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Dr. Jim Green
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Dear Dr. Green,

Please find enclosed an unsolicited proposal entitled “Analysis of Phoenix Entry Data to Support Future Mars Landers”. The main objectives of this proposal are to ensure that an accurate atmospheric entry profile is determined from Phoenix data and archived at the Planetary Data System. Successful completion of these objectives is a necessary precursor to the evaluation of atmospheric predictions made for Phoenix’s landing and to the evaluation of the performance of the Phoenix landing system. It will also lead to improvements in physics-based atmospheric models used to make predictions for future Mars landers. The timely delivery of an accurate atmospheric profile to the Planetary Data System is important to NASA. However, a very low level of funded effort is currently assigned by the Phoenix Science Team to reconstruction of the atmospheric entry profile and delivery of these data products to the PDS.

The objectives of this proposal cannot be accomplished through an R&A program such as MDAP because they require close interaction with the Phoenix project engineers during EDL and information that is not available from the PDS (e.g. position and orientation of gyroscopes and accelerometers). For instance, the PDS archive for Spirit and Opportunity entry data is incomplete which prevents full analysis of that dataset. The justification for submitting an unsolicited proposal is described in more detail in Section 4.

Please direct this proposal to the appropriate program manager(s) for evaluation. I believe that this proposal will be of interest to the Phoenix and Mars Science Laboratory projects, as well as the overarching Mars Exploration Program.

Yours,
Paul Withers

Date of Submission: 14 January 2008

Project Duration: 1 May 2008 - 30 Apr 2009

Proposal Title: Analysis of Phoenix Entry Data to Support Future Mars Landers (Unsolicited Proposal)

Short Title: Analysis of Phoenix Entry Data

Applicant Organization: Trustees of Boston University, 881 Commonwealth Avenue, Boston, MA 02215 (Educational Instution)

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Date

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Date

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Title: Analysis of Phoenix Entry Data to Support Future Mars Landers - Unsolicited Proposal

Short Title: Analysis of Phoenix Entry Data

Abstract

This is a proposal to determine vertical profiles of atmospheric density, pressure and temperature from measurements made during the atmospheric entry of NASA's Phoenix lander at Mars in May 2008. Data products will be archived at the Planetary Data System. This effort will support the goals of the Phoenix mission and reduce risk for future Mars landers, including Mars Science Laboratory. The objectives of this proposal are important to NASA because they must be accomplished before (A) NASA can evaluate the accuracy of atmospheric predictions for Phoenix EDL, (B) NASA can evaluate the performance of the highly-scrutinized Phoenix landing system, and (C) scientists can use the unique Phoenix atmospheric profiles to improve models that will influence the design of future Mars landers and the selection of their landing sites. This proposed effort supports, but does not duplicate, the Phoenix Science Team's existing efforts related to the atmospheric entry profile. An unsolicited proposal is submitted because this effort cannot be accomplished through the standard NASA solicitations.

Summary of Personnel and Effort

Name	Role	Institution	Funded effort	Unfunded effort
Paul Withers	PI	Boston Univ.	4 months	0
Graduate Student	Graduate Student	Boston Univ.	4 months	0

1 - Introduction

Phoenix is a NASA mission to land on the surface of Mars and study the history of water and habilitility near the north pole of Mars (Phoenix, 2008). It will arrive at Mars in late May 2008. Several of Phoenix's scientific sensors are designed to study the martian atmosphere. These studies of present-day climate are designed to support the Phoenix goal "Study the history of water" and the Phoenix objective "Describe Mars' polar climate" (Phoenix, 2008). Understanding the present-day martian climate is essential for understanding the present and past habitability of Mars, the underlying goal of NASA's Mars Exploration Program (MEPAG, 2006).

