainties in the solution for the density permit.
Step 6 – Use the solution for the density and its uncertainty, the density scale height and its uncertainty, the trajectory and its uncertainty, and the known gravitational field, g, and its uncertainty to integrate equation 2, the equation of hydrostatic equilibrium, as a function of altitude, z, to solve for pressure, p, and its uncertainty at each point along the trajectory.

$$p = -\rho g \left(\frac{d}{dz} \ln \rho \right)^{-1}_{z0} - \int_{z0}^{z} \rho g dz \qquad (2)$$

Step 7 – Use the solutions for pressure and density and their uncertainties and the appropriate mean molecular weight, μ, and its uncertainty to solve the equation of state for temperature, T, and its uncertainty. R is the universal gas constant.

$$T = \frac{p\mu}{\rho R} \qquad (3)$$

Step 8 – Iterate using the previous solution to constrain the aerodynamic characteristics for the next solution until consistency is obtained.

As discussed in Section 2 of Withers (2001), I have already developed basic computer techniques for this procedure and tested an accelerometer-only version of them on the Pathfinder data. The techniques require additional development to verify the accelerometer and gyroscope versions, incorporate additional constraints (as discussed in Section 2.4), refine the numerical techniques, and perform a thorough and rigorous uncertainty analysis. I will be assisted in this software development for mission operations by approximately 0.25 FTE of a to-be-determined postdoc.

It is not computationally intensive to derive an atmospheric structure profile. The most time-consuming step is the validation of the data to identify bad data points and artifacts. Assuming that the instruments are behaving in a predictable way, I would be able to generate a preliminary solution for E/PO, MER-B support, and system performance analysis within a week, and possibly faster, of receipt of the requested nominal data. This would not require the post-landing surface gravity measurement.

2.3 – Uncertainties in Derived Data Products

The resolution and uncertainties of the data to be archived with the PDS are as follows:

0.125 s spacing of data points between 100 and 10 km altitude with vertical resolution of 250 m, uncertainty in absolute longitude of 200 m, uncertainty in absolute latitude and longitude of 0.05 degrees, uncertainty in density and pressure of 10%, and uncertainty in temperature of a few %.

8 Hz sampling gives a spacing of 0.125 s in time of the data points (PIP FAQ #7).

The maximum altitude at which useful results can be obtained is set by instrument digitization and noise. The specified delta-v resolution of 6.1E-5 m s^{-1} and sample rate of 8 Hz corresponds to a minimum resolvable aerodynamic acceleration of 4.88E-4 m s^{-2} (PIP FAQ #7). A noise level of 35 microG, or 3.5E-4 m s^{-2}, is close to the resolution limit, so two counts, or 9.76E-4 m s^{-2}, are required for confident detection of the atmosphere (PIP FAQ #7). Precise spacecraft specifications are not provided in the AO or PIP, so I will assume values similar to Pathfinder's. The spacecraft mass will be between its launch mass of 1063 kg and rover mass of 184 kg (PIP, p7 and p8). Pathfinder's entry

mass was 585.3 kg, its reference area was 5.526 m^2 and its entry speed was 7.4 km s^{-1} (Magalhaes *et al.*, 1999) Using a nominal drag coefficient of 2 and equation 1 above, this leads to a minimum detectable density of 2E-9 kg m^{-3}. This density level was reached at above 120 km on Pathfinder and both Vikings (Seiff and Kirk, 1977; Magalhaes *et al.*, 1999). By coupling a thermosphere-only theoretical model (MTGCM) with a lower atmosphere theoretical model (MGCM), the martian upper atmosphere can be studied using general circulation models (Pollack *et al.*, 1990; Bougher *et al.*, 1990, 2000; Zurek *et al.*, 1992; Murphy, 1995). For conditions appropriate to MER entry, this density level is predicted to occur at an altitude of 135 km with a nearby density scale height of 8 km (Bougher, personal communication). Hence, the MER IMU instrument will first detect the atmosphere at an altitude above 120 km. Uncertainties in derived density due to digitization will drop below 10% 2.3 scale heights below this. With a scale height of 8 km predicted by MTGCM and smaller scale heights observed by Pathfinder and both Vikings, this altitude is above 100 km (Seiff and Kirk, 1977; Magalhaes *et al.*, 1999).
These effects give a maximum altitude of above 100 km.

