Cover Pages and Budget Summary
Table of Contents 1
Summary of Proposal 2
Scientific/Technical/Management Section 3
A. Objectives and Significance of Proposed Work 3
A.1 Aerobraking at Mars 3
A.2 Scientific Discoveries from MGS and ODY ACCEL Measurements 4
B. Investigation and Technical Plan 5
B.1 Data Products 5
B.1.1 Densities at fixed altitudes 6
B.1.2 Gridded latitude-altitude cross-sections of densities, pressures, and temperatures 6
B.1.3 Characterization of tidal amplitudes and phases 8
B.1.4 High-altitude density measurements 9
B.2 ACCEL Team Responsibilities 10
B.2.1 Team meetings and publications 10
B.2.2 Data archiving 11
B.2.3 Atmospheric densities from primary science orbit 11
B.2.4 Other team responsibilities 12
B.3 Science analysis 12
B.3.1 Basic survey 12
B.3.2 MGS/ODY/MRO comparison 13
B.3.3 Tidal investigations 13
B.3.4 Comparison of gridded ρ, p, T observations and model predictions 14
C. Importance and relevance to NASA 15
D. Management and work plan 16
D.1 Work plan 16
D.2 PDS Deliverables 16
D.3 Personnel 16
D.4 Management 17
D.5 Cost effectiveness 17
References
Summary of Personnel and Work Efforts
Facilities and Equipment
Budget Justification/Narrative
CV for PI Paul Withers
CV for Co-I Jim Murphy
Statements of Commitment from Murphy and Richardson
Current and Pending Support for PI Withers
Current and Pending Support for Co-I Murphy

Title: Investigation of the martian upper atmosphere using MRO ACCEL data

Summary of proposal:

The MRO ACCEL instrument measures atmospheric densities below about 200 km altitude during aerobraking. Pressures, temperatures, and perhaps winds can also be derived from its measurements. The MGS and ODY ACCEL datasets have been used to study atmospheric tides, upper atmospheric responses to dust storms and solar flux variations, and the thermal structure of the atmosphere. We propose to generate new data products from the ACCEL instrument, including a latitude-longitude-altitude grid of density, pressure, and temperature measurements, to organize team meetings and lead subsequent team publications, and to investigate what the MRO ACCEL instrument reveals about the structure, thermal state, seasonal cycle, and diurnal cycle of the martian upper atmosphere. Working closely with existing ACCEL team members will be essential for successful completion of this effort.

A. OBJECTIVES AND SIGNIFICANCE OF PROPOSED WORK

A three-part effort using Mars Reconnaissance Orbiter (MRO) accelerometer (ACCEL) data is proposed. It involves (1) generation of data products, (2) team responsibilities, and (3) scientific analysis. Data products will include tidal amplitudes and phases, atmospheric pressures and temperatures, and high altitude densities. It may be possible to measure atmospheric density near periapsis during the primary science orbit after the completion of aerobraking. Team responsibilities will include organization of science-focused team meetings, leadership of team publications, and data archiving. Scientific analysis will involve model-data comparisons and studies of tides. This proposal addresses NASA Science Outcome 3C.1 (Progress in learning how the Sun's family of planets and minor bodies originated and evolved) from the ROSES Summary of Solicitation.

A.1 Aerobraking at Mars

Mars Global Surveyor (MGS), Mars Odyssey (ODY), and MRO have used acceleration measurements to determine atmospheric density along the lowest parts of their trajectories (Keating et al., 1998; Withers, 2005; Bougher et al., 2006b). Such density profiles begin at 150-200 km altitude, once the atmospheric density exceeds some threshold set by the accelerometer's performance, pass through periapsis around 100 km, and end at 150-200 km altitude (Tolson et al., 1999, 2002, 2005). The MRO ACCEL instrument, based on its quick-look data products during aerobraking operations, is capable of measuring density profiles up to 190 km or greater (Fig. 1). Due to the elliptical orbit of the aerobraking spacecraft, these density profiles are not vertical, but have significant horizontal extent. Since MGS, ODY, and MRO have all been targeted to sun-synchronous, near-polar orbits, most aerobraking density profiles lie close to lines of constant longitude. This is not the case when periapsis is in the polar regions, which happened briefly for MGS, ODY, and MRO during their aerobraking.

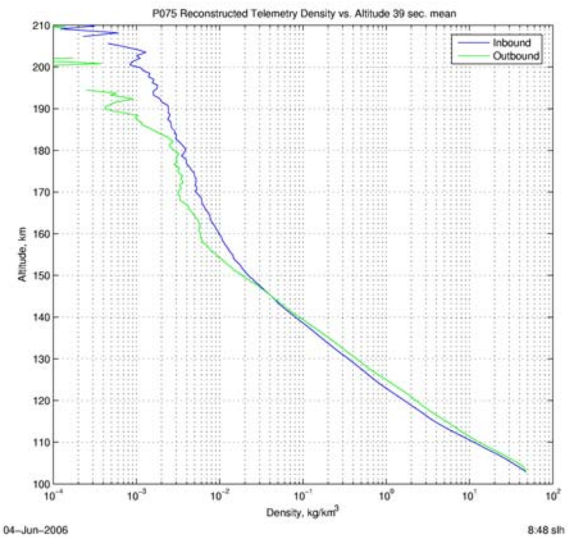

Figure 1. MRO ACCEL density profile from P075 used by the Atmospheric Advisory Group. Instrument noise does not overwhelm the inbound densities until altitudes greater than 200 km.

The altitude, latitude, longitude, season (Ls) and local solar time (LST) of a density measurement affect the scientific interpretation of that measurement. Consecutive profiles have similar vertical-horizontal cross-sections due to the relatively small change in the spacecraft's orbital elements from one orbit to the next. Consecutive profiles have slightly different periapsis latitudes because the orbital periapsis precesses monotonically due to the oblateness of Mars. Consecutive profiles have very different periapsis longitudes because of the rotation of Mars beneath the inertially-fixed spacecraft orbit. Consecutive profiles have similar periapsis LSTs because the aerobraking orbit is nearly sun-synchronous. Figure 2 shows periapsis latitude, LST, Ls, and altitude for MGS, ODY, and MRO.