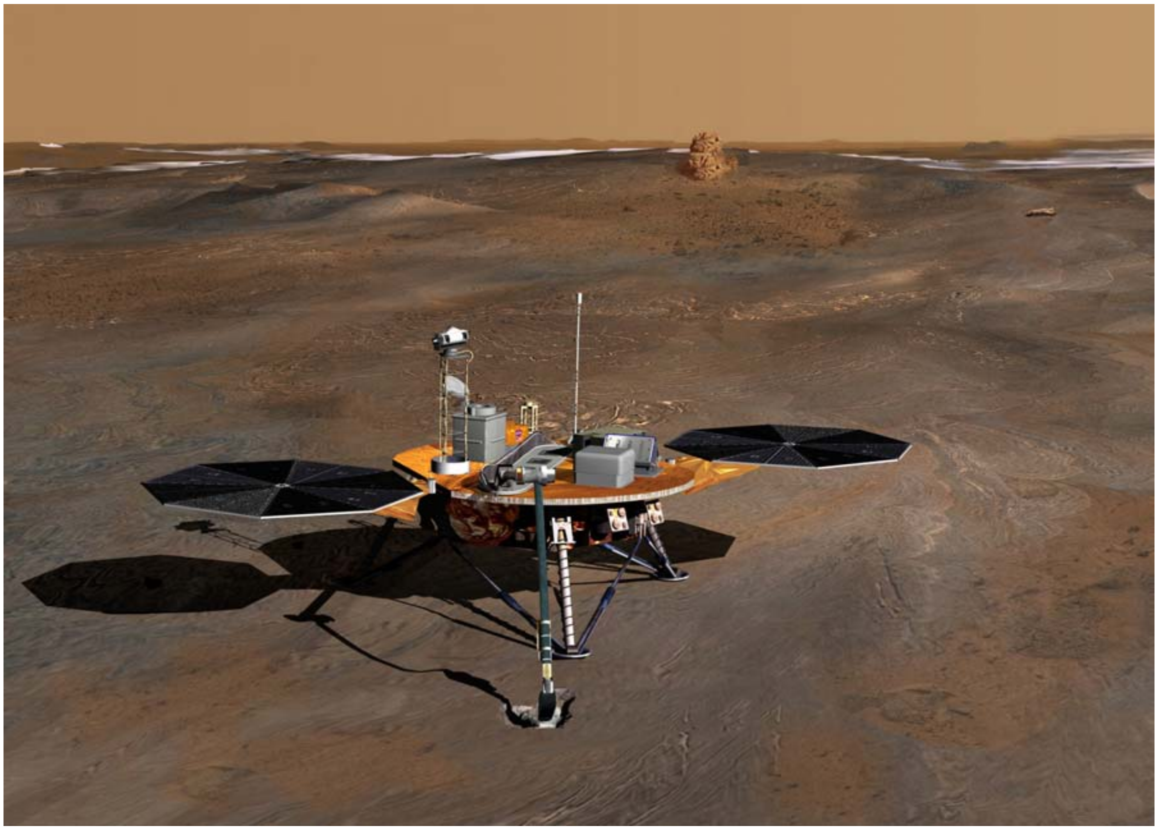

Figure 1. Phoenix lander (http://phoenix.lpl.arizona.edu)

Phoenix is capable of determining vertical profiles of atmospheric density, pressure and temperature during its descent to the martian surface. This will be the first atmospheric entry profile determined in the polar regions of Mars. Such profiles have better vertical range and vertical resolution than comparable remote sensing data from orbiters. Determination of this entry profile will contribute towards the scientific goals of the Phoenix mission. Determination of this entry profile will also help NASA reduce the risks experienced by future Mars landers after Phoenix.

Phoenix contains two Inertial Measurement Units (IMUs). Each IMU contains three single-axis accelerometers, which measure linear acceleration in a specific direction at a specific point, and three single-axis gyroscopes, which measure angular velocity in a specific direction at a specific point. These measurements can be integrated in the equations of motion, given initial conditions known as the entry state, to give the position and velocity of Phoenix as a function of time during its atmospheric entry. The deceleration that will be experienced by Phoenix during its atmospheric entry is related to the local atmospheric density (e.g Magalhaes et al., 1999; Withers et al., 2003a):

$$ma = \rho A v C / 2 \qquad (1)$$

where m is spacecraft mass, a is aerodynamic deceleration in a specific direction, ρ is atmospheric density, A is the reference area of the spacecraft, v is the speed of the spacecraft relative to the atmosphere, and C is a dimensionless force coefficient. The deceleration a is usually chosen to be the deceleration along the spacecraft's symmetry axis. C, which is usually on the order of 2, depends on atmospheric density and the orientation of the spacecraft with respect to its velocity vector.

Figure 2. Artist's impression of Phoenix entry (http://phoenix.lpl.arizona.edu)

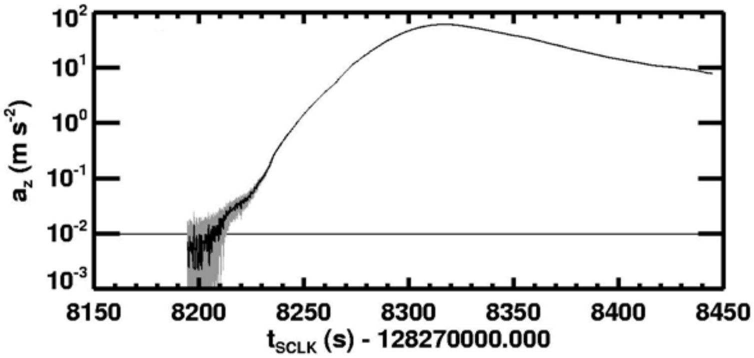

Figure 3. Time series of axial acceleration (m s^{-2}) recorded by Opportunity during its atmospheric entry. Times are spacecraft clock times (seconds). Data after parachute deployment are not shown. 1-σ uncertainties are shown in grey. Peak deceleration is at least 1000 times greater than instrumental uncertainties.

Atmospheric density along the Phoenix trajectory can be determined using Eqn 1 and measurements made by the Phoenix IMUs during entry. Since the entry trajectory is sufficiently close to vertical, the equation of hydrostatic equilibrium can be used to determine atmospheric pressure along the trajectory (Eqn 2). The ideal gas equation of state can then be used to determine atmospheric temperature along the trajectory (Eqn 3). The end results are vertical profiles of atmospheric density, pressure and temperature at the time and location of entry.

$$dp/dz = - \rho g \qquad (2)$$
$$p = \rho k T / \mu \qquad (3)$$

where p is pressure, z is altitude, g is gravity, k is Boltzmann's constant, and μ is atmospheric mean molecular mass.

