Summary of proposal

We propose to reconstruct the atmospheric structure profile for the entry, descent, and landing (EDL) of the Mars Science Laboratory (MSL) mission. This includes archiving the results in the PDS and scientifically interpreting the results. Unless reconstruction results are delivered to a public archive and used to advance Mars atmospheric science, any reconstruction work lacks enduring scientific value. This work differs in several ways from our past successes for Spirit, Opportunity, and Phoenix. Firstly, MSL guided entry and associated period of near-horizontal flight means that pressure cannot always be derived from density using the equation of hydrostatic equilibrium. We will use MEDLI results to compensate. Secondly, we will augment our traditional reconstruction based on accelerometer and gyroscope data by performing an independent reconstruction based on Doppler shifts in MSL's various radio links during entry. This will demonstrate under actual flight conditions our previous proof of concept work that derived an atmospheric temperature profile solely from the Doppler shift in a single radio link.

1 – Introduction

The Mars Science Laboratory (MSL) mission is capable of determining vertical profiles of atmospheric density, pressure and temperature during its descent to the martian surface. 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 MSL mission. Determination of this entry profile will also help NASA reduce the risks experienced by future Mars landers after MSL.

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 MSL entry, descent, and landing (EDL), (B) NASA can evaluate the performance of the highly-scrutinized MSL landing system, and (C) scientists can use the unique MSL atmospheric profile to improve models that will influence the design of future Mars landers and the selection of their landing sites.

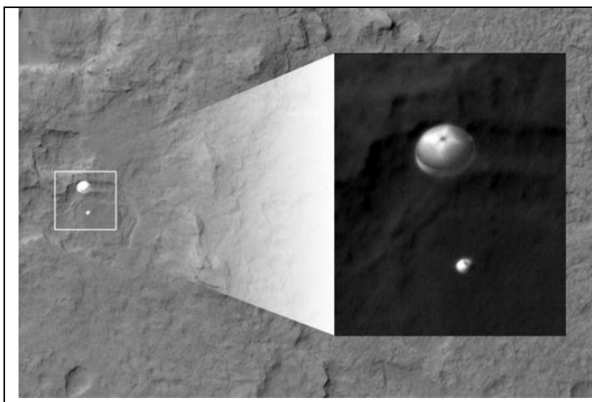

Fig 1A. An orbital view of the MSL descent.

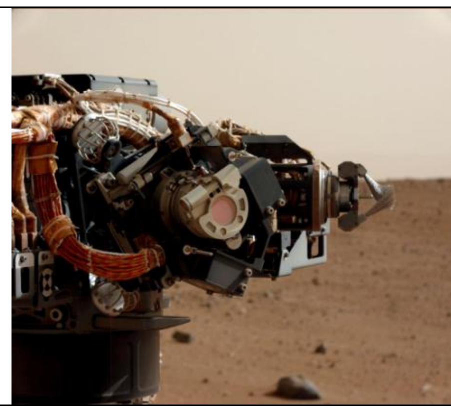

Fig 1B. MSL on the surface of Mars.

2 – Entry atmospheric science

An atmospheric entry probe such as MSL provides a single profile of atmospheric density, pressure, and temperature with excellent vertical resolution and range (Seiff and Kirk, 1977; Magalhaes et al., 1999). Although a single profile seems trivial by comparison to the vast number of MGS TES and MRO MCS profiles, the unsurpassed vertical range and resolution of entry profiles continues to make them scientifically valuable at Mars. Their “whole atmosphere” sampling of thermal structure, their surface-to-thermosphere sampling of atmospheric tides, and their ability to characterize small-scale gravity waves are all useful contributions to Mars science. From a project perspective, they provide a fundamental evaluation of the accuracy of competing atmospheric predictions for EDL and indicators of entry system performance.

Novel features of the MSL EDL system (Steltzner et al., 2010) include lifting flight at 18 degrees angle of attack, guided banking to orient the lift vector, and the spectacular SkyCrane. For engineering and operational reasons, a sophisticated suite of instruments will operate during entry to assure a safe landing and rich post-flight characterization of system performance. These include an IMU with a 3-axis accelerometer and a 3-axis gyroscope, the MEDLI heatshield package of 7 pressure sensors and 7 integrated sensor plugs (each with four thermocouples and a recession sensor), a six beam descent radar, X-band semaphore to Earth, and an 8 kbps UHF link to an Electra-equipped orbiter.

2.1 – Generation of high-level entry data products

We shall generate, archive, and scientifically interpret the MSL entry profile. The basic concepts of a traditional reconstruction of trajectory and atmospheric-structure are well-known (e.g. Seiff and Kirk, 1977). We will use a reconstructed trajectory provided to us by the MSL project.