The minimum altitude at which useful results can be readily obtained is that at which the parachute opens. This will be 10 km (PIP, p8). The aerodynamic characteristics of disk-gap-band parachutes are much more complicated and less well constrained than those of blunt conical heatshields, which greatly increases the uncertainty in the derived atmospheric structure profile. Figure 1 of Magalhaes *et al.* (1999) illustrates the complex motion of Pathfinder once its parachute opened. Future data analysis investigations may be possible using data from the parachute descent phase – see Seiff (1993), Seiff *et al.* (1997), Atkinson *et al.* (1998), Allison and Atkinson (2001) and anticipated results from the long duration parachute descent of Huygens.
These effects give a minimum altitude of 10 km.

The vertical resolution of the data is the product of the vertical speed and the sampling rate. A Pathfinder-like vertical speed at entry of 2 km s^{-1} and a sampling rate of 8 Hz corresponds to a vertical resolution of 250 m (Magalhaes *et al.*, 1999; PIP, p49). The vertical speed will decrease monotonically during descent and the vertical resolution will scale linearly with it.
These effects give a vertical resolution of less than 250 m.

The uncertainty in the absolute altitude of each data point will be affected by:

- Instrument acceleration resolution of 4.88E-4 m s^{-2} which integrates to an uncertainty in altitude of 0.5 x 4.88E-4 m s^{-2} x $(t/s)^2$ = 30 m for a 6 minute entry duration (PIP FAQ #7).
- Uncertainty in vertical entry velocity, which was about 0.2 m s^{-1} for Pathfinder, which integrates to an uncertainty of 0.2 m s^{-1} x (t/s) = 70 m for a 6 minute entry duration (Magalhaes *et al.*, 1999)
- Uncertainty in the entry state altitude, which was about 2 km for Pathfinder (Magalhaes *et al.*, 1999). This can be improved by referencing the trajectory to the landed altitude, which will be known to about 100 m from the landed latitude and longitude derived using the entry state as reference. The landing ellipses are

required to be quite flat on the scale of the uncertainty in the landed latitude and longitude (http://marsoweb.nas.nasa.gov/landingsites/).

- Uncertainty in gravitational acceleration due to uncertainty in position. Uncertainty in gravity equals uncertainty in altitude x 2g/r, which is about 2E-4 m s^{-2} for a 100 m uncertainty in altitude. A first order estimate of this effect using the same formula as for the instrument resolution gives a 15 m uncertainty in altitude.

These effects give a total uncertainty of less than 200 m.

The uncertainty in the absolute latitude and longitude of each data point will be affected by:

- Instrument acceleration resolution of 4.88E-4 m s^{-2} which integrates to an uncertainty in altitude of 0.5 x 4.88E-4 m s^{-2} x $(t/s)^2$ = 30 m for a 6 minute entry duration (PIP FAQ #7)
- Uncertainty in horizontal entry velocity, which was about 0.7 m s^{-1} for Pathfinder, which integrates to an uncertainty of 0.7 m s^{-1} x (t/s) = 250 m for a 6 minute entry duration (Magalhaes *et al.*, 1999)
- Uncertainty in the entry state latitude and longitude, which was about 0.04 degrees for Pathfinder (Magalhaes *et al.*, 1999). A km-scale roll of the spacecraft from the impact point to the position during the first landed transmissions prevents an accurate measurement of the landed position from greatly improving the latitude and longitude of the impact point (PIP, p8)

These effects give a total uncertainty of less than 0.05 degrees.