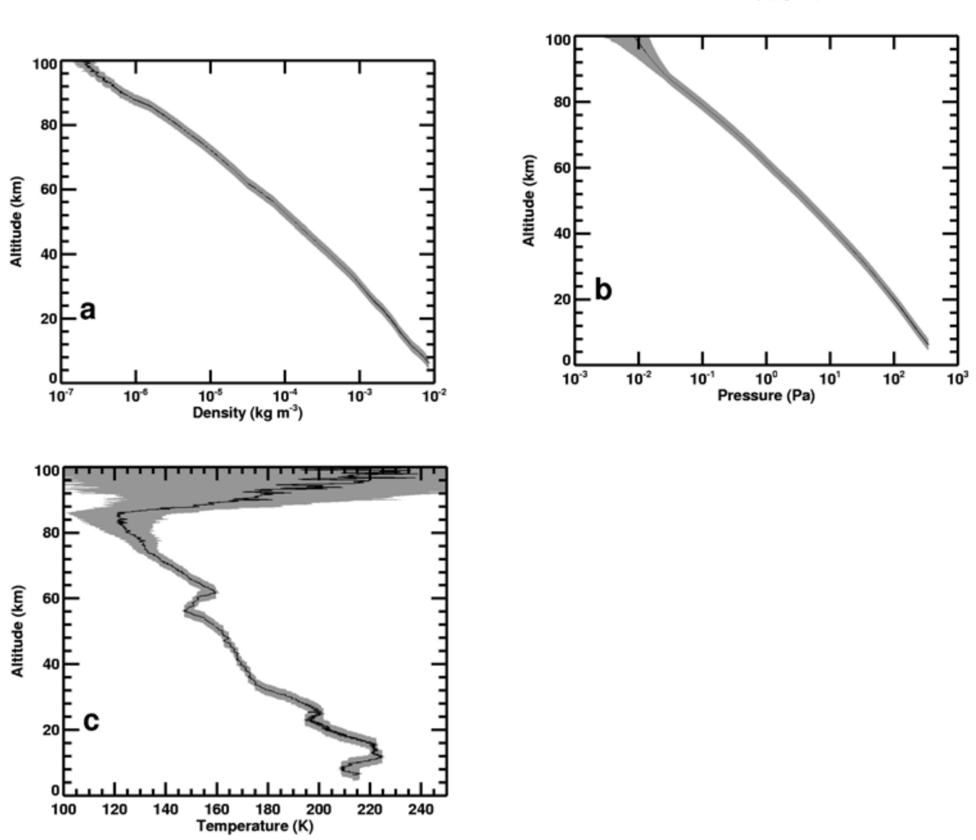

Figure 4. Vertical profiles of (a) density, (b) pressure, and (c) temperature for Opportunity. 1-σ uncertainties are shown in grey. From Withers and Smith (2006).

Such techniques have been used for the entries of Viking 1, Viking 2, Mars Pathfinder, Spirit and Opportunity (Seiff and Kirk, 1977; Magalhaes et al., 1999; Withers and Smith, 2006). Typical vertical range is 10 - 100 km and typical vertical resolution is <1 km. The lower altitude limit is imposed by parachute deployment, when the relationship between deceleration and density becomes more complex. The upper altitude limit is imposed by instrument sensitivity. The vertical resolution is controlled by the instrument's sampling rate. For Spirit and Opportunity, typical uncertainties were 5% in density and pressure and a few K in temperature (Withers and Smith, 2006). These uncertainties were controlled by uncertainties in the spacecraft aerodynamics and measured accelerations. Uncertainties for Phoenix should be similar because (A) Phoenix's aerodynamic database will be generated using the same numerical simulation tools as Spirit/Opportunity and (B) Phoenix and Spirit/Opportunity all use similar engineering-grade IMUs in similar positions (IMUs are not located directly at the center of mass nor on the axis of symmetry). Phoenix will return the full 200 Hz data stream, whereas Spirit/Opportunity returned a 1 Hz average of a high rate data stream. Thus the quality of the Phoenix entry profile should be similar to the published Spirit/Opportunity entry profiles.

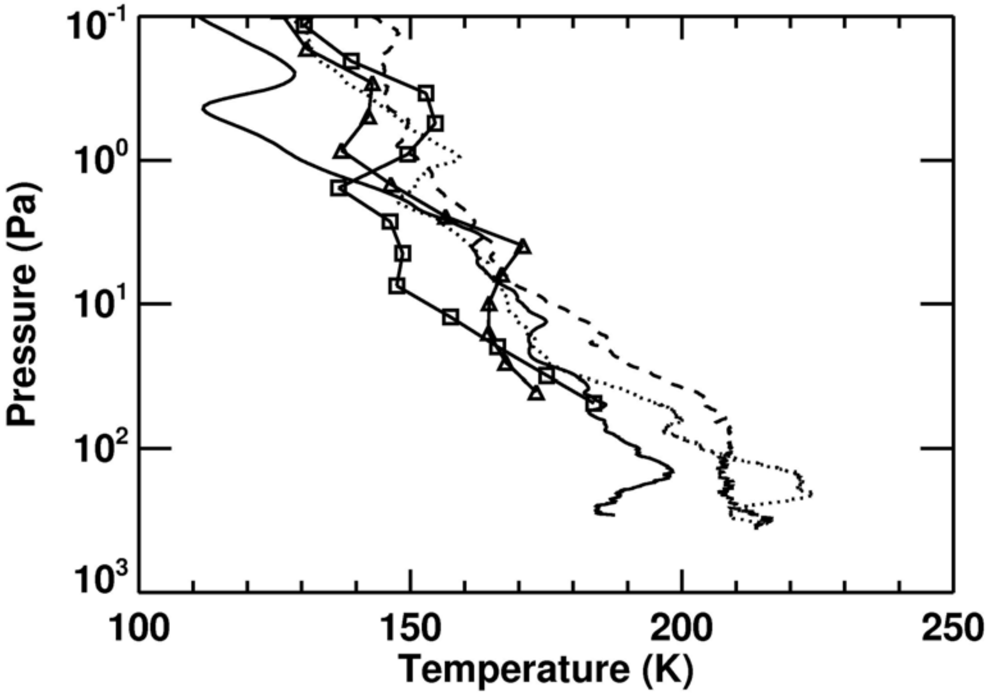

Figure 5. Entry profiles from Viking Landers 1 and 2, Pathfinder, Spirit and Opportunity. Squares are Viking 1, triangles are Viking 2, unmarked solid line is Pathfinder, dashed line is Spirit, and dotted line is Opportunity. Uncertainties are not shown. Variations in overall thermal structure and in temperature oscillations can be seen. These are affected by season, latitude, local time, and atmospheric dustiness. Only one of these previous profiles (Viking 2, 48N) is outside the tropics (30S-30N). Phoenix will land much closer to the polar regions than any previous lander. From Withers and Smith (2006).