Once the trajectory is known, atmospheric densities, ρ, along the trajectory can be found from the drag equation (Eqn. 1). Known mass, m, and area, A, and measured axial acceleration, a, and atmosphere-relative speed, v, are important, as is the appropriate aerodynamic coefficient, C, which is a dimensionless number on the order of 2. The aerodynamic coefficient, which depends on attitude and speed (more precisely, the Mach and Knudsen numbers), is found from an aerodynamic database (generated by the MSL project) that is produced from wind-tunnel and numerical experiments. Since the aerodynamics of parachutes are more complex than those of aeroshells, useful density measurements cease at parachute deployment. For a near-vertical entry, a pressure profile can be derived from the density profile and the equation of hydrostatic equilibrium (Eqn. 2 where z is altitude and g is the gravitational acceleration). A corresponding temperature profile follows from pressure, density, the ideal gas law, and an assumed mean molecular mass, μ (Eqn. 3, where k is Boltzmann's constant). We have demonstrated expertise in this area by archiving and interpreting reconstructed atmospheric properties from Spirit, Opportunity, and Phoenix as shown in Fig. 3 (Withers and Smith, 2006; Withers and Murphy, 2009; Withers and Catling, 2010; Withers et al., 2010). Since the PIP does not give expected IMU and MEDLI performance, we do not estimate the accuracy of reconstructed atmospheric properties along the entry profile - but engineering desire for IMU heritage implies accuracies no worse than for MER or Phoenix.

$m\,a = C\,\rho\,A\,v^2 / 2$ (Eqn. 1)	$dp/dz = -\rho\,g$ (Eqn. 2)	$p = \rho\,k\,T / \mu$ (Eqn. 3)

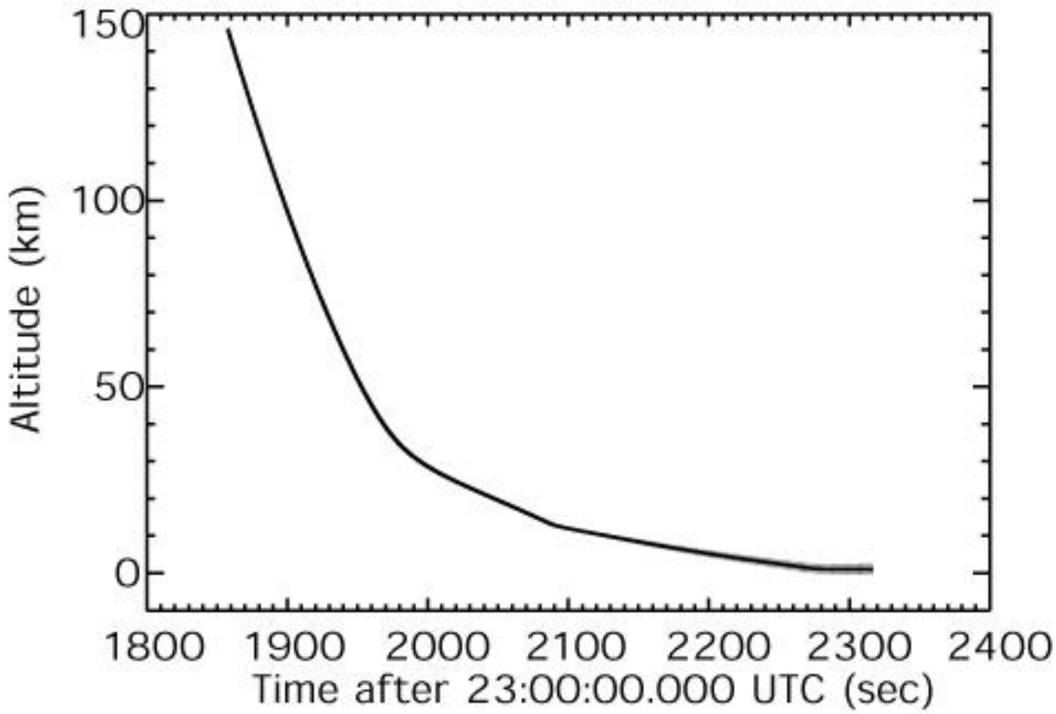

Fig. 2. Reconstructed altitude versus time for Phoenix with 1σ uncertainties shown by the grey envelope (Withers et al., 2010).

Due to its lifting body, MSL has a period of near-horizontal supersonic flight that will occur immediately before parachute deployment. In this case, pressures cannot be derived from hydrostatic equilibrium and nor can temperatures. Luckily, an alternative technique is available which was successfully demonstrated on Viking. MSL's instrumented heatshield (MEDLI) records dynamic pressures in a distributed network of sensors. The desired static atmospheric pressure and temperature can be derived from these dynamic pressures and the reconstructed trajectory. The pressure p_i measured by MEDLI sensor i is a function of the stagnation pressure, p_stag, the free-stream pressure, p_fs (which is the desired atmospheric pressure), and the angle θ_i between the free-stream velocity and the surface normal at the sensor.

$$p\_i = (p\_stag - p\_fs) \cos^2(\theta\_i) + p\_fs \qquad \text{Eqn. 4}$$

Thus values of p_stag, p_fs, and the flow direction can be obtained using values of p_i from multiple sensors. Atmospheric temperatures can be found using p_fs values from MEDLI, atmospheric densities from the accelerometer, and the ideal gas law. Hence the atmospheric density, pressure, and temperature profiles can be continued down until parachute deployment. This explanation is simplified, neglecting likely shape, non-ideal gas, and non-equilibrium thermodynamics effects. Co-I Karatekin has experience including these effects when studying probe flight dynamics and aerothermodynamics.