The uncertainty in the density given by equation 1 at each data point will be affected by:

- Uncertainty in aerodynamic characteristics of up to 10% (PIP FAQ #7).
- Other quantities in equation 1 are known with significantly lower uncertainties.

These effects give a total uncertainty of less than 10%

The uncertainty in the pressure given by equation 2 at each data point will be affected by:

- Uncertainties in the constant of integration, which I neglect since this constant contributes less than 10% of the derived pressure after the first two scale heights.
- Uncertainty in density (due to uncertainties in aerodynamic characteristics of up to 10%) of less than 10 %. If anything is known about the behaviour of the errors in the aerodynamic characteristics, such as becoming uncorrelated over a specified altitude range, then their contribution to the uncertainty in pressure can be reduced.

These effects give a total uncertainty of less than 10%

The uncertainty in temperature given by equation 3 is more subtle. Uncertainties in mean molecular weight are less than 1% below 100 km altitude (Seiff and Kirk, 1977; Magalhaes *et al.*, 1999). However, the uncertainties in density and pressure are not independent. They are both dominated by uncertainties in aerodynamic characteristics and are correlated, so it is wrong to assign an uncertainty of $(10^2+10^2)^{1/2}$=14% to the temperature. If errors in the aerodynamic characteristics are somewhat correlated over a range in altitude then, since the error in pressure at a given altitude is dominated by the

error in the aerodynamic characteristics at and just above that altitude, the errors in density and pressure will partially cancel out. The errors in aerodynamic characteristics will be correlated over a range in altitude since the aerodynamic characteristics are obtained by interpolating a small number of fluid dynamic experiments and numerical modelling experiments. Exact quantification of this effect requires detailed knowledge of the procedure by which the aerodynamic characteristics are estimated, but a simple example illustrates it. Using a fixed drag coefficient of 2, rather than my crude digitization of a state-of-the-art model, I derived a Pathfinder temperature structure, shown on page 60 of Withers (2001), that differs from the nominal PDS temperature by less than 5% over all altitudes. The density and pressure results are in error by much more.
These effects give a total uncertainty of less than a few %.

There are additional effects that must be considered in a complete formal uncertainty analysis. At least one of the two IMUs on each spacecraft will be significantly offset from the centre of mass, so the data will have to be corrected to obtain the centre of mass accelerations. The correction will introduce additional uncertainties. The numerical accuracy of the reconstruction software must be examined, as discussed in Magalhaes *et al.* (1999) and Section 3.6 of Withers (2001). Instrument noise of 3.5E-4 m s^{-2} will average to zero on long timescales, but is important on short timescales (PIP FAQ #7). This noise value is appropriate to the bare sensor. It will be increased for the actual instrument which contains additional electronics between the sensor and the telemetry stream. The noise level can be estimated from the cruise measurements. Winds mean that the spacecraft velocity relative to the atmosphere, which affects the aerodynamic force experienced by the spacecraft, differs from the spacecraft velocity relative to the planet's surface, which is calculated during the trajectory reconstruction. Magalhaes *et al.* (1999) predict winds of 15 m s^{-1} at the time of parachute opening when Pathfinder's speed was 377 m s^{-1}. Depending on the angle between reconstructed spacecraft velocity and predicted wind velocity, this 4% uncertainty in the velocity term in equation 1 can lead to an additional contribution of 8% to the uncertainty in the derived density. It also affects the derived trajectory. Systematic differences between the measured and actual accelerations can lead to significant errors in the reconstructed trajectory and atmospheric structure profile in the lower atmosphere and calibration efforts must minimize them. (Seiff, 1963). Drifts in gains and offsets as a function of temperature and time can cause such differences and pre-flight calibration will be used to model them (PIP, p49). The shock of launch will also contribute to these drifts. Since the IMU measurements will be used to control atmospheric entry, cruise measurements will of necessity be made to constrain the zero offset.

