DERIVATION OF MARTIAN METEOROLOGICAL PARAMETERS USING GROUND-BASED TELESCOPES AND FORWARD-MODELLING

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Overview: Ground-based telescopes offer a number of advantages for characterising the Martian atmosphere, including the ability to use high-resolution (R ~ 30000) spectroscopy and to simultaneously characterise the atmospheric state across an entire hemisphere. In October/November 2005 we obtained high-resolution ground-based spectra of Mars in the 1.6 µm and 2.0 µm CO_2 bands using IRTF/CSHELL and Gemini South/GNIRS with the intention of deriving temperature, pressure and dust optical depth maps from these. We will make use of a forward-modelling technique to iteratively match our observational spectra to simulated spectra created using SMART and VSTAR. We present preliminary results demonstrating our models and observations match closely.

Introduction: Despite the increasing number of spacecraft sent to Mars in recent times, many properties of the Martian atmosphere remain relatively unconstrained (Forget *et al.*, 1999). Indeed, the Martian surface pressure has only been continuously monitored for any length of time at a total of three locations (Leovy, 1979; Golombek *et al.*, 1999). A more complete set of meteorological data is important both for the characterisation of the atmosphere and as input for general circulation models (GCMs) used in the prediction of atmospheric parameters for future Mars missions.

Near-infrared spectroscopy provides a method of obtaining much information about the atmospheric state of a planet. In the 1-2.5 µm region spectral lines of CO_2, H_2O, CO, O_2, O_3 and many others are present to varying degrees. These spectral lines give information not only about the composition of the atmosphere but also about its temperature and pressure via spectral band shapes. Many aerosols, such as Martian dust, also strongly influence the radiative output of Mars in this region.

Their lower spatial resolution notwithstanding, ground-based observations offer a number of advantages over observations taken on orbital platforms. The large distance from Earth allows the atmospheric state of an entire Martian hemisphere to be characterised using a single set of spectra. Observations can also be obtained at significantly higher spectral resolution than is currently possible with instruments like PFS (Formisano, 2005). However, the use of ground-based spectroscopy does introduce the not-insignificant problem of the removal of telluric lines from the observed spectra.

Telluric Lines: Traditionally, telluric spectral features are removed from astronomical spectra by making near-simultaneous observations of a 'featureless' standard star and dividing the planet's spectrum by this. Data reduction done in this manner generally makes the assumption that, in the case of ideal observations, the spectrum of the planet (as seen above the atmosphere) can be reproduced perfectly; however, this is not the case.

Planetary atmospheres with molecular components will have narrow infrared spectral features which will remain unresolved when using low-resolution (R < ~20000) spectroscopy. Consider a low-resolution telluric region of (for the sake of example) 50% transmission calculated using observations of a standard star. If a narrow, unresolved spectral line in the planetary spectrum coincides with a narrow, unresolved band of high transmission in the Earth's atmosphere then the strength of that band will be exaggerated compared to the value obtained by correcting using the 50% value. Conversely, if that line coincides with an unresolved region of strong absorption then using the standard star value will produce an over-correction. This situation is illustrated in Figure 1.

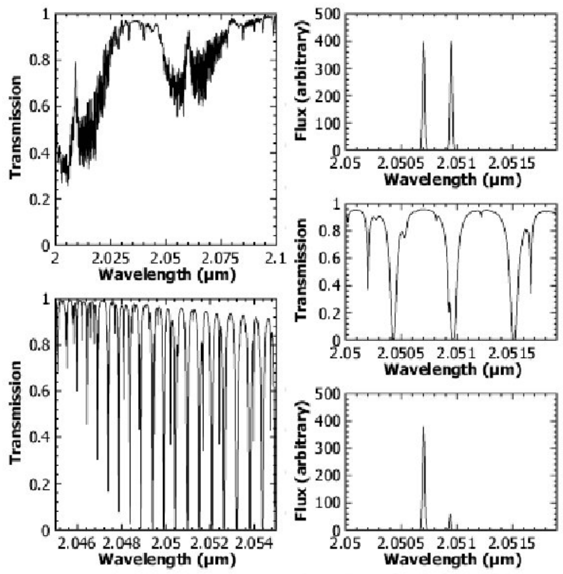

Figure 1: The left side shows the transmission of the Earth's atmosphere at R = 1000 (top) and with all lines fully resolved (bottom). The right side demonstrates the effect of unresolved spectral structure on two lines of equal strength.

For spectra which are uncorrelated with the Earth's atmospheric spectrum (i.e. they have few similar spectral lines) then the net result is that most of these unresolved differences cancel out and the standard star method gives generally accurate results. However, in the case of observations of an atmosphere with similar constituents to our own (e.g. Mars), many of the narrow molecular lines match up, effectively meaning that the standard star method will overcorrect for these lines.