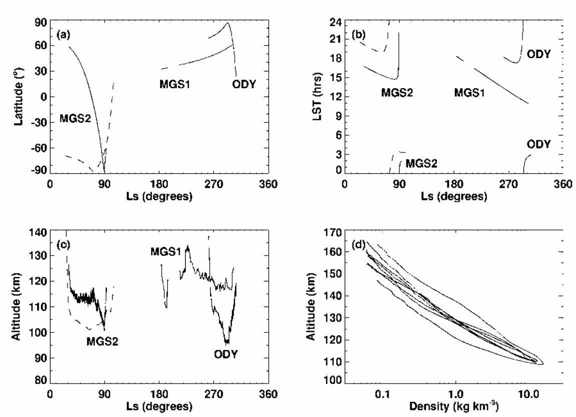

Figure 2. Panels (a), (b), and (c). Periapsis latitude, LST, and altitude for MGS Phase 1, MGS Phase 2, and ODY (solid lines). Predictions for MRO are shown as dashed lines. Panel (d) shows 39-second density profiles for MGS orbits P0963, P0970, P0977, and P0984, whose periapsis latitudes and longitudes spanned only a few degrees. The P0977 profile is clearly distinct.

Atmospheric pressures can be derived from vertical profiles of atmospheric density using the equation of hydrostatic equilibrium and an appropriate boundary condition (Holton, 1992). Atmospheric temperatures can then be obtained using a molecular mass and the ideal gas law (Holton, 1992). Horizontal gradients in these atmospheric properties are, in principle, related to the atmospheric circulation (Holton, 1992). Accelerometer measurements can therefore be used to determine many atmospheric properties, not just densities (Withers, 2003).

A.2 Scientific Discoveries from MGS and ODY ACCEL Measurements

The MGS and ODY accelerometer datasets have stimulated numerous scientific publications on a range of topics. Keating et al. (1998), who discussed the first set of MGS ACCEL measurements, observed rapid and large upper atmospheric responses to a regional dust storm thousands of kilometres away, variability in upper atmospheric densities due to changes in solar extreme-ultraviolet (EUV) flux, and large, planetary-scale variations in density with longitude at fixed LST (Figure 3). The life-cycle of dust storms is a major issue in martian atmospheric science (Leovy, 2001). These measurements during the growth, peak, and decay of a substantial dust storm will benefit studies of the far-reaching effects of dust storms (eg. Bougher et al., 1997; Bridger and Murphy, 1998; Bottger et al., 2004; and many others).

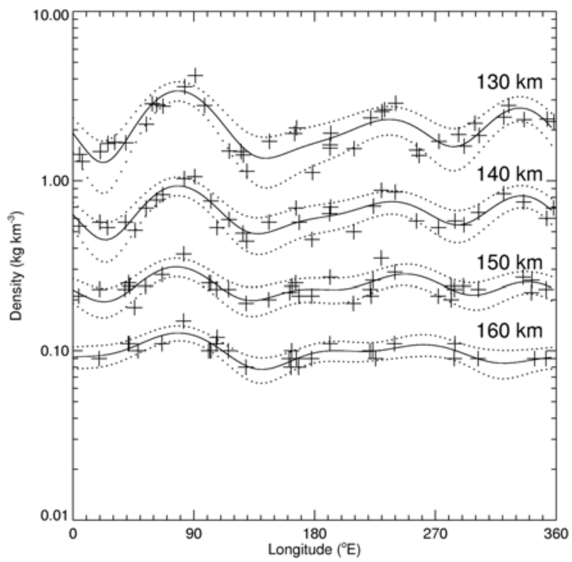

Figure 3. MGS Phase 2 density measurements between 10N and 20N (crosses). Harmonic fits are shown as solid lines, with 1-sigma uncertainties about each fit shown as dotted lines.

Several subsequent papers examined the zonal density variations in more detail. These showed that non-migrating thermal tides launched by variations in the surface topography were responsible for the zonal density variations at 100 km above the surface and identified some of the dominant tidal modes (Joshi et al., 1999; Forbes and Hagan, 2000, Forbes et al., 2002; Wilson, 2002). Comparison of dominant tidal modes in the lower and upper regions of the atmosphere enables studies of how these disturbances propagate upwards and of what the lower atmospheric circulation must be like to permit them to propagate upwards without breaking (Wilson and Hamilton, 1996; Forbes et al., 2001; Forbes, 2004a; Forbes, 2004b). Radio Science measurements show that the altitude of the ionospheric peak on Mars varies with longitude due to these zonal density variations (Bougher et al., 2001; Krymskii et al., 2003; Wang and Nielsen, 2003). Comparison of Radio Science and accelerometer measurements extends the study of tides to latitudes, seasons, and LSTs not probed by the limited accelerometer datasets.

Other research topics have included comparison between ACCEL densities and higher altitude Radio Science densities (Tracadas et al., 2001; Mazarico et al., 2005), traveling waves with periods of 17-20 days (Wilson et al., 2002; Tolson, 2005), gravity waves (Tolson et al., 1999, 2005; Forbes, 2003; Fritts, 2004; Fritts et al., 2006), and polar heating (Bougher et al., 2006a).

In summary, MGS and ODY ACCEL data products are being used productively by the scientific community to address fundamental questions in martian atmospheric science, not just upper atmospheric science. Studies of tides and dust storms, in particular, must consider the lower atmosphere. Data from the MRO ACCEL investigation will be valuable to the Mars science community.

B. INVESTIGATION AND TECHNICAL PLAN

B.1 Data Products

Several useful data products will be supplied to the PDS during this proposed work. Here we describe these data products, the methods by which they will be generated, and their usefulness to the broader scientific community once they become publicly available. The scientific analysis offered by this proposal is discussed in Section B.3.

B.1.1 Densities at fixed altitudes. The existing MRO ACCEL team has generated 39-second running mean density profiles at 1 Hz sampling rate for each aerobraking pass. We will extract densities at 100, 105, 110, ... km altitude levels from each of these profiles. Since the measured density at a given altitude in a profile can be affected by small-scale waviness, an exponential fit to measured densities within a few kilometres of this altitude will be used to determine the background, undisturbed density. Densities at a smaller number of fixed altitude levels (e.g. 110, 120 km) are likely to be archived on a best effort basis by the existing MRO ACCEL team in preparation for PDS archiving (Keating et al., 2001b, 2004b; PDS, 2006d). If that best effort work is accomplished, then this proposed work will extend those data products to finer altitude levels. Close interaction with the existing MRO ACCEL team will be essential to ensure that the same fitting techniques are used on the same density profiles for consistency. Dependences on latitude and altitude for MGS and ODY densities, density scale heights, and temperatures are shown in Figure 4. These temperatures were derived from density scale heights assuming an isothermal atmosphere.