2.4 – Minimizing Uncertainties with Secondary Datasets

There are some secondary data that would benefit this proposal and will be obtained by other investigations.

The landed position of the spacecraft, up to 1 km away from the point of impact (PIP, p8), will be determined, by monitoring the rover's direct-to-Earth transmissions, to within

100 m within 3 sols of landing (PIP, p50). Pathfinder's altitude was eventually determined to metre-scale accuracy (Folkner *et al.*, 1997). This will provide a very accurate reference altitude for the trajectory, even allowing for 1 km of horizontal roll after impact.

Unlike Mars Polar Lander, there will be direct-to-earth transmission of signal tones during entry (PIP, p7). The Doppler shift of these transmissions constrains the spacecraft velocity throughout entry. However, these are *challenging communications conditions*, so it is not clear how accurately the transmissions will constrain the spacecraft entry velocity (PIP, p7). They may be accurate enough to constrain the final atmospheric structure profile, they may only be accurate enough to derive a very rapid and very uncertain trajectory and atmospheric structure profile, or they may be of no use at all. Pre-entry discussions with MER project communications team will define the expected accuracy of these constraints.

Radar altimetry below 2.4 km altitude will constrain the spacecraft position and velocity (PIP, p8). Uncertainties in position increase at least linearly as a function of time since entry, depending on which error term discussed in Section 2.2 is dominant. Constraints on the position near the end of the trajectory will cap this increase in uncertainty. No radar specifications are provided in the PIP, so I cannot quantify this effect.

2.5 – Plan for Producing and Delivering Data to the Planetary Data System (PDS)

MIPL is responsible for generating Level 0 EDRs for all the Athena science instruments (PIP, p80). The IMUs are not listed as science instruments in the AO, but I assume MIPL would be responsible for generating level 0 EDRs for the IMUs if this proposal is accepted. Since *there are currently no selected scientists on the Athena Science Team who will derive atmospheric properties from the accelerometer profiles*, I would be willing to serve as a nominal Payload Element Lead (PEL) for the IMUs in terms of data archiving (PIP FAQ #10). PELs for the science instruments have additional calibration responsibilities, but *JPL engineers have the primary responsibility for designing, calibrating, and operating the* IMUs, since the primary purpose of the IMUs is operations rather than scientific analysis (PIP FAQ #11).

The PDS Data Preparation Workbook (http://pds.jpl.nasa.gov/dpw/) lists six steps in the archiving process:

Orientation - finding out what PDS will expect
Archive planning - deciding what to archive, when, and generally how
Archive design - learning the details of putting an archive data set together
Data set assembly and validation - pulling the pieces together
Data set reviews - the final PDS quality check
Delivery - passing the result to PDS

The Mars Exploration Program Data Management Plan, currently being written, will probably be a greatly expanded version of this schematic (AO, p3). My data delivery will conform with this plan.

Orientation – This will be done in consultation with the DAWG (AO, p80).
Archive Planning – I plan to archive calibrated linear and angular acceleration data as a function of time (Level 1 data) within the six months mandated by the PIP (p81). I plan to archive altitude, latitude, longitude, density, pressure, and temperature measurements as a function of time with the uncertainties and coverage discussed in Section 2.2 (Level 2 data) within six months after the Level 1 archiving. I plan to archive improved versions of these results, as discussed in Section 2.3, in a timely manner. I plan to participate in the generation of the sections of the Project Data Management Plan and the Archive Policy and Data Transfer Plan that involve IMU data.
Archive Design – PDS volume MPAM_0001 is the final dataset associated with the Pathfinder atmospheric structure profile. I plan to use its structure as a template. The EDL portion of this volume is a few Mbytes in size. This proposal should generate a similarly sized dataset.
Data set assembly and validation – I will generate the data products as discussed in Section 2.1. I will validate the software used to generate them on data from similar instruments on other spacecraft missions and pseudo-data generated by the project as part of EDL design. I will validate the data products by comparing them to similar products that will be independently derived by engineering teams analyzing EDL, to pre-existing Mars atmospheric profiles, and to theoretical predictions. I will collaborate with the MMO Science Validation Team on additional validation (PIP, p78).
Data set reviews – This will be led by the PDS.
Delivery – I will transfer the dataset to the PDS electronically, who will ensure that it is copied onto physical media (PIP, p78).