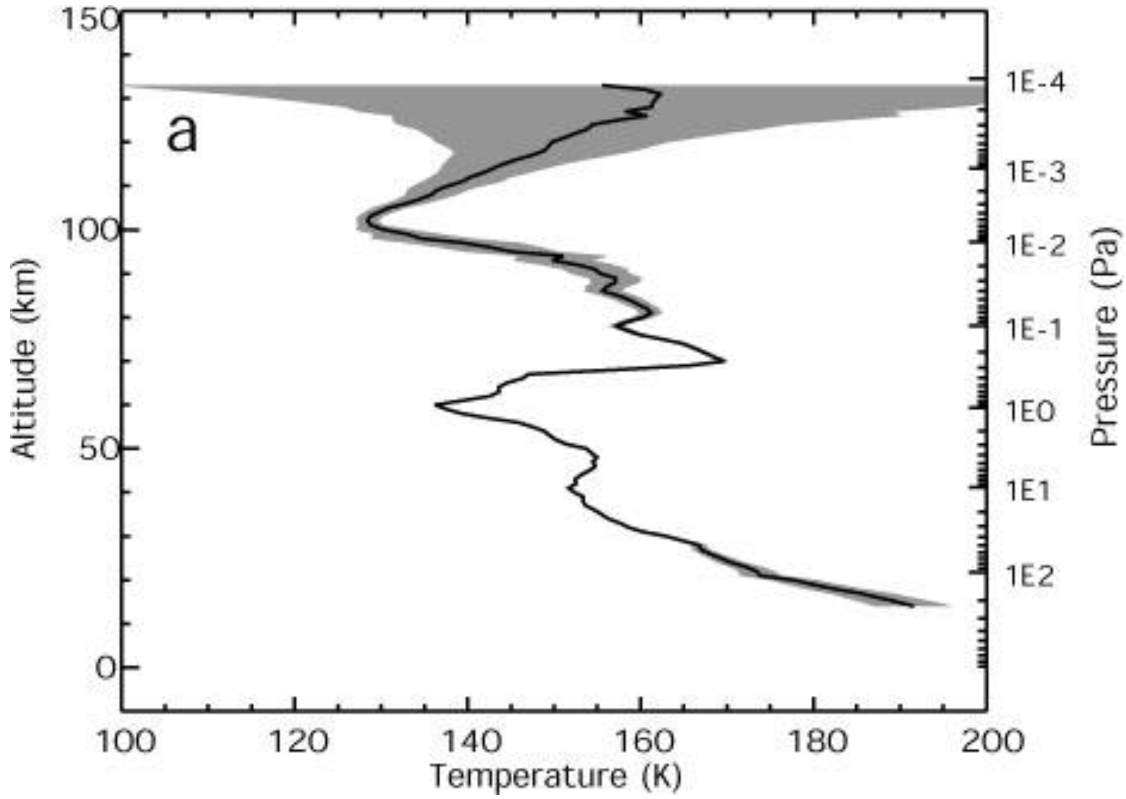

Fig. 3. The Phoenix entry profile. A 1σ error envelope is shown by the gray region. Large-scale oscillations due to thermal tides and small-scale oscillations due to gravity waves are present (Panel A of Figure 1 of Withers and Catling, 2010).

2.2 – Near-real-time reconstruction of trajectory and atmospheric structure

Withers (2010) outlined and demonstrated for Opportunity how the Doppler shift in a radio link between an entry probe and a receiver in Mars orbit or on Earth can be used to reconstruct the probe's trajectory, from which the atmospheric profile can be generated in the usual manner. No information content (e.g. telemetry) in the radio signal is required, nor is an ultrastable oscillator. The key step involves the transformation of the one-dimensional line-of-sight constraint provided by the Doppler shift into a three-dimensional constraint. For a non-lifting vehicle like Opportunity, the assumption that the aerodynamic force is anti-parallel to the velocity vector (pure drag) is sufficient. For a lifting vehicle like MSL, an assumed lift/drag relationship (obtained from the aerodynamic database) and some details of the guidance algorithm are required. Selected results from Withers (2010), who explained this concept in detail, are shown in Figs 4-5.

A near-real time trajectory reconstruction provides a rapid estimate of landing site location, which is useful for a range of engineering purposes. It is also useful for the identification of any anomalous events that may have occurred during entry. A near-real-time atmospheric structure reconstruction provides a rapid assessment of the accuracy of predicted environmental conditions, which is useful for a range of engineering purposes. It also offers a tangible data product for engaging the public. Public interest in the atmospheric entry phase of missions is intense, yet few results are typically available until hours after entry. If a mission fails during atmospheric entry (e.g. Beagle 2, Mars Polar Lander), then this technique may provide the mission's only scientific results.

5.4 – Interpretation of high-level entry data products

The observed entry profile will be compared against other relevant observations, such as radio occultation, MGS TES, or MRO MCS data from appropriate seasons and locations, to develop a more comprehensive picture of climate properties and processes at the time of MSL EDL. It will also be interpreted within the context of data assimilation output.