The benefit to reducing the spacing between these fixed altitude data products from 10 km to 5 km is that the spacing changes from about one scale height to about half a scale height. Two measurements per scale height, rather than just one, are much more useful to data users characterizing vertical structure and investigating the physical processes that affect that vertical structure. Why stop at 5 km? Fixed altitude data products with a spacing of, say, 1 km could be generated, but they will be significantly affected by small-scale waves, rather than being representative of the background density structure through which those waves are propagating.

This task requires collaboration with the MRO project and ACCEL team to ensure that these data products are consistent with the existing best effort fixed altitude data products, plus access to the 39-second density profiles.

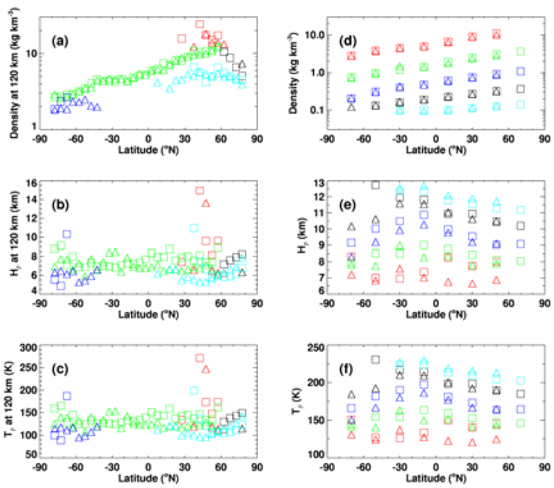

Figure 4. Panel (a): Average density at 120 km. Triangles = inbound, squares = outbound. Red = MGS1, green = MGS2/pm, dark blue = MGS2/am, black = ODY/pm, light blue = ODY/am. Panel (b): As (a), but average density scale heights. Panel (c): As (a), but average temperatures. Panel (d): Average densities at various altitudes for MGS Phase 2, pm. Triangles = inbound, squares = outbound. Red = 120 km, green = 130 km, dark blue = 140 km, black = 150 km, light blue = 160 km. Panel (e): As (d), but average scale heights. Panel (f): As (d), but average temperatures. (Withers, 2005).

<u>PDS DELIVERABLES:</u>
Inbound and outbound density and uncertainty at ..., 100 km, 105 km, 110 km, ... based on exponential fits to 39-second density profiles for each aerobraking pass. The height of the lowest altitude level will be set by periapsis altitude. Only densities greater than the uncertainty will be archived, which fixes the uppermost altitude level.

B.1.2 Gridded latitude-altitude cross-sections of densities, pressures, and temperatures. Changes in density along an individual profile are due to both horizontal and vertical gradients. How can these two effects be separated?

Each profile has a latitude-altitude cross-section. Since periapsis latitude precesses monotonically during aerobraking due to the oblateness of Mars, each profile is slightly displaced in latitude from its predecessor. Horizontal gradients in density can be calculated by comparing densities at a fixed altitude in one profile to densities at the same altitude in a subsequent profile with a slightly different periapsis latitude. Vertical gradients can also be determined in this way.

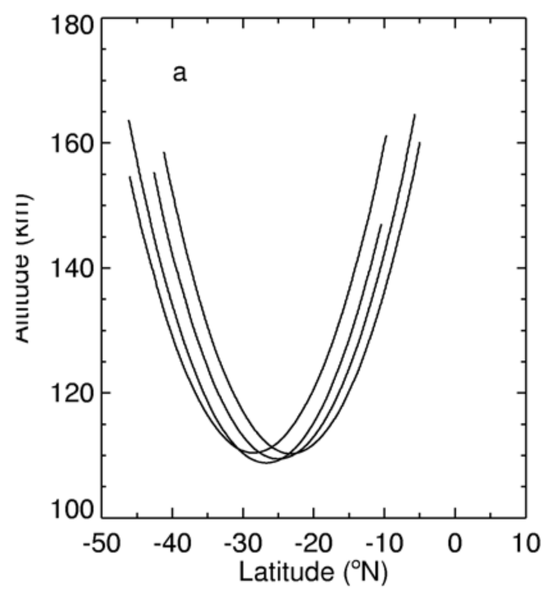

Figure 5. Aerobraking passes for MGS orbits P0963, P0970, P0977, and P0984. Corresponding densities are shown in Panel (d) of Figure 2.

39-second density profiles, generated by the existing ACCEL team, will be subdivided by periapsis longitude into, say, six groups. Each group of density profiles will be used to construct a latitude-altitude grid of density measurements at fixed Ls, LST, and longitude. Synthetic vertical density profiles, unaffected by horizontal gradients in the atmosphere, will be extracted from these grids. The equation of hydrostatic equilibrium will be used to derive a vertical pressure profile from each vertical density profile (Holton, 1992). The common assumption of an isothermal upper boundary will be used to relate the known density scale height to the pressure on the upper boundary (Magalhaes et al., 1999). Since pressure increases exponentially with altitude, errors in the pressure on the upper boundary have negligible effect on pressures two scale heights or more below the boundary (Withers et al., 2003b). Vertical temperature profiles will be obtained from vertical profiles of density and pressure, assumptions about the atmospheric mean molecular mass, and the ideal gas law (Holton, 1992). MRO ACCEL team member Bougher will be able to provide model estimates of mean molecular mass from his numerical simulations (Bougher, 2005; Bougher et al., 2006b).

The spacing in latitude, altitude, and longitude of these gridded properties will be commensurate with the spacings of the 39-second density profiles. Nominal intervals are 5 degrees in latitude, 2 km in altitude, and 60 degrees in longitude.