To quantify these effects, we generated modelled spectra of the atmospheres of both Earth and Mars using the SMART atmospheric modelling tool (as described below). To simulate the standard star calculation, we used the following procedure:

1. High-resolution atmospheric spectra of both Earth and Mars were generated using a model solar spectrum.
2. The Mars spectrum as seen at the top of the Earth's atmosphere was convolved with a gaussian of appropriate properties to simulate a spectrograph at different spectral resolutions.
3. The Earth spectrum as seen at the surface was convolved with the same gaussian to simulate low-resolution observations of a standard star.
4. The high-resolution Mars spectrum was passed through the Earth model, and the resulting spectrum as seen on the ground was convolved with the gaussian to simulate low-resolution observations of Mars.
5. The low-resolution Mars observations in (4) were divided by the low-resolution transmission derived from (3) and compared to the low-resolution Mars spectrum in (2).

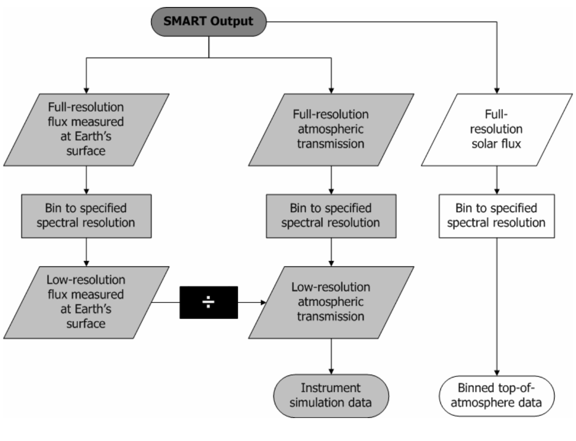

Figure 2: A diagrammatic representation of the algorithm used to simulate the standard star reduction process.

A diagram of this simulation is shown in Figure 2; the results are shown in Figure 3. As can be seen, the difference between 'standard star reduced' and 'actual' values is as much as 50% around strong CO_2 features.

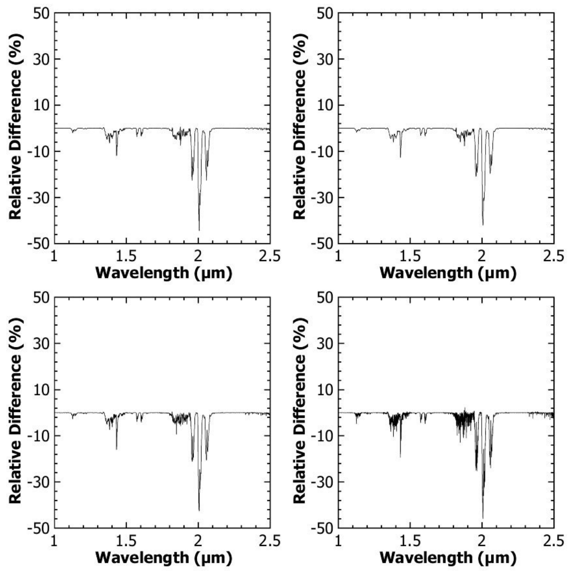

Figure 3: The difference between 'standard star reduced' spectra and 'actual' spectra at spectral resolutions R = 500, 1000, 2000 and 5000 (left-to-right, top-to-bottom).

Forward Modelling: We are in the process of developing an algorithm to obtain a suite of Martian meteorological parameters using the technique of forward-modelling. In essence, we plan to derive the atmospheric state at points across the entire Martian disk by iteratively comparing high-resolution spectroscopic observations to modelled spectra of the same resolution and minimising the error between the two.

Modelling. The forward-modelling technique entails simulating the entire light path of our observations, i.e. two passes through the Martian atmosphere and one through the Earth's atmosphere. To perform this simulation, we have two radiative transfer tools at our disposal; SMART (Meadows and Crisp, 1996) and VSTAR (Bailey, 2006). Both use a line-by-line technique, with the HITRAN database (Rothman *et al.*, 2005) as a source, although their methods of solving the equation of transfer vary.

Our initial atmospheric state is calculated using parameters from the Mars Climate Database (MCD; Lewis, 1999). The value of a least-squares error function is then calculated to determine how good a fit the model is to the data. By making use of partial derivatives calculated by SMART during its processing phase, the parameter space can then be examined for a better fit; the process repeats until the error function passes below a minimum threshold.

The state of the Earth's atmosphere during our observations will be modelled in a similar fashion by making use of standard star observations taken during our runs. The two atmospheres can then be combined to simulate the complete light path.

Observations. We obtained near-infrared spectra of Mars over the nights of October 25-27, 2005 using the 3.0 m NASA Infrared Telescope Facility (IRTF) on Mauna Kea. Spectra were taken using the Cryogenic Near-IR Facility Spectrograph (CSHELL) at a spectral resolution of approximately R = 30000. The spectrograph slit was stepped across the Martian disk to produce a series of data cubes for four CO_2 wavelength bands centred around 1.597 µm, 1.603 µm, 1.607 µm, 2.073 µm and a CO band centred around 2.332 µm. The band width for each was approximately 0.004 µm.

Over the course of the final two nights, we observed the formation of a dust storm approximately 1700 km across, in all wavelength bands (see Figure 4). The dust storm was located in the region of Sinus Meridiani, near the Mars Exploration Rover *Opportunity*.