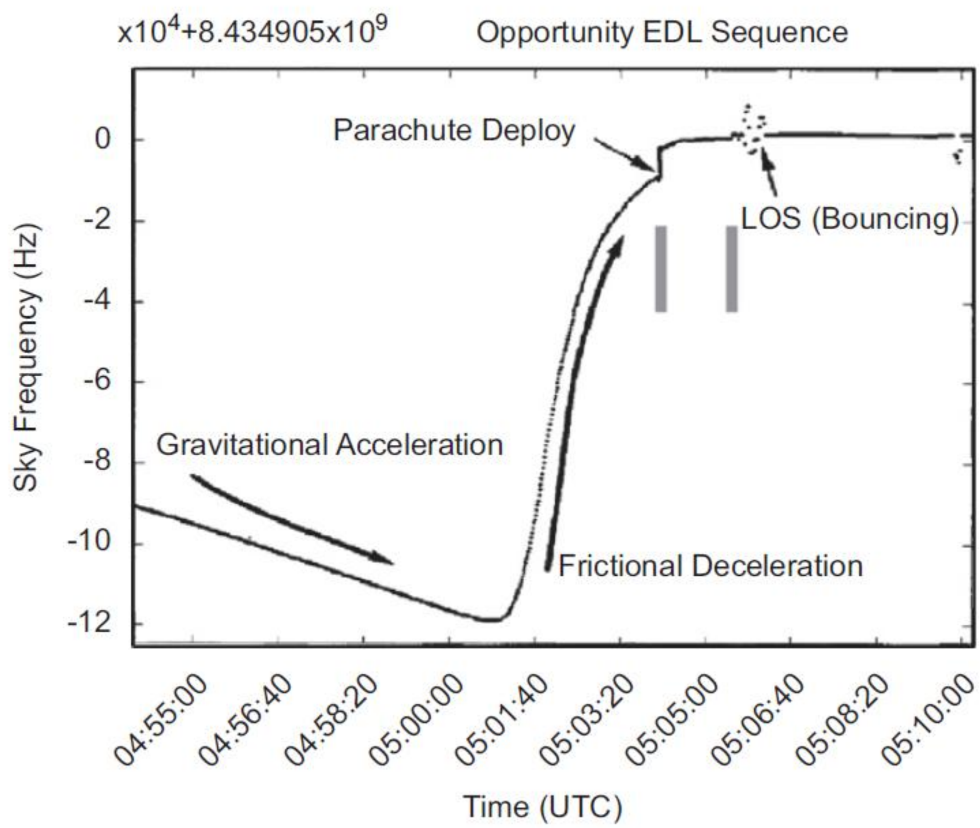

Fig. 4. Received frequencies for Opportunity. Sky frequencies on the vertical axes are transformed into actual received frequencies by multiplying by 10 kHz and adding 8.434905 GHz (Figure 1 of Withers, 2010, modified from Figure 6 of Johnston et al., 2004).

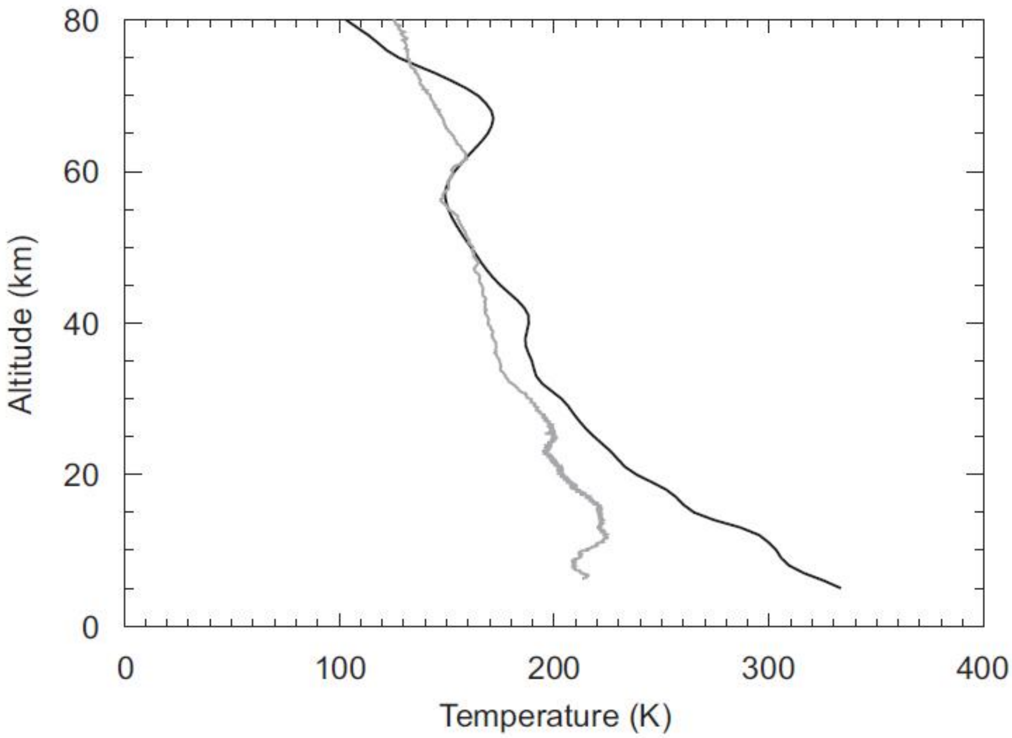

Fig. 5. Opportunity entry temperature profile from Doppler shift (black line) and accelerometers (grey line). The large temperature differences at low altitudes can be attributed to the crudely scanned data used by Withers (2010), rather than fundamental flaws in the technique (Figure 11 of Withers, 2010).

3 – Interaction with MSL project

Successful completion of this project will require productive interactions between our proposing team and several elements of the MSL project. These include the JPL EDL team, the Langley MEDLI team, and the REMS team.

From the JPL EDL team, we will require:

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 MSL 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: MSL trajectory. Reconstructed position vector in a standard reference frame as a function of time during entry.

D: MSL orientation. Reconstructed orientation in a standard reference frame as a function of time during entry.