If MRO aerobraking proceeds as planned, then a swath from the south pole to the northern tropics should be covered around Ls=90 and LST=3 hours. These altitude-latitude cross-sections of density, pressure, and temperature at fixed season, LST, and longitude are valuable because they enable more in-depth studies of meridional heat transport and related processes than are possible using the spaghetti strands of individual profiles. Horizontal pressure gradients are related to atmospheric circulation (Holton, 1992). Comparison between models and these data products should permit some general statements to be made about upper atmospheric circulation (Bougher et al., 1999b, 2000). In the lower martian atmosphere, the equations governing the conservation of momentum can be simplified to obtain the thermal wind equation, the gradient wind equation, and the geostrophic wind equation (Holton, 1992; Hinson et al., 1999; Smith et al., 2001). Do these or similar equations apply in the upper atmosphere? If so, these data products can be used to quantitatively measure the circulation and test whether it varies with longitude due to tides. If not, only general statements about circulation will be possible. These will still be useful because there are very few published measurements of winds in the martian upper atmosphere (Lellouch et al., 1991; Bertaux et al., 2005a). However, some recent, unpeer-reviewed conference abstracts have presented sub-mm and heterodyne measurements of martian winds in the middle atmosphere.

Horizontal gradients are ignored for the data products in Sections B.1.1 and B.1.4. This assumption will be evaluated as the data products in this section are generated.

This task requires collaboration with the MRO project and ACCEL team to test the assumptions related to density scale heights and temperatures, access to the 39-second density profiles, and access to Bougher's mean molecular mass simulations.

PDS DELIVERABLES:
Grid of density, pressure, and temperature, with uncertainties, with 2 km vertical separation, 5 degree meridional separation, and 60 degree zonal separation (nominal values). Vertical range will be 100-150 km, with the upper boundary set by the data quality, and meridional range will be 80S-equator, or greater.

B.1.3 Characterization of tidal amplitudes and phases. MGS data showed zonal variations of 40% or more in density at fixed LST and altitude due to thermal tides (Keating et al., 1998; Withers, 2003a). Variations of similar amplitude have been observed by MRO ACCEL during aerobraking. The general pattern from detailed MGS studies and preliminary impressions of ODY and MRO data is that tides are stronger in the tropics than at the poles, consistent with theoretical expectations (Chapman and Lindzen, 1970; Wilson and Hamilton, 1996). Seasonal dependences may also exist.

Withers (2003) and Withers et al. (2003a) developed software to quantify the amplitudes and phases of dominant harmonics in such zonal density variations. The amplitudes and phases, and their variations with latitude, altitude, LST, and seasons, can be used to identify the dominant tidal modes and study their propagation and dissipation (Wilson and Hamilton, 1996; Forbes et al., 2001, 2002; Withers et al., 2003a). These existing analysis tools will be used to quantify the amplitudes and phases of dominant harmonics in the MRO fixed altitude densities (Section B.1.1). This data product could be used to test numerical models against MRO observations (eg. Angelats i Coll et al., 2005; Gonzalez-Galindo et al., 2005; Crowley et al., 2003; Hartogh et al., 2005). The process of model testing and improvement will lead to better predictions of atmospheric conditions for future aerobraking operations.

This data product is also scientifically valuable. Potential data users might study the dependence of tides on LST using data from 60S latitude, since MRO sampled that latitude on both the dayside and the nightside, which would distinguish between diurnal and semi-diurnal tidal modes. Other possible studies include investigating dissipation and the cascade of energy/momentum to smaller scales based on the variation of tidal amplitudes with altitude and examining interannual variability between the MGS, ODY, and MRO observations.

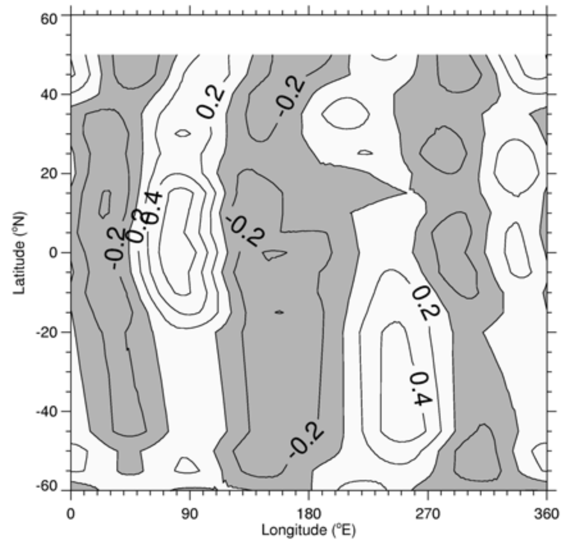

Figure 6. Relative differences between measured density and zonal-mean density at 130 km for MGS Phase 2, pm. Densities smaller than the zonal mean are shaded.

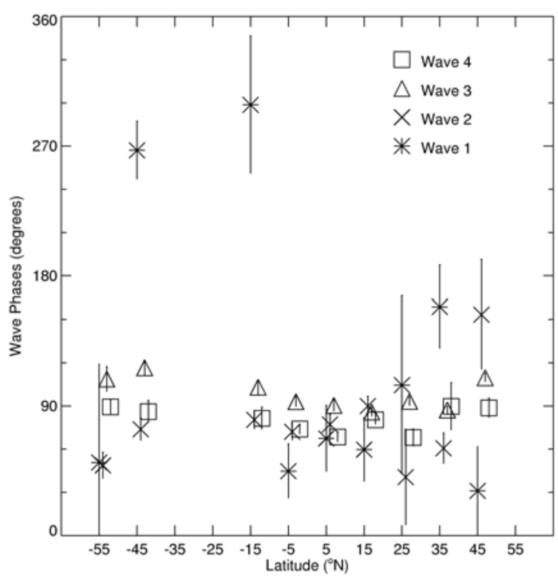

Figure 7. Phases for harmonics (wave-1 to wave-4) in zonal density variations seen in Figure 6.

The maximum value of the wave-*n* phase is $360^o/n$. Phases are very stable with latitude.

PDS DELIVERABLES:
Zonal-mean density, amplitudes and phases of zonal variations in density from wave-1 to wave-4, with uncertainties in each quantity, at 10 km altitude intervals and ten degree latitude intervals. Vertical range will be 100-150 km, with the upper boundary set by the data quality, and meridional range will be 80S-equator, or greater. Results will be provided separately for inbound and outbound measurements and for dayside and nightside measurements.