2 - Objectives and Their Importance to NASA

The main objectives of this proposal are to ensure that an accurate atmospheric entry profile is determined from Phoenix data and that it is archived at the Planetary Data System. Landing spacecraft on Mars is one of the most difficult things that NASA does. Successful completion of these objectives will reduce the risks faced by future Mars landers beyond Phoenix. These objectives are necessary precursors to the following tasks that are important to NASA:

1) Evaluate accuracy of atmospheric predictions for Phoenix landing. Similar models will be used for Mars Science Laboratory (MSL) and other future Mars landers. Uncertainties in atmospheric predictions drive million-dollar mission design decisions and can lead to the rejection of atmospherically unsafe, but scientifically exciting, landing sites. Mission managers need to know the likely accuracy of such predictions. Comparison of model $\rho(z)$ predictions and actual $\rho(z)$ entry data is an important way of quantifying which models are reliable and which models are not. For example, atmospheric predictions for Spirit and Opportunity included empirical models (MarsGRAM - Justus et al., 2000; Kass-Schofield - Golombek et al., 2003) and physics-based models (Rafkin and Michaels, 2003; Toigo et al, 2003). Many of these models are validated against extensive MGS TES $T(p)$ profiles. $T(p)$ profiles are then converted into $\rho(z)$ using Viking lander surface pressure data, extrapolated to the appropriate latitude, season, time of day, and Mars year. A similar range of models is used to support Phoenix site selection and EDL planning.

2) Improve physics-based atmospheric models used to make predictions for future Mars landers. The Phoenix atmospheric entry profile will be the first 10-100 km $\rho(z)$ profile with <1 km vertical resolution from the polar regions. The polar regions are an important part of the Mars climate system due to the seasonal condensation of CO_2 from the atmosphere onto the polar caps, which controls the annual surface pressure cycle and strongly influences atmospheric circulation patterns. If this atmospheric entry profile is determined by the Phoenix engineering team, but not published nor archived, then these measurements will not be available to scientists who develop such models.

3) Evaluate the performance of Phoenix entry, descent, landing system. NASA has flown two types of Mars landers. One (Viking, Mars Polar Lander, Phoenix) uses legged platforms with retrorockets. The other (Pathfinder, Spirit, Opportunity) uses unfolding platforms with airbags. Past lunar landers (Surveyor, Apollo) also used legged platforms with retrorockets and future lunar landers may also use this system. The Phoenix landing system shares extensive heritage with that of Mars Polar Lander, which was lost due to a landing system failure. Testing of the Phoenix landing system has raised significant concerns, one of which resulted in the remarkable decision to fly, but not use, the MARDI camera (MARDI, 2007). Given this background, NASA is likely to carefully study the performance of the Phoenix landing system after EDL in order to determine whether this type of landing system should be considered for future missions or not. Since an abnormal landing could be due to abnormal system performance or abnormal atmospheric conditions, reconstruction of the atmospheric profile is necessary for this evaluation.

3 - Proposed Interface with Phoenix Project

One member of the Phoenix Science Team, David Catling, is involved in the reconstruction of atmospheric entry profiles for Phoenix. This proposal is intended to support, not duplicate, his efforts. Since he is based at a non-US institution (University of Bristol, Great Britain), his NASA-funded level of effort on the Phoenix mission is zero. Since he was based at a US institution at the time Phoenix was selected, no foreign funding agency is committed to supporting his work on Phoenix either.

Please see the attached letter from Catling that states his willingness to collaborate with this proposed effort if it is funded.

Catling's responsibilities related to the atmospheric entry profile include (A) correcting raw data for gain errors, bias offsets, and other sources of error; (B) determining the best approach for averaging the 200 Hz datastream; (C) reconstructing the EDL trajectory; (D) reconstructing the atmospheric profile; (E) converting data products into PDS-compliant formats; (F) documenting the instrument and the data processing in PDS-compliant formats; (G) revising PDS data volume in response to PDS review process. These responsibilities are more appropriate to a multi-person instrument team than to a single scientist. The timely delivery of an accurate atmospheric profile to the Planetary Data System is important to NASA. Support for this proposed effort will reduce the risk that an accurate entry profile will not be archived in a timely manner.

If this proposal is selected, PI Withers will work closely with Catling to ensure that an accurate atmospheric entry profile is determined from Phoenix data and archived at the Planetary Data System. Labelling PI Withers as an affiliate of the Phoenix Meteorology team would be one possible way for NASA to manage this proposed effort. This proposal will have no effect on Phoenix mission operations. Phoenix already plans to return all necessary data to Earth and to Phoenix Co-I Catling.

4 - Why is it Necessary to Fund This Proposal to Accomplish These Objectives?

1) The JPL engineering team that is implementing the Phoenix mission is capable of generating atmospheric profiles like those described here. However, they are unlikely to publish their results in the peer-reviewed literature or archive derived data products in the Planetary Data System. The Spirit and Opportunity engineering team obtained atmospheric profiles soon after landing, but these profiles have never been published nor archived (described in Desai and Knocke, 2004). The raw IMU measurements were archived, but this archive is incomplete (Kass et al., 2004). The Spirit and Opportunity entry states are not archived alongside the IMU measurements. The directions of the x,y, and z axes for the gyroscopes are not given, which makes the gyroscope data useless. The positions of the IMUs with respect to the center of mass are not given, which makes it impossible to evaluate the effects of angular corrections. Derived attitude quaternions are accurate for Spirit, but not Opportunity (Withers and Smith, 2006). The aerodynamic database is not provided.