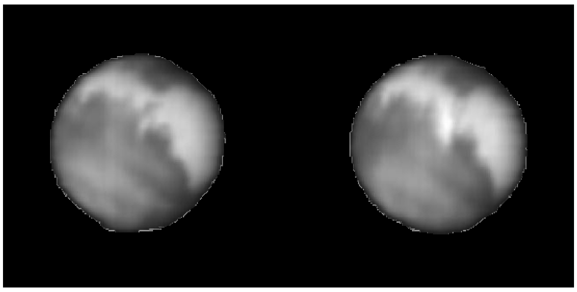

Figure 4: Comparison of continuum images from 26/27 Oct using IRTF/CSHELL showing a dust storm forming (near the centre of each image).

We also have a number of data cubes obtained via queue-scheduled observing using the Gemini Near Infra-Red Spectrograph (GNIRS) on Gemini South at Cerro Pachon, Chile. Observations were taken in a similar fashion to the IRTF observations described above, using a 0.1” slit at a spectral resolution of R = 18000. Observations were taken in a single band centred on 1.6 µm (see Figure 5).

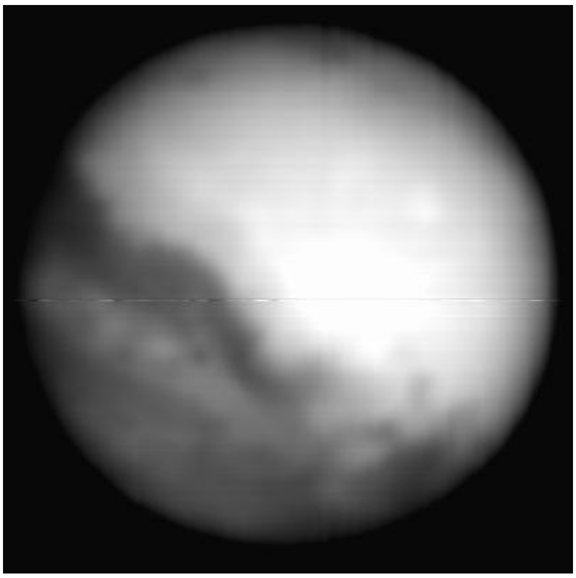

Figure 5: Continuum image of Mars taken on 14 Nov using Gemini South/GNIRS at R = 18000.

Preliminary Results: Figure 6 shows a comparison of a simulated Martian spectrum generated using SMART and observed data from 27 October. The modelled spectrum was based on input parameters taken from the Mars Climate Database which roughly match the observation parameters. The dust optical depth used for the model was $\tau = 0.5$. As can be seen in the figure, the model closely matches the observations.

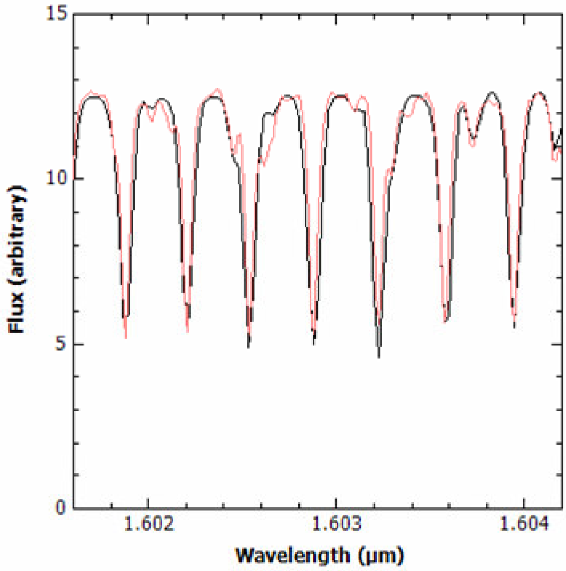

Figure 6: Comparison of modelled data generated using MCD atmospheric profiles at $\tau = 0.5$ (black) and observed data from 27 Oct (red) in the 1.603 µm CO_2 band.

Future Work: Once all observations have been completed, we will be using the forward-modelling technique described above to derive the surface temperature, constituent partial pressures and integrated column optical depth for each resolved point on the Martian disk. It may also be possible to retrieve each of these quantities as a function of altitude. Our intention is to be able to generate pressure, temperature and dust maps and to analyse the small-scale variability in these parameters as a function of both position and time. We anticipate our pressure maps will be similar to those produced by Chamberlain *et al.* (2006).

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References:

Bailey, J. 2006, (these proceedings)

Chamberlain, S. *et al.* 2006 (these proceedings)

Forget, F. *et al.* 1999, J. Geophys. Res., 104, E10, 24155

Formisano, V. *et al.* 2005, Planetary & Space Sci., 53, 10, 963

Golombek, M. P. *et al.* 1999, J. Geophys. Res., 104, E4, 8523

Leovy, C. B. 1979, Ann. Rev. Astron. Astrophys., 17, 387

Lewis, S. R. *et al.* 1999, J. Geophys. Res., 104, E10, 24177

Meadows, V. S., Crisp, D. 1996, J. Geophys. Res., 101, E2, 4595

Rothman, L. S. *et al.* 2005, J. Quantitative Spectroscopy & Radiative Transfer, 96, 2, 139