B.1.4 High-altitude density measurements. The PDS archive of MGS ACCEL data includes densities based on 39-second running means and densities based on 7-second running means (Keating et al., 2001a). The former extend to higher altitudes than the latter due to a square-root-of-N reduction in measurement uncertainty. Density profiles based on averages over even longer periods should therefore extend to even higher altitudes. The drawback to averaging, say, five minute's worth of measurements is worsening vertical resolution. Once the vertical resolution exceeds a scale height, the derived densities are difficult to interpret and compare against models.

In this task, atmospheric densities at the greatest altitudes possible shall be determined. This will be achieved by averaging the time series of acceleration measurements as much as possible. The duration (in seconds) of the averaging window will be adjusted from orbit to orbit so that it corresponds to 15 km (a typical scale height) of vertical motion of the spacecraft at 200 km altitude. That interval is about 25 seconds for an orbital period of 12 hours and periapsis of 100 km, increasing to 100 seconds for a 3 hour period and 250 seconds for a 2 hour period. Note that the 39 second averaging interval corresponds to a vertical range in excess of one scale height for orbital periods longer than about 8 hours. Densities calculated in this task will therefore terminate at a lower altitude than the 39-second density profiles for orbits with periods longer than about 8 hours (roughly the first 30% of MRO aerobraking passes).

Once the time series of averaged accelerations is determined, we shall extract those values that correspond to altitudes of 150 km, 155 km, and so on. The upper limit will be set by the requirement for the averaged acceleration to exceed the measurement uncertainty. Next, these accelerations will be converted into densities using

$$ma = \frac{\rho A v^2 C}{2} \qquad (1)$$

where m is the spacecraft mass, a is the aerodynamic acceleration, ρ is the atmospheric density, A is the spacecraft area, v is the atmosphere-relative velocity, and C is a dimensionless drag coefficient (Magalhaes et al., 1999). A, v, and m for each aerobraking pass will be supplied to us by the MRO project. At high altitudes, where the spacecraft aerodynamics are in the free molecular flow regime, C is solely a function of the orientation of MRO with respect to the atmospheric flow velocity (Takashima and Wilmoth, 2003, 2004; Tolson et al., 2005). The existing ACCEL team has the tools to determine C using MRO angular rate data and we request that they provide us with the appropriate values of C. High altitude densities will not be obtained if accelerometer measurements are contaminated by thruster firings or other spacecraft activities.

An averaging interval of 100 (or 250), rather than 39, seconds decreases the acceleration uncertainty to 60% (or 40%) of its original value, increasing the maximum altitude of measurements by half (or one) scale height. The 39-second density profiles terminate so close to the exobase that increasing the maximum altitude by a significant fraction of a scale height, rather than several scale heights, does have scientific value. This will also help improve predictions of densities at 255 km, periapsis for the MRO primary science orbit, which will help HiRISE and CRISM target their observations.

This task requires collaboration with the MRO project and ACCEL team, specifically the delivery to us of values of *A*, *m*, *v*, and *C*, information on thruster firings, and comparison of these very high altitude density values to the highest altitude densities from the standard ACCEL data products.

PDS DELIVERABLES:
Inbound and outbound density and uncertainty at 150 km, 155 km, etc., for each aerobraking pass, plus averaging time interval for each aerobraking pass. Only densities greater than the uncertainty will be archived, which fixes the uppermost altitude level.

B.2 ACCEL Team Responsibilities

B.2.1 Team meetings and publications. This Participating Scientist proposal involves joining a team. A team should be greater than the sum of its parts. For example, the MGS MOLA instrument team has written a series of important papers on martian geology, tectonics, and geophysics (Smith et al., 1999; Zuber et al., 2000; Phillips et al., 2001; Solomon et al., 2005). These papers are based on the research work of their authors, but they are not simply research articles. Their scope is broader. Nor are these papers reviews of previously published results. Instead, they contain a synthesis of new results from the ongoing research of their authors, often before the detailed description of that research was published in a more specialized journal. Due to its broad scope and high-quality science, this series of papers has had tremendous influence on current research in Mars science. This would not have occurred if the team members had simply downloaded data from the Web and worked in isolation on their own research projects. We want the MRO ACCEL team to publish papers with a similar impact on the field of martian upper atmospheric science. Previous aerobraking accelerometer teams have had a poor record in this area, with one team paper deriving from MGS and none from ODY (Keating et al., 1998).

To accomplish this goal, this proposal requests funds to support two MRO ACCEL team meetings (2 days) each year focused on primarily on science and publications. Less frequent meetings would be too far apart to preserve the momentum developed at these meetings. One team publication per year is anticipated. A strawman list of attendees at a 2-day team meeting includes Bougher, Keating, Murphy, Tolson, Withers, a student, and two other invited scientists. A small number of scientists from outside the ACCEL team will be invited to each meeting to share their specialized expertise related to the topic of the meeting.

Possible themes of meetings and subsequent papers are (1) Comparison of MGS, ODY, and MRO ACCEL observations with other middle/upper observations (e.g. MRO MCS, MEX SPICAM), (2) Evaluation of numerical models. What aspects of the MRO ACCEL datasets are well-described by models such as the Bougher MTGCM, Justus MarsGRAM, LMD-Oxford GCM, Crowley ASPEN GCM (Bougher et al., 2000; Justus et al., 2000; Crowley et al., 2003; Angelats i Coll et al., 2005; Gonzalez-Galindo et al., 2005), and which aspects are not? What does that imply for numerical modelling of important physical processes and the predictability of climate and weather during future aerobraking missions? (3) Tides. What connections exist between tides in the lower atmosphere (generation region, TES and MCS data), middle atmosphere (propagation region, MCS and SPICAM data), and upper atmosphere (dissipation region, ACCEL and SPICAM data)? How predictable are tides in the martian upper atmosphere?

A strawman agenda for a 2-day meeting is: Day 1 - Host introduction, meeting logistics (1 hour), followup items from previous meeting (1 hour), theme of this meeting (1 hour), latest news on experiment status, calibration, data processing, and new data products (1 hour), science presentations (4 hours). Day 2 - Synthesis of science presentations with meeting theme (1 hour), plan rough structure of paper related to meeting theme, assign sections and figures to individuals (1 hour), individuals develop detailed plans for their sections of paper (1 hour), the group comments on detailed plans for each section of paper, and the group revises the structure of paper accordingly (1 hour), plan research and analysis necessary to complete first draft of paper, assign tasks (1 hour), programmatic topics (1 hour), other science topics (1 hour), plan next meeting (1 hour).