3 – Mission Requirements

3.1 – Constraints on Mission Operations

This proposal involves no changes to mission operations. The PIP implies that the MER project is already committed to returning the primary data required by Section 2 of this proposal (PIP, p49).

The data and instrument performance required to achieve the scientific objectives of this proposal have been outlined in Section 2. If instrument performance is less than nominal, then the changed uncertainties in the derived data products can be calculated following the calculations of Section 2.2.

3.2 – Descope Options

Useful science can be done if instrument performance is less than nominal. As long as one z-axis accelerometer on one spacecraft is able to operate without violating any of the conditions listed below, I would recommend continuing with this proposal:

- Instrument resolution of 5 m s^{-2} or worse, which, scaling linearly from page 65 of Withers (2001), gives an minimum error in temperature of 10K between 20 and 50 km altitude for the Pathfinder reconstruction and larger errors elsewhere.

- Noise level of 5 m s^{-2}, following the reasoning above.
- Uncorrectable systematic offset of 1 m s^{-2} or worse, which gives an error in position of 40 km after 6 minutes.
- Instrument range of 0 to 0.1 m s^{-2} or worse, which corresponds to an altitude of above 80 km in the Pathfinder reconstruction.
- Sample rate of 0.1 Hz or worse, which corresponds to a vertical resolution of 20 km.

3.3 – Opportunities Created by the Beagle 2 Lander

Rapid analysis of the MER-A entry is currently planned by the MER EDL team to support MER-B entry. There are two aspects to this analysis: *How well was the atmospheric structure profile predicted prior to entry?* and *Did the spacecraft perform in a nominal way during its passage through this atmospheric structure?* The performance, nominal or otherwise, of Beagle 2 just prior to MER-A entry is of minimal immediate interest to the MER project. However, derivation of only the fourth atmospheric structure profile ever measured on Mars on 26 December 2003, just prior to MER-A entry, is of great immediate interest to the MER project. I developed the techniques and wrote the software that will be used by John Zarnecki's group at the Open University to derive that profile (Withers, 2001). I anticipate being given the opportunity to participate in the analysis of this dataset, if only to explain my software to those using it. My presence within the MER project places the MER project in a better position for negotiating access to that data with an agreement between the University of Arizona and Zarnecki's Open University group.

Maximizing the scientific return from the atmospheric structure profiles derived by MER requires comparison and contrast with the near-simultaneous Beagle 2 atmospheric structure profile. If this proposal is accepted, I will be in a unique position to understand the exact derivation and uncertainty analysis of all three near-simultaneous atmospheric structure profiles, which will enhance my scientific analysis.

I maintain good relations with my colleagues on the Beagle 2 project.
I am not committed to any further effort on the Beagle 2 project.
I am not able to commit the Beagle 2 project to anything.
No exchange of funds or breach of ITAR regulations is proposed here.

In this proposal, I do not propose to include the Beagle 2 project, or any foreign participation, in the MER project. In this proposal, I propose to advocate negotiation by the MER project for access to the Beagle 2 (Mars entry on 26 December 2003) accelerometer data with the aim of supporting the MER-A entry with Beagle 2 data just as the MER-B entry will be supported with the MER-A data. This proposed advocacy would take place within the MER project and hence this proposal does not require a response to the amended Section 6.7.2 of the AO.

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Resume, Relevant Experience, Curriculum Vitae for Paul Withers

Fourth year PhD candidate and Graduate Research Associate,
Lunar and Planetary Laboratory, University of Arizona.