2) It is possible, but not certain, that NASA might solicit proposals for Phoenix Participating Scientists in early 2008. Successful determination of atmospheric profiles relies on close interaction with mission engineers and managers who can provide the necessary ancilliary information. This process must take place around the time of landing

or earlier. For example, if the initial attitude of Phoenix at the top of the atmosphere is not determined with sufficient accuracy via tracking, it will not be possible to use the gyroscope data to reconstruct Phoenix's attitude. This will reduce the accuracy of the atmospheric profiles. Participating Scientists selected through an AO that has not yet been released would not be involved in the mission soon enough to address these concerns.

3) This work cannot be performed successfully under the Mars Data Analysis Program (MDAP) or a similar R&A program. Unless this work is closely connected with mission operations, the problems described above for the Spirit and Opportunity entry data will be repeated.

4) The recent (May 2007) call for proposals by JPL's Mars Critical Data Products program did not solicit proposals related to Phoenix. It was focused on MSL.

5 - Information Required From the Phoenix Project

A: Time series of accelerations and angular velocities measured during EDL.

B: Aerodynamic database. A tabulation, generated by numerical simulations, that specifies the three-dimensional force and moment coefficients of the Phoenix spacecraft as a function of atmospheric conditions and spacecraft attitude with respect to the atmosphere-relative velocity vector. The drag coefficient is not the only necessary piece of aerodynamic information, although it is the most useful.

C: Entry state. Position vector and velocity vector in a standard reference frame at a defined time just prior to atmospheric entry.

D: Entry orientation. Attitude of Phoenix in a standard reference frame at a defined time just prior to atmospheric entry.

E: Position and orientation of each accelerometer and gyroscope in a defined frame. The deceleration experienced by Phoenix at the center of mass is related to atmospheric density. The acceleration at the actual sensor, which is displaced from the center of mass, contains a contribution from angular effects (centrifugal forces). Knowledge of the position and orientation of each accelerometer and gyroscope is necessary to correct the measurements for these angular effects.

F: Measured accelerations and angular velocities prior to atmospheric entry. These are used to establish the zero offset of each sensor and to support the correction of angular effects.

G: Post-landing measurements at known martian surface gravity for calibration. These are used to confirm the gain of each sensor.

H: Position of the center of mass in a defined frame. See E.

I: Spacecraft mass and reference area. Derived atmospheric density depends on these (Eqn 1).

J: Moment of inertia tensor. This is used to remove the effects of oscillations on measured accelerations (Spencer et al., 1999).

6 - Description of Data Products that will be Archived

6.1 - Measured quantities

Time series of measured accelerations (3 axes for each of 2 IMUs)
Time series of measured angular velocities (3 axes for each of 2 IMUs)
Time series of corrected accelerations (3 axes for each of 2 IMUs)
Time series of corrected angular velocities (3 axes for each of 2 IMUs)

6.2 - Ancilliary quantities

Entry state (3 component position vector, 3 component velocity vector, scalar time)
Entry attitude (1 attitude quaternion, scalar time)
Position of each accelerometer (3 components for each of 3 accelerometer sensors in each of 2 IMUs)
Orientation of axis of each accelerometer (3 components for each of 3 accelerometer sensors in each of 2 IMUs)
Position of each gyroscope (3 components for each of 3 gyroscope sensors in each of 2 IMUs)
Orientation of axis of each gyroscope (3 components for each of 3 gyroscope sensors in each of 2 IMUs)
Position of center of mass (3 components)
Aerodynamic database (3 force coefficients and 3 moment coefficients for approximately 10 densities, 10 pitch angles and 10 yaw angles)
Mass (1 scalar)
Area (1 scalar)

6.3 - Derived quantities

Time series of Phoenix position and velocity (3 component position vector, 3 component velocity vector, time at each time step)
Time series of Phoenix attitude (pitch angle, yaw angle, angle of attack, time at each time step)
Time series of aerodynamic properties (3 force coefficients, 3 moment coefficients, time at each time step)
Time series of atmospheric properties (density, pressure, temperature, time at each time step)

Uncertainties will accompany all archived data products. The PDS standards for documentation, directory structure, delivery media, and so on will be followed (PDS, 2006a, b, c). Activities will comply with the Mars Exploration Program Data Management Plan (MEP, 2008). The sequence of major events leading up the peer-review of data products will be as follows: generate data products; generate documentation; format data products, documentation, and associated labels; organize files into correct structure; create high-level index files; deliver preliminary volume to PDS Atmospheres Node on CD for review; assist PDS in preliminary verification of correct format and documentation. The PDS will then organize the peer-review. It is likely that peer reviewers will submit reports to the PDS electronically, then participate in a telecon that will recommend a list of changes. After we make these changes, we shall submit our revised volume to the PDS on CD. After any final checks by the PDS, it will be deposited into the PDS archive and made publicly available. Anticipated data volume is small, a single CD based on comparison to previous missions.

7 - Qualifications of Proposer

PI Withers has worked on entry accelerometer data for Huygens, Spirit and Opportunity, and on aerobraking accelerometer data for Mars Global Surveyor and Mars Odyssey (Withers et al., 2003a, b; Fulchignoni et al., 2005; Withers, 2006; Withers and Smith, 2006). He was a member of the Spirit and Opportunity Atmospheric Advisory Team for EDL and wrote the only publication that contains Spirit and Opportunity atmospheric profiles (Withers and Smith, 2006). Software programs to accomplish this data processing and analysis have already been written and validated (Withers et al., 2003a; Withers and Smith, 2006).

He is currently supported by the Mars Critical Data Products program to archive the Spirit and Opportunity atmospheric profiles at the Planetary Data System. Experience with PDS archiving procedures will be obtained with the Spirit and Opportunity atmospheric profiles at no cost to this effort. Withers has served as a reviewer for the PDS and ESA Planetary Science Archive for datasets from Spirit, Opportunity, MRO, Huygens and Rosetta.