E: Position and orientation of each accelerometer and gyroscope in a defined frame. The deceleration experienced by MSL 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).

K: Time series of received frequencies for all Mars orbiters and ground stations monitoring the MSL EDL transmissions.

From the Langley MEDLI team, we will require:

L: Time series of derived freestream pressures.

From the REMS team, we will require:

M: Discussions on the scientific interpretation of entry and landed measurements of atmospheric conditions.

4 – Archiving

We shall archive data products and associated uncertainties for entry atmospheric science. Data volumes are small.

We shall make one delivery of a set of entry data products to the PDS. We shall archive the high-level time series data products that we produce from the calibrated IMU data. They will contain SCLK time, UTC time, position vector, velocity vector, attitude quaternion, axial force coefficient CA, normal force coefficient CN, angle of attack, Mach number, Knudsen number, atmospheric density, atmospheric pressure, and atmospheric temperature. The trajectory will extend from the entry interface to the surface, whereas atmospheric properties will terminate at parachute deployment (unless descent phase data from REMS are collected and useful). We anticipate these data products being reported in a single ASCII table. Documentation and formatting of our archived entry data products will be similar to the Spirit, Opportunity, and Phoenix datasets we have previously archived (Withers and Murphy, 2009; Withers et al., 2010). The archive preparation tools demonstrated on these existing datasets will be re-used for MSL.

5 – Relevance

The overall scientific thrust of our investigation is the characterization of atmospheric conditions at the MSL site, which is aligned with MSL Science Objective 8 (characterization of the local environment). It is also consistent with MEPAG Objective II-A (Characterize Mars' atmosphere and present climate) and several of its underlying investigations.

PI Withers has substantial experience on NASA Mars missions, but not yet as a fully-fledged Science Team member. By directly participating in the MSL mission, he would become well-qualified to support NASA's mission by assuming more responsible roles in future spaceflight missions. In particular, NASA has lacked entry science (not engineering) expertise since the end of Al Seiff's group at NASA Ames. PI Withers has worked to fill this niche by ad hoc post-flight participation in Spirit, Opportunity, Phoenix, and Huygens, but his capabilities would be greatly improved by embedded participation alongside the MSL mission's EDL engineering team.

6 – Personnel

This investigation will be performed by PI Paul Withers, a Boston University postdoctoral researcher, and Co-I Ozgur Karatekin (Royal Observatory, Belgium).

PI Withers will be responsible for the success of this investigation. PI Withers has studied tides in the upper (Withers et al., 2003), middle (Withers et al., 2009; Pratt et al., 2010), and lower (Withers and Catling, 2010) atmosphere of Mars. He has supported the MSL mission and its "Atmospheric Council" (Chen/Vasavada) with surface pressure studies (Withers, 2009) via an MCDP award. He was responsible for generating, archiving, and interpreting atmospheric entry profiles for Spirit, Opportunity, and Phoenix (Withers and Smith, 2006; Withers and Murphy, 2009; Withers and Catling, 2010; Withers et al., 2010). He is familiar with the challenges of mission operations via participation in aerobraking atmospheric advisory groups for MGS and Odyssey, in the EDL atmospheric advisory team for Spirit and Opportunity, and in science teams for Huygens HASI, MEX radio science, and VEX radio science.

A postdoctoral researcher will be hired by Boston University to work on this project. The remainder of this individual's effort will be supported by other funded projects related to planetary science. We desire a recent PhD recipient with interests in planetary atmospheres, preferably with prior experience working closely with spacecraft datasets.

Co-I Ozgur Karatekin is a research scientist at the Royal Observatory of Belgium. He has studied the flight dynamics and aerothermodynamics of planetary entry probes for the last decade (Wang et al., 1999; Karatekin et al. 1998, 2004, 2008, 2010). He is Co-PI of the atmospheric entry experiment AMELIA on ESA's ExoMars Descent Module where his role includes the use of heatshield instrumentation for atmospheric reconstruction activities, which is directly relevant to our proposed use of MEDLI pressure data. The unique capability provided by Co-I Karatekin is a scientific perspective on the use of heatshield data from atmospheric entry probes.

7 – Work plan with key projected milestones, accomplishments, and deliverables

Requested levels of effort for this two-year project are 1 summer month per year for PI Withers and 8 months per year for a Boston University postdoctoral researcher. Day-to-day work on this project will be conducted by the postdoctoral researcher under the guidance and supervision of PI Withers. The requested levels of effort are based on our prior experience with Spirit, Opportunity, and Phoenix, bearing in mind the additional complexities of MSL. These are the guided trajectory of MSL, the need to use independent pressure measurements from MEDLI, and the independent reconstruction using the radio links.