I have worked with the processed results of accelerometer data from aerobraking from Mars Global Surveyor and Mars Odyssey, performing both an operational role and scientific analysis (Withers *et al.*, 1999, 2000, 2001a, 2001b). This has been through the membership of my advisor, Steve Bougher, in Atmospheric Advisory Groups for these missions. Working with this data, I have become familiar with the necessary data processing, as detailed in Cancro *et al.* (1998) and Tolson *et al.* (1999, 2000), and its scientific applications. I also assisted in the PDS peer review of the MGS dataset.

During the summer of 2001, I was a research consultant with the Beagle 2 project at the Open University in Great Britain. The environmental science package, whose PI is John Zarnecki of the Open University, of this Mars lander contains an accelerometer and many other instruments (Towner *et al.*, 2000). I learned how entry accelerometer data had been processed and analysed on previous missions by reviewing the extensive literature (*e.g.* Chapman, 1958; Seiff, 1963; Peterson, 1965a, 1965b; Sommer *et al.*, 1967; Seiff *et al.*, 1973; Hopper, 1975; Inogoldby *et al.*, 1976; Kerzhanovich, 1977; Seiff and Kirk, 1977; Seiff *et al.*, 1980; Avduevskiy *et al.*, 1983; Seiff *et al.*, 1996; Blanchard *et al.*, 1999; Magalhaes *et al.*, 1999; Spencer *et al.*, 1999). Starting with the equations of motion and the drag equation, I developed computer techniques to reconstruct trajectory and atmospheric structure from accelerometer measurements, as detailed in Section 2.2 above. Using only crude knowledge of the Pathfinder aerodynamic characteristics and the spacecraft entry state, mass, reference area, and accelerometer measurements archived in PDS volume MPAM_0001, I reproduced the earlier results of Magalhaes *et al.* (1999) and Spencer *et al.* (1999). My results are described fully in Section 3 of Withers (2001). My techniques were successful and will be used by the Beagle 2 project to perform its trajectory and atmospheric structure reconstruction.

I have several years of experience of working with accelerometer data and I have already developed computer techniques that can generate scientifically useful results from accelerometer and/or gyroscope atmospheric entry data.

Summer research placements

- Beagle 2 project at the Open University, Great Britain, summer 2001
- MOLA group at NASA/GSFC, summer 2000
- Theoretical Astrophysics Program at Caltech, summer 1997
- Isaac Newton Group of Telescopes on La Palma, Spain, summer 1996

Academic Status

- Completed all PhD requirements except final dissertation
- 4.0 GPA at the University of Arizona
- GRE Physics, 92nd percentile, and GRE General, over 97th percentile in all subjects

- BA and MS in Physics, University of Cambridge, all grades First Class (equivalent of 4.0 GPA)
- I plan to graduate in the summer of 2003.

Mission Involvement

- Mars Global Surveyor (Accelerometer and Laser Altimeter)
- Mars Climate Orbiter (Accelerometer)
- Mars Odyssey (Accelerometer)
- Beagle 2 (Accelerometer).

Community Involvement

- Peer-reviewer for *Science* and *Meteoritics*
- Member of AGU's Planetary Sciences Section and AAS's Division of Planetary Sciences since 1999.
- Member of Solar System Exploration Decadal Survey E/PO Community Panel and Community Discussion Forum Moderator (DPS 2001 poster 14.02 and http://www.aas.org/~dps/decadal/)
- Attended several E/PO and teaching workshops
- Invited colloquium presentation at Imperial College, Great Britain, summer 2001
- Highly Commended – Daily Telegraph's Young Science Writer of the Year contest, 2000 (UK national newspaper)
- Winner – NASA's Deep Space 2 naming contest, out of 17,000 entrants

