TES LIMB-GEOMETRY OBSERVATIONS OF AEROSOLS.

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Introduction: The Thermal Emission Spectrometer (TES) on-board Mars Global Surveyor (MGS) has a pointing mirror that allows observations in the plane of the orbit anywhere from directly nadir to far above either the forward or aft limbs (see [*1*] for details about the TES instrument). Nadir-geometry observations are defined as those where the field-of-view contains the surface of Mars (even if the actual observation is at a high emission angle far from true nadir). Limb-geometry observations are defined as those where the line-of-sight of the observations does not intersect the surface. At a number of points along the MGS orbit (typically every 10° or 20° of latitude) a "limb sequence" is taken, which includes a stack of overlapping TES spectra from just below the limb to more than 120 km above the limb. A typical limb sequence has ~20 individual spectra, and the projected size of a TES pixel at the limb is 13 km.

Thermal Emission Spectrometer (TES) observations of the limb have two key advantages over nadir observations. First, information about the vertical distribution of aerosols and water vapor are possible since observations at different tangent heights above the surface sample different vertical levels of the atmosphere. Nadir-geometry observations, even those with varying emission angle always sample the entire atmosphere and the surface. Limb-geometry observations do not directly sample the surface or the atmosphere below the tangent height of the observation at all. Some photons from the surface and lower atmosphere can be scattered into the observed beam, but those contributions are relatively small and can be computed. The different heights sampled by limb observations allow the retrieval of information about the vertical distribution of aerosols, which is very limited or not possible to get from nadir-geometry data.

The second key advantage of limb-geometry observations is that because there is always a large thermal contrast between the atmosphere and the background of deep space, aerosol retrieval can be performed for all seasons, latitudes, and times of day. Nadir-geometry retrievals are limited to times when the surface temperature is sufficiently greater than bulk atmospheric temperature to produce measurable spectral features. In practice, this limits nadir retrievals to daytime conditions away from the winter pole when the surface temperature is > 220 K. On the other hand, limb-geometry observations always have sufficient thermal contrast, so pole-to-pole coverage is possible for all seasons, as well at both day and night.

Retrieval Method: Four "spectral quantities" are abstracted from the limb-geometry TES spectra: 1) a band depth centered at 470 cm^{-1} (expressed as a radiance) that is characteristic of dust absorption, 2) a change in slope (or an "elbow") in the spectrum at 300 cm^{-1} that is characteristic of water ice absorption, 3) a radiance index based on the averaged band depth of 6 water vapor bands between 200 and 400 cm^{-1}, and 4) the radiance at 470 cm^{-1}, which is used to verify the overall scaling of retrieved optical depth. We use just these four spectral quantities instead of the entire radiance spectrum for several reasons. Firstly, using only these four spectral quantities (instead of the several dozen observed radiances in this spectral region) greatly reduces the computational burden for the retrieval. Secondly, use of band depths removes offset and slope calibration errors that are apparent in TES limb data.

The four spectral quantities for each limb-geometry spectrum are then binned. Daytime and nighttime data are treated separately. The bins used have a size 10° in latitude, 6° in Ls (seasonal date), and 3 km in height above the limb. This gives a total of ~1800 bins each for day and night. All longitudes are binned together, so results are zonal-mean quantities. The data presented here cover the two Martian years from the beginning of MGS mapping at Ls=103°, March 1999 to Ls=111°, December 2002.

For each time-of-day, Ls, and latitude, the four spectral quantities in the set of bins from 12 km to 69 km above the surface are used in the retrieval. Six quantities are retrieved: 1) total dust extinction optical depth, 2) Conrath parameter, □, describing the height to which dust extends above the surface [*2*], 3) total water ice extinction optical depth, 4) height of the bottom of the cloud deck, 5) total column abundance of water vapor, and 6) height of the top of the water vapor. The vertical distribution of dust is defined through the Conrath parameter [*2*] and is based on a physical model balancing vertical mixing and gravitational settling. The vertical distribution of water ice is given by the height of the bottom of the cloud deck. There is no water ice below that level, and the cloud optical depth drops off above that level with a scale height one-third that of the atmosphere (giving a typical cloud thickness of a few km). The vertical distribution of water vapor is given by the height of the top of the water vapor. Below that level water vapor is well-mixed with the rest of the atmosphere. Above that level there is no water vapor.