Our planned deliverables are:

- Results of preliminary atmospheric reconstruction using radio links (Powerpoint presentation emailed to contract manager, March 2013)
- Results of preliminary atmospheric reconstruction using IMU data (Powerpoint presentation emailed to contract manager, March 2013)
- Presentation of latest technical results at International Planetary Probe Workshop (July 2013)
- Synopsis of near-final technical results (Report emailed to contract manager that will provide a template for subsequent publications in scientific journals, July 2013)
- Presentation of scientific results at Fall AGU meeting (December 2013)
- Initial delivery of data products to PDS (February 2014)
- Results of final reconstruction using radio links (Report emailed to contract manager and manuscript submitted to a scientific journal, May 2014)
- Delivery of revised data products to PDS after review and lien resolution (July 2014)
- Results of final reconstruction using IMU data and scientific analysis (Report emailed to contract manager and manuscript submitted to a scientific journal, September 2014)
- Quarterly reports (emailed to contract manager, every 3 months)

We are likely to discover minor obstacles to our work as we proceed. The above schedule is based on the expectation that by March 2013 we will have found many issues and have crudely and imperfectly resolved most of them. By July 2013, we expect to have identified all the obstacles to reconstruction that we are going to encounter, to have fully resolved most of them, and to have strategies to resolve those that remain. By December 2013, we expect to have completed our direct reconstruction work. Our subsequent efforts will be focused on PDS archiving (formatting, documentation, lien resolution), scientific analysis, and the preparation of scientific manuscripts.

We also request support for the following travel costs.

- 1 trip by PI Withers to JPL in November 2013 to attend MEDLI Technical Interchange Meeting and resolve any outstanding issues with the transfer of EDL data and supporting information to Boston University.
- 1 trip by PI Withers and postdoctoral researcher to JPL in March 2013 to report progress to date.
- 1 trip by Co-I Karatekin to Boston in spring 2013 to discuss complexities introduced by period of near-horizontal flight, which has not been encountered by any planetary entry probe since Viking in 1976, and our status at resolving them.
- 1 trip by PI Withers and postdoctoral researcher to IPPW meeting in summer 2013 to report technical results to date and receive feedback from peers.
- 1 trip by postdoctoral researcher to Fall AGU meeting in December 2013 to report scientific results to date and receive feedback from peers.

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Citizenship: British (Green Card holder)

Education

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

Professional Experience

- Assistant Professor, Astronomy Department (Boston Univ.) — 2010-present
- Senior research associate — Dr. Michael Mendillo (Boston Univ.) — 2007 – 2010
  Research associate — Dr. Michael Mendillo (Boston Univ.) — 2003 – 2007
  Analysis of ionospheric data from Venus, Mars and Earth, plus numerical modeling
- Graduate research assistant — Dr. Stephen Bougher (Univ. of Arizona) — 1998 – 2003
  Studied tides in the martian upper atmosphere. Played an advisory role in mission operations for Mars Global Surveyor and Mars Odyssey aerobraking

Selected Fellowships, Honors, and Awards

- NASA Early Career Fellowship — 2009
- 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
- Nominated for the Meteoritical Society/Geological Society of America's Best Student Paper in Planetary Sciences Award — 2002

Membership of Committees and Working Groups

- DPS Nominating Committee — 2008-present
- Mars Exploration Program Analysis Group (MEPAG) Goals Committee member — 2008-present
- Mars Exploration Program Analysis Group (MEPAG) Mars Human Precursor Science Steering Group - Atmospheric Focus Team member — 2004-2005

Selected Peer Reviewed Publications

- **Withers** and Catling (2010) Observations of atmospheric tides at the season and latitude of the Phoenix atmospheric entry, Geophysical Research Letters, 37, L24204, doi:10.1029/2010GL045382
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- **Withers** and Neumann (2001) Enigmatic northern plains of Mars, Nature, 410, 651
- Lorenz, Lunine, Withers, and McKay (2001) Titan, Mars and Earth: Entropy production by latitudinal heat transport, Geophysical Research Letters, 28, 415 – 418

Biographical Sketch for Collaborator Ozgur Karetkin

Education

- **2001:** Ph.D. in applied sciences. Université Libre de Bruxelles (ULB) and the von Karman Institute for fluid dynamics (VKI), Belgium on “Aerodynamic Stability of a Planetary Entry Vehicle at low Speeds”.
- **1995:** M.S. in Aeronautical Engineering, Middle East Technical University, Ankara.
- **1993:** B.S. in Aeronautical Engineering, Middle East Technical University, Ankara.

Employment

- **2001-Present**: Research Scientist. ROB, Brussels, Belgium.
- **1996-2001**: Research Assistant. VKI, Brussels, Belgium
- **1993-1996**: Teaching Assistant. METU, Ankara. Turkey.

Experience Related to the Investigation

- Research on aerothermodynamics and flight dynamics of planetary entry capsules.
- Co-I on the 2016 Exomars Trace Gas Orbiter spectrometer NOMAD.
- Co-I on the proposed DREAMS investigation for the ExoMars Entry Descent and Landing Demonstrator Module (EDM) surface science.
- Co-PI on the proposed IDEAS (Investigations During Entry, and Atmospheric Science) investigation for the ExoMars Entry Descent and Landing Demonstrator Module (EDM), Entry and Descent Science.

Related Publications

Karatekin Ö., Paris S., Adam O. Multiple Pressure measurements on a planetary atmospheric vehicle for attitude and density determination. 7th International Planetary Probe Workshop, Barcelona, 14-18 June 2010.

Karatekin Ö. Dynamic stability of entry capsules, in Experimental determination of dynamic stability parameters. *VKI Lecture series Monograph 2008-02*. ISBN978-2-930389-81-8, 2008.

Karatekin Ö., J.-M. Charbonnier, F. Wang, and V. Dehant. "Dynamic stability of atmospheric entry probes". In *ESA SP- 544: Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science*, pages 101-108, Feb. 2004.

Wang F.Y., **Karatekin O.** , and Charbonnier J.-M. Low-speed aerodynamics of a planetary entry capsule. *Journal of Spacecraft and Rockets*, 36(5), 659-667, 1999.