These meetings will only be successful if individuals work on topics related to meeting themes at their home institutions, not just in a plane on the way to a meeting. The best way to achieve that is to focus on topics that interest many team members. Impromptu discussions at other scientific meetings and occasional telecons will also help maintain direction and schedule. One team paper per year is anticipated from this investment in science-focused ACCEL team meetings. The budget for each team meeting is estimated as $6,940, based on airfare ($500), hotel and per diem for two nights ($370), ground transportation ($50) for seven travelling attendees, plus $500 for host expenses (facilities, refreshments).

B.2.2 Data archiving. Deliverable data products were described in Section B.1. They will be documented and delivered to the PDS for peer-review and subsequent archiving (PDS, 2006a, b, c). Since the ACCEL team is currently required to document and archive the basic ACCEL dataset, the documentation required for our data products is limited to an accurate description of those data products and how they were produced. The acceleration measurements, instrument, mission, and so on will already be documented. Data files will be ASCII files. The size of our data products will not be excessive, on the order of megabytes, not gigabytes. All data products will have error bars.

The PDS standards for formatting, documentation, directory structure, delivery media, and so on, will be followed (PDS, 2006a, b, c). 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.

B.2.3 Atmospheric densities from primary science orbit. MRO quick-look densities provided to the AAG, based on 39-second running means of acceleration measurements, have sometimes reached 200 km altitude where the scale height is about 15 km (Bougher et al., 1999b, 2000; Withers, 2005). The MRO primary science orbit will have a periapsis at 255 km over the south pole. Will the MRO ACCEL instrument be able to detect atmospheric drag during the primary science orbit? Densities equal to those observed at 200 km during aerobraking will be observed at higher altitudes during a dust storm due to the inflation of the lower atmosphere. During the Noachis regional dust storm that affected MGS aerobraking, northern hemispheric density levels moved upwards in altitude by one scale height. It is plausible that a large dust storm close to the edge of the southern polar cap could raise density levels at the south pole by two scale heights. If so, the density at 255 km will only be a factor of e^2, or 8, less than the 39-second running mean detection threshold. Using a 39-second x 8^2 (40 minutes) running mean will change the detection threshold such that periapsis density should be detectable - if the atmospheric density remains close to the periapsis density for 40 minutes of the 120 minute orbit.

This rough estimate suggests that the MRO ACCEL instrument <u>may</u> be able to detect the atmosphere during the primary science orbits. We expect the ACCEL team to attempt such observations during the primary science phase and we propose to support that effort by analysing acceleration measurements and performing error calculations. Dust storm season occurs during Year 2 of this proposal.

B.2.4 Other team responsibilities. In addition to the interactions with the existing ACCEL team members described in sections B.1 and B.3, this proposed effort will also contribute to the success of the ACCEL experiment by evaluating ACCEL data products and documentation as our data products are generated. Feedback from this informal review process will improve the quality of archived ACCEL data products, which will be beneficial for all ACCEL data users.

The data products offered by this proposal will be much more useful to the community if they are generated by the MRO participating scientist program than by the MDAP program, which only supports analysis of publicly available data. First, much of the information and data required to generate these data products will either not be archived or will only be archived on a best-effort basis. Second, data products generated by this proposal will be scrutinized and critiqued by the MRO ACCEL team at various stages before initial delivery to the PDS, be incorporated into the official MRO ACCEL archive on the PDS, be responsive to changes in instrument calibration, undergo thorough peer review by the PDS, and satisfy PDS documentation and format standards. In contrast, data products generated by a similar MDAP proposal would only be required to be made publicly available on a personal website, not a long-term depository, would not be peer-reviewed, and would not be as well-documented.

Two weeks of effort per year will be devoted to providing materials to the MRO project for incorporation into their E/PO activities and participation in their E/PO programs.

B.3 Science analysis

Scientific analysis of ACCEL data products will proceed in parallel with the generation of new data products. Scientific analysis of the data products will identify problems with data product formatting, highlight unusual and possibly erroneous data points, highlight interesting features in the data products that later users may wish to investigate, and lead to the development of unplanned data products in response to discoveries.

B.3.1 Basic survey. This task will be performed early in Year 1 and its results presented at scientific meetings as soon as possible. Our aim is to provide guidance and background to potential ACCEL data users in a timely fashion. They will then be better prepared to mine the ACCEL dataset for interesting features, to plan research projects, and to develop funding proposals.

This task consists of a survey of atmospheric densities to characterize trends with altitude, latitude, LST, and season. Unusual or unexpected features will be highlighted. Many papers on the MGS and ODY ACCEL datasets have focused on tides, so a search for the effects of tides in the MRO measurements will be conducted and, if they are present, their variations with latitude and altitude will be described.

The experience of the ACCEL team will be invaluable here. Their observations from aerobraking operations will guide us towards interesting trends and unusual features, so we shall collaborate with existing team members closely for this task. ACCEL team member Tolson has described such trends and features in MGS and ODY observations (Tolson et al., 1999, 2000, 2005).

B.3.2 MGS/ODY/MRO comparison. Densities in the martian atmosphere vary with season, latitude, and LST. MRO will not be able to sample the atmosphere at all possible combinations of season, latitude, and LST. The comparison of MGS, ODY, and MRO densities will piece together a more complete picture of the climatology of the martian upper atmosphere. Inter-annual variabilities can be studied using MGS Phase 2 and MRO data (Ls=90, LST=2 hours). Seasonal variations in the tropics can be studied using ODY and MRO data (LST=2 hours, Ls = 300 and 100).

Density profiles from all three missions exhibit variability or small-scale structure. Part of this variability will be caused by variability in the background atmosphere, such as gravity waves, and part might be due to unidentified instrumental/spacecraft effects. The variability will be quantified using the technique outlined in Withers (2005) and its dependence on latitude and season compared with published predictions for gravity waves on Mars (eg Creasey et al., 2006, and references).

Since the existing MRO ACCEL team members (Keating, Bougher, Tolson) were all involved in MGS and ODY aerobraking, their advice and insights will be solicited to support this task.