8 - Plan of Work

If this proposal is funded, PI Withers will work with Phoenix project management and Phoenix Co-I Catling to ensure that this work is coordinated with Catling's efforts and other project efforts. The Phoenix project may elect to modify the proposed work plan to achieve this.

Tasks will be performed by PI Withers (PW) and a Boston University Graduate Student (GS). Efforts assigned to each task are given in weeks.

1) Adapt existing software for Phoenix data and verify using sample datasets (2 wks PW, 4 wks GS).

2) Acquire ancilliary information (2 wks PW). Request necessary information from Phoenix project. Identify appropriate project personnel to provide best possible information from documented sources. Determine whether ancilliary information can be published or whether additional permissions are needed.

3) EDL (2 wks PW). Spend 1 week immediately before EDL and 1 week immediately after EDL at the Phoenix mission operations center. Test data pipelines and data processing software on sample datasets, prepare to provide support after EDL. Provide best-effort trajectory and atmospheric profile to Phoenix project 24 hours (initial profile) after receipt of entry data and 5 days (revised profile) after receipt of entry data. Return to home institution.

4) Inspection, evaluation, and processing of raw data (3 wks PW, 4 wks GS). Determination of instrument noise levels, biases, and any errors. Correction and calibration of raw measurements.

5) Determination of final atmospheric profile (3 wks PW, 4 wks GS). Determine how best to average the 200 Hz data with the aim of minimizing measurement uncertainties whilst retaining appropriate vertical resolution. Determine how best to impose upper boundary condition on equation of hydrostatic equilibrium. Determine sensitivity of results to assumptions, including neglect of winds (Withers and Smith, 2006).

6) Prepare dataset for PDS (2 wks PW, 4 wks GS). Convert data products into PDS-compliant formats. Produce documentation in PDS-compliant formats.

7) Ensure that proper authorization exists to deliver all measured, ancilliary and derived information to a public archive (2 wks PW).

8) Participate in PDS review of dataset and revise dataset accordingly (2 wks PW, 2 wks GS).

Total effort for PW is 18 weeks = 4 months. Total effort for GS is 18 weeks = 4 months.

9 - Access to Information

PI Withers is a British citizen working at a US institution. The Phoenix project has already committed to export all the information necessary for this work to David Catling, a British citizen, at his institution in Great Britain. Phoenix has approximately six Co-Is from foreign institutions who have complete access to Phoenix scientific data. Withers was given access to the Spirit/Opportunity aerodynamic database and all entry data as a member of the Spirit/Opportunity Atmospheric Advisory Team.

Raw data from the Pathfinder, Spirit and Opportunity IMUs have been publicly archived (MPF, 2000; Kass et al., 2004). Atmospheric profiles from all five previous NASA Mars landers have been published and archived (Seiff and Kirk, 1977; Magalhaes et al., 1999; MPF, 2000; Withers and Smith, 2006). The aerodynamic databases for Pathfinder, Spirit and Opportunity have been published (Gnoffo et al., 1996, 1999; Moss et al., 1999; Schoenenberger et al., 2005a, b). Entry states, entry orientations, spacecraft masses, and spacecraft areas for many past missions have been made public. The exact locations of instruments on NASA spacecraft are regularly disclosed in scientific papers and in documentation accompanying PDS datasets. Extensive details of the Viking and Pathfinder atmospheric structure instruments were published by Seiff (1976) and Seiff et al. (1997).

10 - Additional Possibilities

This proposal is focused on obtaining data products from Phoenix atmospheric entry that will lead to the greatest risk reduction for future NASA flight projects. This section gives a brief summary of several additional tasks that could be performed once this effort is completed. They could be supported directly by flight projects or competitively through NASA's R&A programs. They are not included in the work plan or budget. The purpose of this summary is to show that the data products offered in this basic proposal can be used in a variety of interesting ways once they are properly archived at the PDS.

Phoenix will use a radar during its parachute descent to measure altitude and descent speed. If it decelerates to terminal velocity (v_t), which will be apparent in the radar data, then its descent speed can be related to atmospheric density (Withers, 2007):

$$mg = \rho A v_t C / 2 \qquad (4)$$

The vertical profiles of density, pressure, and temperature can then be extended from the hypersonic entry phase to the descent phase, making it easier to compare the entry/descent data with the landed meteorology data. The same techniques could be applied to the Pathfinder, Spirit and Opportunity terminal descent radar data.

If the aerodynamic database is sufficiently accurate, then the ratio of normal to axial acceleration can be used to infer the attitude of Phoenix with respect to the velocity vector of Phoenix relative to the atmosphere (e.g. Spencer et al., 1999; Withers et al., 2003a). The trajectory reconstruction involving gyroscopes provides the inertial attitude of Phoenix. The difference between these two attitudes is related to the speed and direction of atmospheric winds. There are very few measurements of atmospheric winds on Mars, yet they play a major role in designing landers and selecting safe landing sites. Careful study of the Phoenix entry data could provide information on wind speeds and direction between approximately 10 and 30 km.

The angle of attack of a typical entry probe oscillates between zero and a maximum value of a few degrees (e.g. Spencer et al., 1999, Figure 18). The period of oscillation is related to the atmospheric density (Schoenenbeger et al., 2005a, Eqn 1).

$$\omega^2 = - \rho v^2 A D C_{ma} / 2I \qquad (5)$$

where ω is the frequency of oscillation, D is a reference length, C_{ma} is the derivative of the pitching moment coefficient with respect to angle of attack, and I is a moment of inertia. C_{ma} is negative, so ω^2 is positive. This relationship can be used to determine atmospheric densities using observed angle of attack oscillations. These densities would be derived independently of the drag coefficient, thereby providing a check on the consistency of the aerodynamic database.

Radio transmissions (MSFK tones only, no telemetry) from Spirit and Opportunity were observed by the DSN on Earth during their EDLs. The received frequency was recorded as a function of time.

