Determining Nighttime Atmospheric Optical Depth Using Mars Exploration Rover Images. K. M. Bean[1] and M. T. Lemmon[2], [1]Jet Propulsion Laboratory, California Institute of Technology, Keri.Bean@jpl.nasa.gov, [2]Texas A&M University, lemmon@tamu.edu.

Introduction: Martian weather patterns play an important role in radiative transfer and the energy balance budget [1]. To characterize the full impact of clouds and dust, the complete diurnal cycle needs to be understood. One of the best methods of tracking variations is by measuring optical depth. Spatial and temporal trends in atmospheric opacity can provide insight into the water and dust cycles.

This project explores obtaining measurements of nighttime optical depth using images from the Mars Exploration Rover *Spirit*, both to validate the photometry method as able to obtain nighttime optical depth and to look for any significant nighttime weather phenomena.

Past spacecraft missions have measured optical depth. *Viking* showed higher optical depth just after dawn, attributed to condensed water [2]. *Pathfinder* found some evidence for a higher optical depth at night due to water ice clouds [3]. Several Mars GCM runs suggest water ice clouds at night due to radiative cooling and the clouds causing anomalously warm surface regions due to trapped radiation, which agrees with MOLA data [4,5].

Processing Nighttime Images: Most of the images analyzed were not taken for nighttime optical depth measurements, but instead as part of an unsuccessful meteor search [6]. Due to using solar power, the nighttime images could only be taken during the southern summer season. *Opportunity* did not perform any useful nighttime optical depth imaging so only data from *Spirit* is used in this analysis.

Raw images of stars, obtained from the PDS, were taken and the expected brightness of stars was compared to the observed brightness of stars. The images analyzed were all from the L1 filter due to it having a large bandpass covering nearly all visible light and some near infrared light [7].

The Pancam instrument was not designed for point source photometry, and while capable of long exposures, it could not track stars and thus the image sensitivity was limited by the stars moving across the CCD at a rate of one pixel every four seconds. These longer exposures also allowed for cosmic ray interference, so to reduce interference, images were paired with another image close in time to look for matching star trails.

The star information was obtained from *The Astronomical Almanac Online* 2008 bright star list. Conversions were done to turn the list's Earth-centric data into Mars-centric data and to convert the given star magnitudes to Pancam fluxes. Checks were performed to reduce the effects of camera noise from the star flux measurements and to look for bad stars, such a variable stars and multi-star systems. An example of a processed image is in Figure 1. The list of all stars observed, which sol, and the LTST are in Table 1.

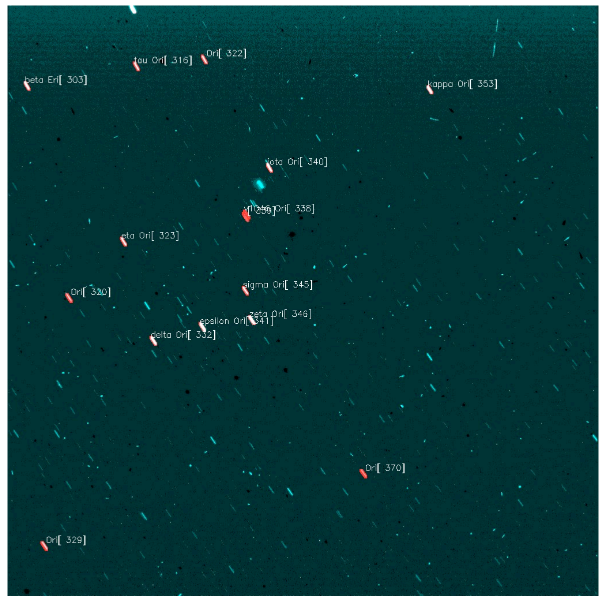

Figure 1: An example of a processed nighttime image. This is of the constellations Orion and Eridanus on *Spirit* sol 632.

Sol	Stars Observed	LTST
67	ζ Ori, α Ori	02:02
607	AE Cet, β Cet	01:00
632	β Eri, β Ori, δ Ori, ι Ori, ε Ori, ζ Ori, κ Ori, η Ori, γ Ori, μ Gem, ε Gem	00:44
643	α Eri, α Hyi, β Phe, ν Oct	21:54
647	α Eri, α Hyi, ν Oct	21:53
664	α Tau, δ Tau, γ Tau, ε Tau, θ Per	01:20
666	α UMi	03:28
667	α Leo	02:50
668	λ Vel, δ Vel, ε CMa, σ CMa, δ CMa	01:51
687	ε Tau, α Tau	04:07
694	γ Hyi, β Dor, α Ret, β Ret, δ Ret, β And	22:38
1941	β And, ω And	02:13
1949	α Car	22:06

Table 1: All Stars Observed and Measured for Nighttime Optical Depth.