Wang F.Y., **Karatekin O. ,**Charbonnier J.-M. and Paris S.. Utilization of Low-Speed Experiments in Transonic Capsule Stability Research. *Journal of Spacecraft and Rockets.* 36(5):774--776, 1999.

Karatekin O., Wang F.Y. and Charbonnier J.M. Aerodynamic stability of planetary entry capsules. In Hrsg. R.A. Harris editor, *3rd European Symposium on Aerothermodynamics for Space Vehicles*, ESTEC, Noordwijk, NL, ESA SP-426, ISBN 92-9092-704-6, pp. 171-178, 1998.

Letter of Commitment from Collaborator Ozgur Karetkin

Subject: Re: MSL Participating Scientist proposal
From: Ozgur Karatekin <karatekin.ozgur@gmail.com>
To: withers@bu.edu
Date: Fri, 18 May 2012 03:11:29 +0200

Dear Paul,

I acknowledge that I am a Collaborator on your proposal to JPL entitled "EDL reconstruction for MSL". I intend to fulfill the roles outlined for me in the proposal, which are focused on the use of heatshield measurements to support the reconstruction.

Ozgur Karatekin,

Royal Observatory of Belgium
3, Av. Circulaire, B-1180,
Brussels Belgium.

Current and Pending Support for Paul Withers

Current Support

Principal Investigator: Paul Withers
Project/Proposal Title: Thermospheric Variability Observed by Past Aerobraking Missions and Radio Occultation Experiments
Source of Support: NASA MCDP
Award: 1407345
Award Amount (or Annual Rate): $192,802 Period Covered: 05/2010-09/2012
Person Months Committed to Project per year: Cal: Acad: Summ: 1.00

Principal Investigator: Paul Withers
Project/Proposal Title: Exploring the ionosphere of Mars
Source of Support: NASA Mars Data Analysis Program
Award: NNX12AJ39G
Award Amount (or Annual Rate): $159,393 Period Covered: 05/2012-05/2015
Person Months Committed to Project per year: Cal: Acad: Summ: 0.50

Principal Investigator: Paul Withers
Project/Proposal Title: The ionosphere of Venus
Source of Support: NSF Astronomy and Astrophysics Research Grants (AAG) Program
Award: Pending
Award Amount (or Annual Rate): $294,211 Period Covered: 08/2012-07/2015
Person Months Committed to Project per year: Cal: Acad: Summ: 1.00

Pending Support

Principal Investigator: Paul Withers
Project/Proposal Title: Radio occultation studies at Mars
Source of Support: NASA ECF Start-up
Award: Pending
Award Amount (or Annual Rate): $99,999 Period Covered: 05/2011-04/2013
Person Months Committed to Project per year: Cal: Acad: Summ: 0.45

Principal Investigator: Paul Withers
Project/Proposal Title: Atmospheric science with EDL and REMS instrumentation
Source of Support: NASA MSL Participating Scientist Program
Award: Pending
Award Amount (or Annual Rate): $499,738 Period Covered: 09/2011-01/2015
Person Months Committed to Project per year: Cal: Acad: Summ: 2.40
(Plus buyout of Fall 2012 semester)

Principal Investigator: David Pawlowski (Univ. Michigan) with Co-I Paul Withers
Project/Proposal Title: Comparative Ionosphere-Thermosphere Space Weather at Earth and Mars
Source of Support: NASA/NSF LWS Collaborative Space Weather Modeling Program
Award: Pending
Award Amount (or Annual Rate): $446,211 Period Covered: 10/2012-09/2017
Person Months Committed to Project per year: Cal: Acad: Summ: 1.00

Principal Investigator: Paul Withers
Project/Proposal Title: CEDAR: The ionospheric electrodynamics produced by the weird and wonderful magnetic fields of Mars (identical tasks to a NASA Heliophysics/Geospace proposal and a NASA MFRP proposal)
Source of Support: NSF CEDAR Program
Award: Pending
Award Amount (or Annual Rate): $255,533 Period Covered: 11/2012-10/2015
Person Months Committed to Project per year: Cal: Acad: Summ: 1.00

Principal Investigator: David Pawlowski (Eastern Mich. Univ.) with Co-I Paul Withers
Project/Proposal Title: CEDAR: The effects of solar flares on the ionospheres and thermospheres of Earth and Mars (identical tasks to a NASA Heliophysics/Geospace proposal)
Source of Support: NSF CEDAR Program
Award: Pending
Award Amount (or Annual Rate): $153,592 Period Covered: 11/2012-10/2015
Person Months Committed to Project per year: Cal: Acad: Summ: 0.50

Principal Investigator: Paul Withers
Project/Proposal Title: The ionospheric electrodynamics produced by the weird and wonderful magnetic fields of Mars (identical tasks to an NSF CEDAR proposal and a NASA MFRP proposal)
Source of Support: NASA Heliophysics/Geospace Supporting Research Program
Award: Pending
Award Amount (or Annual Rate): $228,363 Period Covered: 03/2013-02/2016
Person Months Committed to Project per year: Cal: Acad: Summ: 0.50