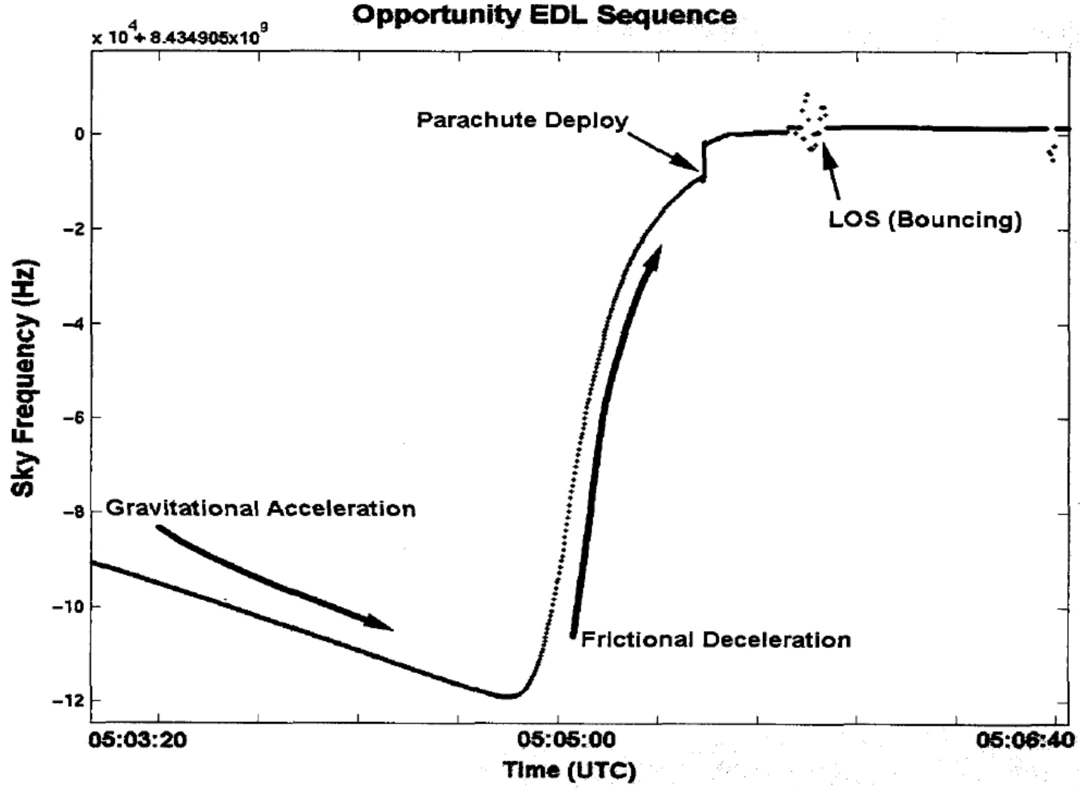

Figure 6. Sky frequency observed by the DSN during Opportunity EDL. The effects of atmospheric drag (frictional deceleration) are clearly visible. From Johnston et al. (2004).

Similar data products may be obtained for Phoenix, either from direct-to-Earth observations at the DSN or from Mars relay orbiters with sophisticated radio equipment. The received Doppler-shifted frequency can be related to the spacecraft's descent speed, given some reasonable assumptions about aerodynamic deceleration always being aligned with the velocity vector. Thus it should be possible to obtain an independent time series of aerodynamic accelerations for use in Equation 1. In principle, such observations of direct-to-Earth tones can be used to reconstruct the entry trajectory and atmospheric structure in real time, giving mission managers instant data about system performance during EDL and an instant E/PO product. Although this capability cannot be developed, validated, and thoroughly tested for the Phoenix entry by this proposed effort, future Mars landers may consider this capability valuable.

11 - Opportunities for Education/Public Outreach (E/PO) Activities

All NASA missions are committed to E/PO activities. This effort will produce several data products that might be used by the Phoenix E/PO team. The drag equation (Eqn 1) is a good example of forces and conservation of momentum. The final vertical temperature profile can be used to show how the martian atmosphere differs from the troposphere/stratosphere/mesosphere/thermosphere structure of the terrestrial atmosphere. Graphics based on the derived data products will be made available to the Phoenix E/PO team and we will work with the Phoenix E/PO team as directed by the Project.

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Withers et al. (2003b) The effects of topographically-controlled thermal tides in the martian upper atmosphere as seen by the MGS accelerometer, Icarus, 164, 14-32.

Withers (2006) Mars Global Surveyor and Mars Odyssey accelerometer observations of the martian upper atmosphere during aerobraking, Geophys. Res. Lett., 33, L02201, doi:10.1029/2005GL024447.

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Withers (2007) A technique to determine the mean molecular mass of a planetary atmosphere using pressure and temperatures measurements made by an entry probe: Demonstration using Huygens data, Planet. Space Sci., 55, 1959-1963.

Reports and Deliverables

Quarterly progress reports delivered to NASA grant/contract manager (every 3 months)
Annual progress report (final report) delivered to NASA grant/contract manager (every 12 months)
One copy of all scientific papers produced as a results of this work delivered to NASA grant/contract manager (every 12 months)

Measured, ancilliary, and derived data products delivered to Planetary Data System for peer review and archiving as outlined in Section 6 (no later than 12 months after start of this effort)

Letter from Phoenix Co-I David Catling

From: David Catling <davidc@atmos.washington.edu>
Subject: Phoenix
Date: Mon, 14 Jan 2008 12:38:36 +0000
To: Paul Withers <withers@bu.edu>

Dear Paul,

Thank you for sending me a copy of your proposal to NASA to become involved in the reconstruction of Phoenix atmospheric structure profiles.

If your proposal is judged suitable for funding by NASA, I would be willing to collaborate with you in this effort.