The retrieval requires knowledge of surface and atmospheric temperatures. They are retrieved from the 15-µm CO_2 band of the TES spectra beforehand [*3*] and binned in the same Ls/latitude/time-of-day bins as the limb data. Scattering properties (single-scattering albedo and phase function information) are also required and are taken from [*4*] and new numerical experiments performed for this study.

The retrieval is accomplished by performing an iterative non-linear minimization between computed and observed spectral quantities (the four band depth quantities described earlier). Spectral quantities are computed for a given set of aerosol optical depth and vertical distribution parameters by a radiative transfer code. Scattering by aerosols is treated using discrete ordinates. Gas absorption (water vapor) is treated using the correlated-k approximation. The diffuse field is computed using a plane-parallel model, but the observed spherical-geometry radiance is approximated by taking a curved path through the plane-parallel results that has a path-length and angle with respect to vertical that is computed using spherical geometry and the given tangent height for that particular ray. The finite vertical size of the TES pixel is accounted for by integrating over a number of rays spaced every 3 km in tangent height. The retrieval for one bin typically takes several minutes on a modern desktop computer.

Results: Figure 1 shows daytime results for dust optical depth and effective height of the top of the dust computed from the retrieved Conrath parameter. The seasonal and latitudinal dependence of dust optical depth is very similar to TES nadir-geometry results [*5*]. However, now we can see dust optical depth from pole-to-pole instead of in a band that follows the Sun. This is important (for example) in looking at the latitudinal extent of the dust storms. With nadir-geometry data alone it is not possible to track through the storm the extent to which the northern-hemisphere polar vortex excludes dust from its interior. In Fig. 1 we can see that indeed the polar vortex does act as an efficient barrier to meridional transport. The effective height of the top of the dust vertical distribution is important for correctly modeling thermal structure and the resulting circulation patterns. The bottom panel of Fig. 1 shows that during dust storms dust is lofted considerably higher (well above 5 scale heights or ~50 km) than during non-dusty times. During the decay of dust storms, dust remains aloft higher above the surface at low latitudes than at mid- and high latitudes, perhaps because of rising motions at low latitudes caused by the Hadley circulation. In the aphelion season, and at almost all seasons at polar latitudes, dust remains confined near the surface.

Figure 2 shows an example of the limb-geometry's ability to detect differences between daytime and nighttime. Although it is unlikely that dust changes very much on a diurnal cycle, water ice condensate clouds can form and sublimate given small changes in atmospheric temperature. Solar thermal tides and changes in the direct solar heating can potentially create diurnal temperature changes large enough to cause large diurnal variations in water ice optical depth. Indeed, Fig. 2 does show such large differences. In particular, the most prominent daytime feature (the aphelion season, Ls=0°–140°, cloud belt) is reduced at low latitudes but enhanced at higher latitudes. At Ls=300°, a prominent low-latitude cloud appears at nighttime in both years but does not seem to have any daytime counterpart.

However, a very important point to remember is that because the TES pixel is 13 km wide at the limb, we cannot see anything in the limb-geometry below about 10 km above the limb. Near-surface fogs and hazes and low-lying ice and dust clouds are not detected by the TES limb-geometry data. It is possible (or even probable) that water ice clouds that are above 10 km height during the daytime (and thus visible in limb-geometry observations) can move to below 10 km height during the nighttime (and thus not be visible in limb-geometry observations). Combination of limb-geometry and nadir-geometry observations (which views all levels of the atmosphere) can potentially resolve this question and provide even better information on aerosol vertical distribution.

Summary: TES limb-geometry spectra can be used to retrieve the optical depth and vertical distribution of dust, water ice, and water vapor. The pole-to-pole coverage of the retrievals, information on the vertical distribution of aerosols, and the ability to compare daytime and nighttime results are all advantages that limb-geometry observations have over nadir-geometry. However, limb-geometry observations cannot see the lowest 10 km of the atmosphere, and they have relatively sparse seasonal/spatial coverage. When combined, nadir and limb observations can be used to provide further constraints on the vertical distribution of aerosols and a more complete description of aerosols than is possible using either one by itself.