Principal Investigator: David Pawlowski (Eastern Mich. Univ.) with Co-I Paul Withers
Project/Proposal Title: Quantifying the ionospheric response to solar flares at Earth and Mars (identical tasks to an NSF CEDAR proposal)
Source of Support: NASA Heliophysics/Geospace Supporting Research Program
Award: Pending
Award Amount (or Annual Rate): $130,145 Period Covered: 03/2013-02/2016
Person Months Committed to Project per year: Cal: Acad: Summ: 0.50

Principal Investigator: Josh Semeter (Boston University) with Co-I Paul Withers
Project/Proposal Title: Magnetic cusps at Earth and Mars
Source of Support: NASA Heliophysics/Geospace Supporting Research Program
Award: Pending
Award Amount (or Annual Rate): $100,307 Period Covered: 11/2012-10/2013
Person Months Committed to Project per year: Cal: Acad: Summ: 0.46

Principal Investigator: Paul Withers
Project/Proposal Title: Meteoric plasma layers on Venus and Mars
Source of Support: NASA Planetary Atmospheres Program
Award: Pending
Award Amount (or Annual Rate): $233,584 Period Covered: 03/2013-02/2016
Person Months Committed to Project per year: Cal: Acad: Summ: 0.50

Principal Investigator: Paul Withers
Project/Proposal Title: The ionospheric electrodynamics produced by the weird and wonderful magnetic fields of Mars (identical tasks to a NASA Heliophysics/Geospace proposal and an NSF CEDAR proposal)
Source of Support: NASA Fundamental Research Program
Award: Pending
Award Amount (or Annual Rate): $229,776 Period Covered: 03/2013-02/2016
Person Months Committed to Project per year: Cal: Acad: Summ: 0.50

Principal Investigator: Paul Withers
Project/Proposal Title: EDL reconstruction for MSL
Source of Support: NASA/JPL
Award: Pending
Award Amount (or Annual Rate): $199,497 Period Covered: 10/2012-09/2014
Person Months Committed to Project per year: Cal: Acad: Summ: 1.00

If all Professor Withers's pending proposals are funded, leading to over-commitment in the three months of academic summer each year, then this problem can be alleviated by a buyout of his teaching commitments during the academic year.

Budget Narrative

Name	**Role**	**Institution**	**Funded Effort per year**	**Unfunded Effort per year**
Dr. Paul Withers	PI	Boston Univ.	1 months	0
TBD	Postdoctoral researcher	Boston Univ.	8 months	0
Dr. Ozgur Karatekin	Collaborator	Royal Obs. of Belgium	0	As needed

Personnel
The names, titles, and levels of effort of the personnel involved in this proposed work are as follows:

Principal Investigator – Paul Withers
Professor Withers will be responsible for the success of this investigation and for compliance with all reporting requirements. He will direct and mentor the postdoctoral researcher, providing strategic oversight for their work on the IMU-based reconstruction, the radio link-based reconstruction, and the preparation of data products for archiving.

Postdoctoral researcher – TBD
The postdoctoral researcher will conduct the day-to-day work on this project. They will perform the IMU-based reconstruction, perform the radio link-based reconstruction, prepare data products for archiving, present results at scientific conferences, and draft manuscripts for publication.

Salaries are estimated to increase 3% annually. Fringe benefits are budgeted in accordance with the most recent Rate Agreement between the University and DHHS, dated 2/13/2012: 25.9% applied to professional salaries and 9.0% applied to graduate student salaries.

Publications
$2000 in Year 2 for two publications (technical results of radio-based reconstruction; scientific results of IMU-based reconstruction). This cost is based on typical page charges for the Journal of Geophysical Research.

Travel
#1 (Domestic) BU personnel will conduct working visits to JPL in order to discuss project status and resolve problems with data access and uncertainties in data interpretation. Year 1 cost per person-trip is airfare $500, 3 day per diem $588, and ground transportation $100 (total $1188). There will be three person-trips in Year 1 (Paul Withers in November 2012 for a MEDLI Technical Interchange Meeting and Paul Withers and the postdoctoral researcher in March 2013 for a meeting with the contract manager and associated people) and zero person-trips in Year 2.

#2 (Domestic) Present scientific results at Fall AGU conference in order to obtain critical feedback from peers and disseminate results to colleagues. Year 1 cost per person-trip is airfare $500, 5 days per diem $1130, registration fee $500, and ground transportation $100 (total $2230). There will be zero person-trips in Year 1 and one person-trip in Year 2 (postdoctoral researcher in December 2013).

#3 (Foreign) Collaborator Karatekin will visit Boston to discuss project status and develop solutions for identified problems. Year 1 cost per person-trip is airfare $1200, 3 days per diem $816, and ground transportation $100 (total $2116). There will be one person-trip in Year 1 (Collaborator Karatekin in spring 2013) and zero person-trips in Year 2.

#4 (Domestic) Present technical results at International Planetary Probe Workshop (IPPW) in order to disseminate results to entry probe community and receive feedback from peers. Assumed location is San Francisco, CA. Year 1 cost per person-trip is airfare $500, 5 days per diem $1130, registration fee $500, and ground transportation $100 (total $2230). There will be two person-trips in Year 1 (Paul Withers and postdoctoral researcher in summer 2013) and zero person-trips in Year 2.

Facilities and Administrative (F&A) Costs
F&A costs are calculated at a rate of 63.7% in accordance with the most recent Rate Agreement between Boston University and DHHS, dated 2/13/2012.

Facilities and Equipment
Existing facilities and equipment at Boston University and the Royal Observatory of Belgium will be used to perform the proposed research.