Sincerely, David Catling

Phoenix Science Team Co-I

EU Marie Curie Chair, University of Bristol, UK
Affiliate Prof., University of Washington, Seattle.

CV for PI Paul Withers

Center for Space Physics
Boston University
725 Commonwealth Avenue
Boston MA 02215

Tel: (617) 353 1531
Fax: (617) 353 6463
Email: withers@bu.edu
Citizenship: British

Education

- PhD, Planetary Science, University of Arizona 2003
- MS, Physics, Cambridge University, Great Britain 1998
- BA, Physics, Cambridge University, Great Britain 1998

Recent Professional Experience

- Research associate Dr. Michael Mendillo (Boston Univ) 2003-present
  Analysis of ionospheric data from Mars and Earth, plus numerical modelling
- Graduate research assistant Dr. Stephen Bougher (Univ. of Arizona) 1998 – 2003
  Studied weather in the martian upper atmosphere. Played an advisory role in mission operations for Mars Global Surveyor and Mars Odyssey aerobraking

Fellowships, Honors, and Awards

- CEDAR Postdoctoral Fellowship from NSF for upper atmospheric research 2003
- Kuiper Memorial Award from the University of Arizona for excellence in academic work and research in planetary science. 2002

Selected Peer Reviewed Publications and Other Major Publications

- Crosby, Bothmer, Facius, Griessmeier, Moussas, Panasyuk, Romanova, and **Withers** “Interplanetary Space Weather and its Planetary Connection” (2007) *Space Weather*, under review.
- Christou, Vaubaillon, and **Withers** “The dust trail complex of comet 79P/du Toit-Hartley and meteor outbursts at Mars” (2007) *Astronomy and Astrophysics*, 471, 321-329.
- **Withers** “A technique to determine the mean molecular mass of a planetary atmosphere using pressure and temperature measurements made by an entry probe: Demonstration using Huygens data” (2007) *Planetary and Space Science*, 55, 1959-1963, doi:10.1016/j.pss.2007.04.009.
- Montabone, Lewis, Read, and **Withers** “Reconstructing the weather on Mars at the time of the MERs and Beagle 2 landings” (2006) *Geophysical Research Letters*, 33, L19202, doi:10.1029/2006GL026565.
- **Withers** and Smith “Atmospheric entry profiles from the Mars Exploration Rovers Spirit and Opportunity” (2006) Icarus, 185, 133-142, doi:10.1016/j.icarus.2006.06.013.
- Mendillo, **Withers,** Hinson, Rishbeth, and Reinisch “Effects of solar flares on the ionosphere of Mars” (2006) *Science*, 311, 1135-1138.

- Bougher and 4 colleagues, including **Withers** “Polar warming in the Mars thermosphere: Seasonal variations owing to changing insolation and dust distributions” (2006) *Geophysical Research Letters*, 33, L02203, doi:10.1029/2005GL024059.
- **Withers** “Mars Global Surveyor and Mars Odyssey Accelerometer observations of the martian upper atmosphere during aerobraking” (2006) *Geophysical Research Letters*, 33, L02201, doi:10.1029/2005GL024447.
- Fulchignoni and 42 colleagues, including **Withers** “In situ measurements of the physical characteristics of Titan's environment” (2005), *Nature*, 438, 785-791, doi:10.1038/nature04314.
- **Withers** and Mendillo “Response of peak electron densities in the martian ionosphere to day-to-day changes in solar flux due to solar rotation” (2005) *Planetary and Space Science*, 53, 1401-1418, doi:10.1016/j.pss.2005.07.010.
- **Withers** “What is a planet?” (2005) *Eos*, 86(36), 326, doi:10.1029/2005EO360004.
- **Withers**, Mendillo, Rishbeth, Hinson, and Arkani-Hamed “Ionospheric characteristics above Martian crustal magnetic anomalies” (2005) *Geophysical Research Letters*, 32, L16204, doi:10.1029/2005GL023483.
- **Withers**, Bougher, and Keating, “The Effects of Topographically-Controlled Thermal Tides in the Martian Upper Atmosphere as seen by the MGS Accelerometer”, (2003) *Icarus*, 164, 14-32.
- **Withers**, Towner, Hathi, and Zarnecki, “Analysis of entry accelerometer data: A case study of Mars Pathfinder”, (2003) *Planetary and Space Science*, 51, 541-561.
- **Withers** and Neumann, “Enigmatic northern plains of Mars” (2001) *Nature*, 410, 651.
- **Withers**, “Meteor storm evidence against the recent formation of lunar crater Giordano Bruno” (2001) *Meteoritics and Planetary Science*, 36, 525 – 529.

Professional Activities and Service

• Reviewer of MER, MRO, Huygens, and Rosetta for NASA PDS and ESA	2004 - present
• Review panel member for NASA Mars Data Analysis Program, NASA Planetary Atmospheres Program, NASA Venus Express Participating Scientist Program, NASA Mars Fundamental Research program, NSF Astronomy and Astrophysics Research Grants Program	2004 - present
• Reviewer for Advances in Space Research, Annales Geophysicae, Icarus, Journal of Geophysical Research, Journal of Spacecraft and Rockets, Mars, Meteoritics and Planetary Science, Planetary and Space Science, and Science.	2001 - present
• Funded co-investigator on NASA Mars Scout Phase A grant for “The Great Escape” mission	2007
• Huygens SSP and HASI/ACC Team Member	2005 - present
• NASA 2003 Mars Exploration Rovers – Atmospheric Advisory Team.	2002 – 2004
• Beagle 2 Environmental Sensor Suite Team Member	2001 - 2003

Professional Affiliations: Member of the American Geophysical Union’s Planetary Sciences Section, the American Astronomical Society’s Division for Planetary Science, and the British Planetary Forum.