Selected Publications

- Withers and Neumann (2001) Tectonism in the Northern Plains of Mars, *Nature*, **410,** 651 [http://www.lpl.arizona.edu/~withers/pppp/pdf/molanature2001.pdf]
- Withers (2001) Meteor Storm Evidence Against Recent Formation of Lunar Crater Giordano Bruno, *Meteoritics,* **36,** 525-529 [http://www.lpl.arizona.edu/~withers/pppp/pdf/mapsbruno2001.pdf]
- Lorenz, Lunine, Withers, and McKay (2001) Titan, Mars and Earth: Entropy Production by Latitudinal Heat Transport, *Geophys. Res. Lett*., **28,** 415-418 [http://www.lpl.arizona.edu/~withers/pppp/pdf/mepgrl2001.pdf]
- Withers (2001) "You are required to assist on the Atmospheric Structure Reconstruction using the Beagle 2 Entry, Descent, and Landing Accelerometer", Final Report to the Planetary and Space Sciences Research Institute, The Open University, for Consultancy Contract 01249983\001 [http://www.lpl.arizona.edu/~withers/pppp/pdf/oureport.pdf]
- Withers *et al.* (2001) Short term variability in the martian upper atmosphere according to the Mars Global Surveyor Accelerometer, *Geophys. Res. Lett.,* to be submitted in December 2001
- Withers *et al.* (2001) Mars Global Surveyor Accelerometer Results, *J. Geophys. Res.,* in preparation

Conference Presentations

- Withers *et al.* (1999) The martian upper atmosphere during phase 2 of Mars Global Surveyor aerobraking: comparison to predictions, *Fifth International Conference on Mars*, Abstract #6073
- Withers (2000) Angle of repose-limited shapes of asteroids, 2000, *Lunar Planet. Sci. Conf.*, **31,** Abstract #1270
- Withers *et al.* (2000) New results from the Mars Global Surveyor Accelerometer, 2000, *Lunar Planet. Sci. Conf.*, **31,** Abstract #1268
- Withers and Neumann (2000) Shallow Ridges in the Martian Northern Plains, *Fall AGU*, Abstract #P62B-02
- Withers and Lorenz (2001) Simple Tests of Simple Climate Models, *Spring AGU*, Abstract #U32A-05
- Withers (2001) Meteor storm evidence against the recent formation of lunar crater Giordano Bruno, 2001, *Lunar Planet. Sci. Conf.*, **32,** Abstract #1007
- Withers *et al.* (2001) Harmonic Analysis of Zonal Density Structures in Martian upper atmosphere, 2001, *Spring AGU*, Abstract #P41A-05
- Withers *et al.* (2001) Unpredictable day-to-day variability in the martian upper atmosphere, *AAS DPS Conf.*, **33,** Abstract #19.29
- Withers *et al.* (2002) Development and Verification of Analysis Techniques for Beagle 2 Entry Accelerometer Data, *Lunar Planet. Sci. Conf.*, **33,** in preparation

Statement of Commitment for Education/Public Outreach

I understand and intend to participate in and contribute [to] the Mars Exploration Education and Public Outreach program as planned and executed by the JPL Mars Program Office.

The Lunar and Planetary Laboratory has a long and distinguished history of making the results of solar system exploration accessible to the public. It compiled the first Lunar Atlas (Kuiper) and led the first projects to image the outer solar system (Gehrels for Pioneer and B. Smith for Voyager). More recently, it led the Imager for Mars Pathfinder project (P. Smith) whose images appeared on the cover of National Geographic, US postage stamps, and TV screens around the world; the Gamma Ray Spectrometers for Mars Observer and Mars Odyssey (Boynton); and has just been awarded the high-resolution imaging system for the Mars Reconnaissance Orbiter (McEwen). It hosts a NASA Regional Planetary Image Facility and the State of Arizona's Space Grant program. All of these had or have an important E/PO component and contribute to institutional experience with education and public outreach. This experience and expertise will aid my E/PO efforts on behalf of the MER project. I can suggest several ideas for E/PO activities related to this proposal that I think would be particularly worthwhile and/or unique.