B.3.3 Tidal investigations. A tidal mode is a planetary scale disturbance in the atmosphere with a defined meridional structure, vertical wavelength, zonal wavenumber, and period related to the solar day (Chapman and Lindzen, 1970). Several different tidal modes can cause the same variation in density with longitude observed by a sun-synchronous orbiter (Forbes and Hagan, 2000). Tidal modes affecting the MRO ACCEL observations will be identified and the vertical propagation of tides will be studied.

First, the tidal modes that are most likely to be responsible for the observed zonal structure will be identified using a simple approach and a complex approach. The simple approach involves rejecting candidate tidal modes whose vertical or meridional structure makes them unlikely to be excited in the lower atmosphere or to propagate up to the upper atmosphere (Withers et al., 2003a). The complex approach involves general circulation model simulations. The simulations, unlike the data, cover all latitudes, longitudes, and times of day, so dominant tidal modes can be identified in the simulations. Simulations by Co-I Murphy (0-80 km) and ACCEL team member Bougher (80-200 km) will be used (Murphy et al., 1995; Bougher, 2005; Bougher et al., 2006).

Second, the vertical propagation of tides will be investigated. The tidal modes that are dominant in the upper atmosphere are generated in the lower atmosphere (Wilson and Hamilton, 1996; Forbes and Hagan, 2000; Withers et al., 2003a). Their amplitudes are very small in the lower atmosphere, so their effects are masked by stronger tides that cannot propagate upwards without dissipating (Banfield et al., 2000). The tides that dominate in the lower atmosphere dissipate as they propagate upwards, whereas the tides that dominate in the upper atmosphere amplify (eg. Forbes et al., 2001). A transition region must exist in the middle atmosphere where these two groups of tides have similar amplitudes.

MRO aerobraking spans approximately Ls=20-100. Interannual variability in the martian lower atmosphere is known to be small at this season (Smith, 2004). We will compare the tidal amplitudes and phases that are extracted from the MRO ACCEL data as functions of latitude and altitude to similar data products generated by the MRO MCS team from their 2008 data (Read et al., 2006). MRO MCS team member Richardson is a collaborator on this proposal, giving us a clear point of contact with the MCS team. This comparison will show how tides, which are an important part of martian atmospheric dynamics, change in amplitude and phase as they propagate upwards, then dissipate. The propagation of tides is affected by both atmospheric structure and atmospheric dynamics (eg. Chapman and Lindzen, 1970; Forbes et al., 2001). MCS observations reveal the atmospheric structure, but not dynamics, so model simulations of propagating tides that accurately reproduce observations can be used to make inferences about the speed and direction of atmospheric winds. This task directly addresses questions of lower-upper atmosphere coupling.

B.3.4 Comparison of gridded ρ, p, T observations and model predictions. The structure and dynamics of the martian upper atmosphere are controlled by balances between heating and cooling and between dynamical and radiative processes. Observations only reveal the state of the atmosphere. By themselves, they do not show which physical processes are controlling the atmosphere. Numerical simulations, if reasonably similar to the observations, can investigate the importances of different processes by (A) switching processes on and off, and (B) spanning all latitudes, longitudes, and local times. ACCEL team member Bougher has used his thermospheric general circulation model (MTGCM) to simulate atmospheric conditions during MRO aerobraking (Bougher, 2005; Bougher et al., 2006). The gridded density, pressure, and temperature data products will be compared to his simulations. First, the accuracy of these predictions will be evaluated, which will help future mission planning. Second, we shall investigate which physical processes are most responsible for the observed state of the atmosphere. For example, where does dynamical heating lead to high temperatures? Where does dynamical cooling lead to low temperatures? Do current models of non-LTE CO_2-O cooling accurately predict the vertical thermal structure (Lopez-Valverde et al., 2000)? An important topic will be the atmospheric circulation. Comparison between observations and simulations should enable us to infer the approximate strength and direction of the wind. For example, a fast eastward wind will be associated with very different meridional pressure gradients than a fast westward wind (Holton, 1992).

The excellent performance of all three axes of the MRO accelerometer and the MRO gyroscopes raises the possibility that atmospheric winds might be measured directly based on the spacecraft's attitude and the torques it experiences. ACCEL team member Tolson has a particular interest in this area. If winds are measured in this way, they can be compared to those inferred in this task. Close collaboration with existing ACCEL team members is an essential component of this task.

C. IMPORTANCE AND RELEVANCE TO NASA

This proposed effort will support both NASA's operational goals and NASA's science goals.

Accelerometer instruments are common on NASA solar system exploration spacecraft, including orbiters, landers, and entry probes, serving both operational and scientific purposes. However, NASA has lost critical expertise with the breakup of Al Seiff's group at NASA-Ames. Although still active, the generation to which NASA-Langley's Blanchard, Keating, and Tolson belong will reach retirement age in the near future. NASA faces a skills shortage for its missions in the decades ahead. This proposed work will provide on-the-job training for a young scientist (Withers) that will augment the human capital available to NASA for its future mission needs.

NASA's Mars Exploration Program will send more orbiters to Mars in the years ahead. The risk and cost of these future missions will be reduced if the state of the martian upper atmosphere can be predicted more accurately. The data products delivered by this proposal can be used by other workers to validate and improve numerical models with predictive capabilities.

Turning to NASA's science goals, the martian thermosphere is the foundation upon which the exosphere sits. Its structure and dynamics influence many escape processes and the ongoing loss of volatiles. A comprehensive response to the mantra "Follow the water" includes observations of the thermosphere through which water travels before escaping into space.

This proposal is aligned with MEPAG goals, including the following (MEPAG, 2006):
Investigation 1 of MEPAG Objective II.A - Determine the present state of the upper atmosphere (neutral/plasma) structure and dynamics; quantify the processes that link the Mars lower and upper atmospheres.
Investigation 3 of MEPAG Objective II.C - Determine the atmospheric mass density and its variation over the 80-200 km altitude range.
Investigation 4 of MEPAG Objective II.C - Determine the atmospheric mass density and its variations at altitudes above 200 km.

This proposal is responsive to two of the scientific objectives of the MRO mission: (1) Characterize Mars' global atmospheric structure and (2) Characterize the upper atmosphere in greater detail. The data products related to densities at fixed altitudes, high altitude densities, and gridded atmospheric properties characterize the upper atmosphere. The data products related to tides characterize both the global atmospheric structure and the upper atmosphere. The scientific analysis tasks on the basic survey and MGS/ODY/MRO comparisons characterize the upper atmosphere. The scientific analysis tasks on tides and comparison of gridded atmospheric properties and models characterize both the global atmospheric structure and the upper atmosphere.