References:

[1] Christensen et al. (2001) *J. Geophys. Res., 106,* 23,823. [2] Conrath (1975) *Icarus, 24,* 36. [3] Conrath et al. (2000) *J. Geophys. Res. 105*, 9509. [4] Wolff and Clancy (2003), *Constraints on the size of Martian aerosols from Thermal Emission Spectrometer Data*, submitted to *J. Geophys. Res.*. [5] Smith et al. (2001) *J. Geophys. Res. 106*, 23,929.

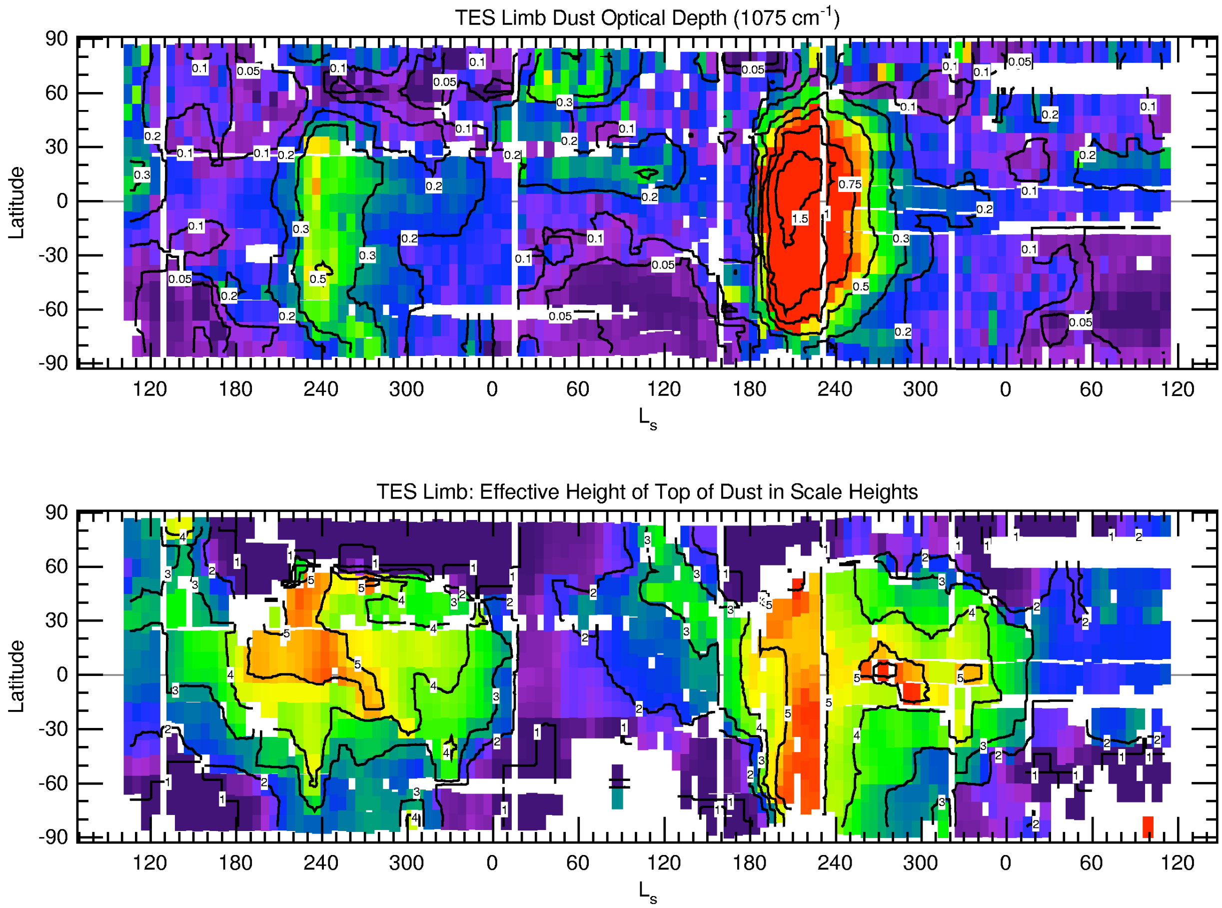

Figure 1. (top) Dust extinction optical depth (1075 cm^{-1}) as a function of season (Ls) and latitude from TES limb-geometry observations. The color scale goes from 0 (purple) to >1 (red), (bottom) The effective height of the top of the dust (computed from the retrieved Conrath parameter) expressed in terms of scale heights above the surface. The color scale goes from 1 (purple) to >5 (red) scale heights.