Many planetary missions and individual instruments have names and patches. Such symbols provide an accessible, unifying theme for a dispersed and complex scientific activity. The IMU instruments have no logo, name, or theme. As they will produce Atmospheric Structure Profiles, they should bear the name ASP. The twisting, turning nature of the T(z) plot, the data product most easily accessible to the public, is reminiscent of the meandering and slithering body of a snake. I plan to solicit designs from the public for a patch for the ASP experiment, similar to many NASA naming contests in the past. This state's World Champion baseball team, the Arizona Diamondbacks, also has a snake motif, so they may be interested in some involvement in this contest. The initial announcement of the contest could be made in collaboration with a local zoo and their snakes. A reward for the successful design is included in my budget.

Many undergraduate students learn how to integrate accelerations to velocities and positions during their introductory physics curriculum or learn about lift and drag in introductory engineering curriculum. I suggest working with the MER project's E/PO team to produce a simplified, idealized set of accelerations and initial conditions that enable students to make discoveries about the martian atmosphere. This will support two of OSS's three goals for E/PO (*Share the excitement of space science discoveries with the public* and *Enhance the quality of science, mathematics, and technology education*).

To my mind, two aspects of the Pathfinder mission captured the most public attention – the Sojourner rover and the bouncing of the airbag landing. The IMU accelerometer and gyro data can calculate how high the landers bounced, how far they rolled, and how many times they bounced (Golombek *et al.*, 1999). These results can effectively engage the public in the MER mission even before the first image is returned.

Management and Cost Plan

Management Plan

Existing facilities and equipment at the University of Arizona will be used to perform this proposed work. Two computers will be purchased, installed, and operated in accordance with university policy.

Cost Plan

Goods and services offered at no cost to NASA – none. Labor costs include a major portion of my salary for the duration of the project, a major portion of a graduate student assistant's salary for the final two years of the project, and minor contributions to postdoctoral salaries for software development and scientific data analysis over limited periods. Equipment costs are for two computers to perform the data analysis and mission operations. Extensive travel is required by the AO, including the Science Team meetings at JPL, the ORTs at JPL, the rover fieldtests at JPL, the expensive and long duration landed mission at JPL, the Science Team meetings at Ithaca, and the Science Team meeting in Europe. I have also included some additional travel, including several short trips away from JPL during the long duration landed mission, an annual 2 day trip to JPL for instrument calibration and other activities, 2 scientific conferences in each of the last 2 years of the proposal to present my results to the wider scientific community, and a technical meeting at the launch site. The E/PO costs reflect my commitment to the mandated E/PO activities. Other costs are to support my research. The materials cost includes books (technical publications to provide ready access to background information and new developments), computer consumables (Zip disks, CD-RWs, etc), and office supplies. Software costs are primarily for an IDL license. Conference registrations of approximately $100 per conference are needed to attend the scientific conferences, such as the Spring and Fall AGU meetings. Publication and reprint charges assume page charges of up to $100 per page and between $100 and $200 for each set of reprints. These will likely be used to write one paper discussing the IMU instrument and its calibration and performance and another discussing the detailed scientific results of this proposal. Express shipping is needed to send hard copies of newly updated information to colleagues and reports and papers to journals and MER project staff. Xerox costs are included to make personal copies of useful scientific papers and sections of books. Long distance costs are needed to communicate with colleagues and MER project staff.

The precise responsibilities of each salaried individual will be provided in the Implementation Plan, to be delivered after selection (AO, p8). The data analysis postdoc would be responsible for comparing the derived profiles with the many and varied orbital remote sensing datasets. I anticipate that this postdoc would already be familiar with these datasets. The software development postdoc would share responsibility with me for incorporating the constraints of Section 2.4 and uncertainty analyses into my software. The graduate research assistant would assist in the scientific analysis of the data. I would be responsible for all other tasks and be in overall charge.