The proposed work on ACCEL team meetings/publications and support of efforts to measure atmospheric densities during the primary science phase will characterize the upper atmosphere.

MRO Participating Scientist roles include: (1) instrument operations, (2) validate scientific data, (3) publish results, (4) archive data products, and (5) support E/PO. Our support of efforts to measure atmospheric densities during the primary science phase will contribute to ongoing mission operations. Validation of scientific data and preparation of archival data products is addressed by many of the data products and scientific analysis tasks. Organization of ACCEL team meetings will increase the published scientific output of the ACCEL team.

D. MANAGEMENT AND WORK PLAN

D.1 Work plan

Year 1. Determine densities at fixed altitudes (Withers 0.5 months, Student 2m). Generate gridded latitude-altitude cross-sections of densities, pressures, and temperatures (Withers 0.5m, Student 2m). Begin characterizing tidal amplitudes and phases (Withers 0.5m). Basic survey (Withers 1m, Student 2m). Begin analysis of gridded data products (Withers 1m). Plan team meetings and related papers (Withers 1m). Documentation and archiving (Withers 1m). E/PO (Withers 0.5m). Supervise student and serve as link between Withers and Student (Murphy 0.5m).

Year 2. Support attempts to measure atmospheric densities at periapsis of primary science orbit (Withers 1m). Finish characterizing tidal amplitudes and phases (Student 2m). Finish analysis of gridded data products (Student 3m). Begin comparison of MGS/ODY/MRO densities (Withers 1.5m, Student 1m). Plan team meetings and related papers (Withers 1m). Documentation and archiving (Withers 1m). E/PO (Withers 0.5m). Work on papers not related to team meetings (Withers 1m). Supervise student and serve as link between Withers and Student (Murphy 0.5m).

Year 3. Generate high altitude density measurements (Withers 1m). Finish comparison of MGS/ODY/MRO densities (Withers 0.5m, Student 2m). Study lower-upper atmosphere tides using MCS and ACCEL data (Withers 1m, Richardson 1m, Student 2m). Plan team meetings and related papers (Withers 1m). Documentation and archiving (Withers 1m). E/PO (Withers 0.5m). Work on papers not related to team meetings (Withers 1m, Student 2m). Supervise student and serve as link between Withers and Student (Murphy 0.5m).

D.2 PDS Deliverables

Fixed altitude densities (end of Year 1)
Gridded densities, pressure, and temperatures (end of Year 1)
Tidal amplitudes and phases (end of Year 2)
High altitude densities (end of Year 3)

D.3 Personnel

PI (Paul Withers) Postdoctoral research associate Dr. Withers will be responsible for the successful completion of the proposed tasks, delivery of the deliverables, and use of funds. His recent research has touched upon many aspects of the martian atmosphere, including the thermosphere, ionosphere, and results from thermosphere-to-surface entry profiles, and has involved the scientific analysis of processed MGS and ODY ACCEL data (Withers, 2003; Withers et al., 2003a, b; Withers and Mendillo, 2005; Withers and Smith 2005; Withers et al., 2005a, b, c; Withers, 2006). He has extensive experience working with unprocessed accelerometer data, including identifying errors in the Pathfinder volume at the PDS (see errata.txt in PDS volume MPAM_0001), deriving atmospheric properties and participating in EDL operations for MER, and deriving atmospheric properties for Huygens (Withers et al., 2003b; Withers and Smith, 2005;

Fulchignoni et al., 2002, 2005). He participated in MGS and ODY aerobraking operations via the AAG. Withers has recently received funds from the Mars Odyssey Participating Scientist Program, through a grant to his BU colleague Michael Mendillo, to reduce the raw ODY ACCEL data and deliver documented data products to the PDS. The skills and tools acquired under that grant will be used to support the work proposed here at no cost to the MRO project.

Co-I (Jim Murphy) Professor Murphy was a member of Atmospheric Advisory Groups for MGS, ODY, and MRO aerobraking. His research background in the lower atmosphere will be helpful for interpretation of our results in terms of whole-atmospheric processes and couplings between atmospheric regions (Murphy et al., 1990, 1993, 1995, 2002; Bridger and Murphy, 1998; Haberle et al., 1999). He has extensive experience with PDS policies and procedures, including the peer reviews of the MGS and MER ACCEL datasets. His office is in the same building as the PDS Atmospheres Node, which will greatly facilitate our interactions with the PDS. Full academic year salary support is provided by NMSU, and thus his participation will occur at no cost to this proposal.

Student The NMSU Astronomy department has ~25 graduate students, approximately 7 of whom are presently engaged in planetary science research. This position will support a beginning PhD student. Student's responsibilities begin with the generation of some of the simpler data products, transition towards scientific analysis of data products, and conclude with the writing of a scientific paper.

Collaborator (Mark Richardson) Professor Richardson, a member of the MCS instrument team, will provide characterization of lower atmospheric tides from MCS data at Ls=20-100 and work with Withers and Murphy on scientific analysis of tides.

D.4 Management

Withers (in Boston) will not directly supervise Student (in New Mexico). Regular telecoms between Withers and Murphy, with Student included as appropriate, will manage the BU-NMSU interface and monitor progress. Face-to-face discussions between Withers and Murphy/Student will occur at scientific meetings, in addition to ACCEL team meetings. Funds for Withers and Student to attend one week-long scientific meeting per year are requested. Potential data users planning data analysis projects and proposals will benefit from seeing the results of our work at meetings, and our work will benefit from their feedback. Student's professional development will also benefit from Student's attendence at meetings. The FAQ states that students, but not Co-Is, may be funded. The budget follows those guidelines.

D.5 Cost effectiveness

We believe that this is a cost-effective proposal. Salary support is requested for a student and a postdoc, with the efforts of more senior personnel provided at no cost to this proposal. Murphy has become familiar with the spacecraft, instrument, and its quick-look data products through participation in MRO's aerobraking operations, Murphy has acquired expertise in PDS policies and procedures, and Withers has developed tools for data processing and scientific analysis - all at no cost to this proposal. Travel costs are relatively large, but this investment in ACCEL team meetings will significantly improve the scientific productivity of the entire ACCEL team.

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