Obtaining Optical Depth: To get the optical depth measurements, the following form of the Beer-Lambert Law was used:

$$\tau_N = -\ln\left(\frac{FR}{FR_0}\right)\cdot\frac{1}{\eta}$$

where τ_N is the nighttime optical depth, FR is the observed flux ratio from Pancam, FR_0 is the flux ratio at zero airmass, and η is the airmass factor. All flux ratios were calibrated to assume a zenith view, since the elevation varied between images which affects the path length through the atmosphere. A linear fit check accounted for the fact using Pancam for small aperture photometry captures 10% less flux than imaging with a diffuse source. The error for each observation accounts for the flux ratio error multiplied by one over the airmass factor, the baseline flux error, and a 5% uncertainty due to short timescale variations [8].

Looking for Variations: Optical depth values were averaged together per sol and per star to look for overall variation from the daytime optical depth values and to look for small-scale variation across each image.

Sol-Averaged Variations Between Daytime and Nighttime Optical Depth Values: Figure 2 shows the plot of the majority of the optical depth data, which was obtained between *Spirit* sols 600 and 700. Nearly all sol-averaged nighttime optical depth values matched the daytime optical depth values to within the error bars. Only two sols were outside a 2-sigma level: sol 67 and sol 607, and these sols were outside a 3-sigma level of the daytime optical depth value. However, they vary in that sol 67 is vastly below the daytime value, and sol 607 is vastly above the daytime value. Therefore it's more likely that these are non-Gaussian errors than one night of clouds and one night of an unknown atmospheric process.

It is possible that sol 607 shows fog or cloud development, although it is unlikely. The images were taken around 01:20 LTST, which is close to 02:00 which is when *Mars Pathfinder* saw a peak in nighttime optical depth values, although the peak was within their error bars [3].

Small-Scale Variability: A search for variability across images was also carried out, to look for spatial variations that would result from a cloud only covering part of an image. Only 3% of the stars were outside a 2-sigma level, which indicates a non-statistically significant result and these "bad" stars were likely the result of other non-Gaussian errors. Sol 607 star values were high, with one star outside of 2-sigma and one star just inside the 2-sigma level. This sol still presents the strongest case of cloud or fog detection, but it is still unlikely.

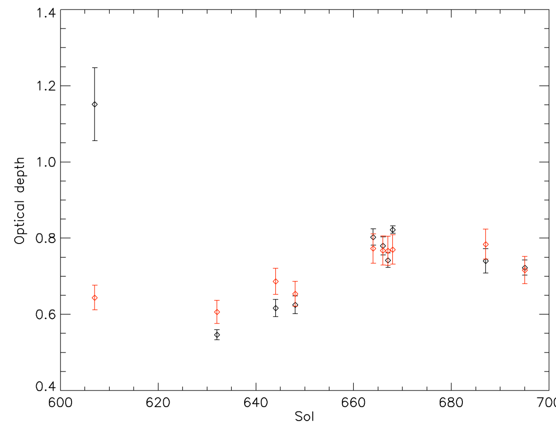

Figure 2: Sol Averaged Optical Depth. Black indicates nighttime optical depth, and the red indicates daytime optical depth. Daytime optical depths were obtained from the PDS.

Lessons Learned: The lessons learned from this analysis can be applied towards future surface nighttime optical depth imaging campaigns. Use of GCMs can provide insight into the best times to take images. Picking a few constellations per season with many bright stars and few variable and multi-star systems is best, and systematically imaging them throughout the Martian seasons and at various times throughout the night would provide lots of valuable data. Consistent exposure times and other imaging parameters would also help provide better data and cross-calibration.

Conclusions: Images taken at night from the surface of Mars can be used to obtain nighttime optical depth measurements. Sol-averaged nighttime values closely match the daytime values, within the error bars. It is unlikely *Spirit* saw any clouds or fog, especially since the images were taken in the "dry" summer season. Lessons learned from this analysis can be used to set up nighttime optical depth campaigns for other current future Mars surface missions.

References: All work was done as a part of K. M. Bean's thesis. [1] Rodin A. V. et al. (1999) *Adv. Space Res., 23,* 1577-1585. [2] Colburn D. S. et al. (1989) *Icarus, 79,* 159-189. [3] Thomas N. et al. (1999) *JGR, 104*, 9055-9068. [4] Richardson M. I. et al. (2002) *JGR, 107,* 1-29. [5] Wilson R. J. et al. (2007) *GRL, 34*, 7-10. [6] Domokos A. et al. (2007) *Icarus, 191,* 141-150. [7] Bell III J. F. et al. (2003) *JGR, 108,* 1703-1709. [8] Lemmon M. T. et al. (2004) *Science, 306,* 1753-1756.