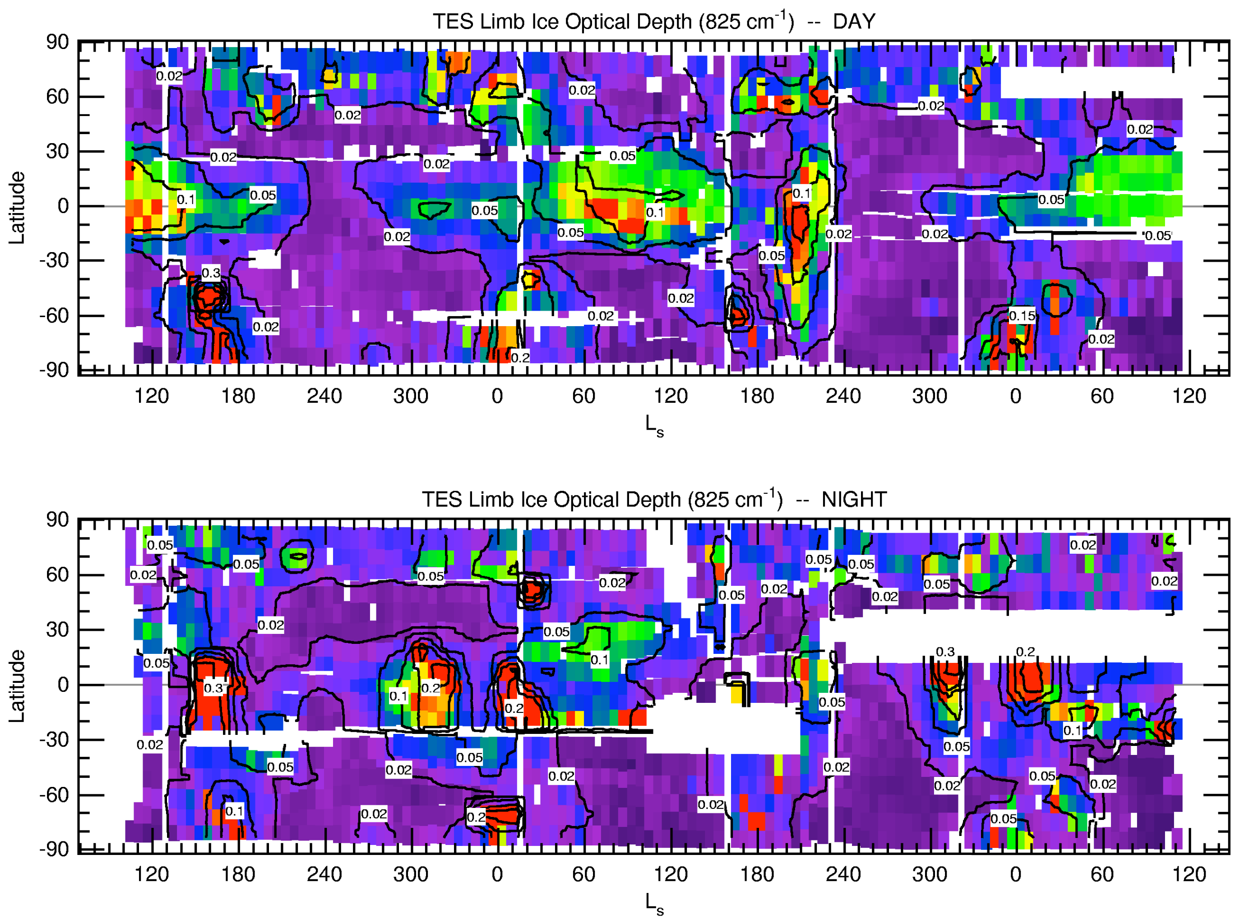

Figure 2. (top) The daytime (2:00 PM) water-ice extinction optical depth (825 cm^{-1}) as a function of season (Ls) and latitude from TES limb-geometry observations. (bottom) The nighttime (2:00 AM) water-ice extinction optical depth as a function of season and latitude. The color scale goes from 0 (purple) to 0.2 (red) for both panels.