DIURNAL AND SEASONAL VARIATIONS OF AEROSOL OPTICAL DEPTH AT JEZERO CRATER, MARS

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Introduction: The two upward-looking TIRS sensors from the MEDA instrument suite on-board the Perseverance rover enable the retrieval of total aerosol optical depth (dust plus water ice cloud) above the rover for all observations when TIRS is taken. Because TIRS observes in the thermal-IR, the retrievals are possible during both the day and night and thus, they provide an excellent way to monitor both the diurnal and seasonal variations of aerosols above Jezero Crater.

TIRS Data: The Thermal InfraRed Sensor (TIRS) package on the Perseverance rover consists of five sensors used to characterize the upward and downward fluxes of visible and infrared radiation at the rover site (Rodriguez-Manfredi et al., 2021). Of interest here are the sensors TIRS IR1, which covers a broad portion of the thermal-infrared spectrum over the range 6–35 µm and TIRS IR2, which covers the CO_2 band between 14.5 and 15.5 µm. Both sensors view upward at an elevation angle centered at 35° above the rover deck. The field of view of the TIRS IR1 and IR2 sensors is 20° in the vertical direction by 40° in the horizontal direction. As part of the MEDA suite of atmospheric sensors, TIRS observations are taken systematically throughout the sol at a frequency of 1 Hz. Observations in one-hour blocks are generally taken so that odd-numbered hours are covered on odd-numbered sols, while even-numbered hours are covered on even-numbered sols. In that way the entire 24-hour diurnal cycle is fully covered over a span of 2 sols. Occasionally, additional one-hour blocks are added to this baseline providing additional coverage, and observations are also routinely taken during the first five minutes of each hour. These observations are a part of the background baseline set for MEDA that runs essentially every day providing excellent diurnal and seasonal coverage.

Aerosol Optical Depth Retrieval: We use a radiative transfer model to compute the expected TIRS IR1 and IR2 signal for a given aerosol optical depth and temperature profile. We can then perform the retrieval by varying the atmospheric temperatures and aerosol optical depth to match the values observed by TIRS. The radiative transfer model includes aerosol scattering using a 2-stream approximation (e.g., Smith et al., 2006) and treats absorption by CO_2 gas using the correlated-k approximation (Lacis & Oinas, 1991). The elevation angle above the horizon for the TIRS is important and is computed for each observation using the known rover pitch, tilt, and yaw.

Determination of atmospheric temperatures. In general, the observed signal from TIRS IR1 and IR2 is sensitive to a combination of the atmospheric opacity (from aerosols and gases) and the atmospheric temperature profile. In practice, because of the very high opacity of CO_2 in the middle of the 15-µm band compared to aerosols, the IR2 signal is only sensitive to atmospheric temperatures in the lowest 1 km of the atmosphere and is nearly insensitive to aerosols. As a baseline, we use the temperature profile returned from the Mars Climate Database (MCD) (Forget et al., 1999; Millour et al., 2018) for the given latitude, longitude, local time, and Ls of each observation. We use our radiative transfer model to compute the expected IR2 signal and we offset the temperature profile in the lowest 1 km until the computed IR2 signal matches the observed signal. Outside of the case of large dust storms, the offset typically no larger than a few K.

The temperature profile above an altitude of 10 km is estimated using concurrent observations taken by the EMIRS thermal-IR spectrometer on-board the Emirates Mars Mission (Edwards et al., 2021, Smith et al., 2022), with output from the MCD used to help link the two regions where EMIRS and TIRS IR2 are sensitive.

Once the temperature profile has been estimated we are left with a single observation (TIRS IR1) and a single unknown (total aerosol optical depth), which results in the straightforward task of varying aerosol optical depth in our radiative transfer model until the computed IR1 value matches the observed value.

The relative contributions from dust and water ice cloud cannot be separated using TIRS data alone. To perform the retrieval, we assume a seasonally dependent dust vs. ice fraction based on climatology (e.g., Smith, 2004). In practice, the retrieved total aerosol optical depth is not very sensitive to this fraction for any reasonable values.

Results: Figure 1 shows the retrieved aerosol optical depth for TIRS observations taken between sol 15 (5 March 2021, MY 36, Ls=13°) and sol 364 (28 February 2022, MY 36, L_s=182°) as a function of season (Ls) and local true solar time (LTST). Retrievals are performed on 5-minute blocks of data, which are the averages of 300 individual observations. Shown here is the total aerosol extinction optical depth referenced to 1075 cm^{-1} (9 μm), which includes scattering. Periods of time when the Sun was within the TIRS field-of-view are excluded since those results are often unreliable.

Apparent in Figure 1 between Ls=30° and 130° is the aphelion cloud belt. During this period there is a clear and consistent diurnal variation of aerosol optical depth with highest values between 6:00 and 9:00 LTST. This diurnal variation is almost certainly caused by a variation in water ice clouds, which is superimposed on top of a low baseline of dust optical depth. While there is a clear seasonal trend, there is also significant variation from one sol to the next, which is most likely caused by water ice clouds as well.

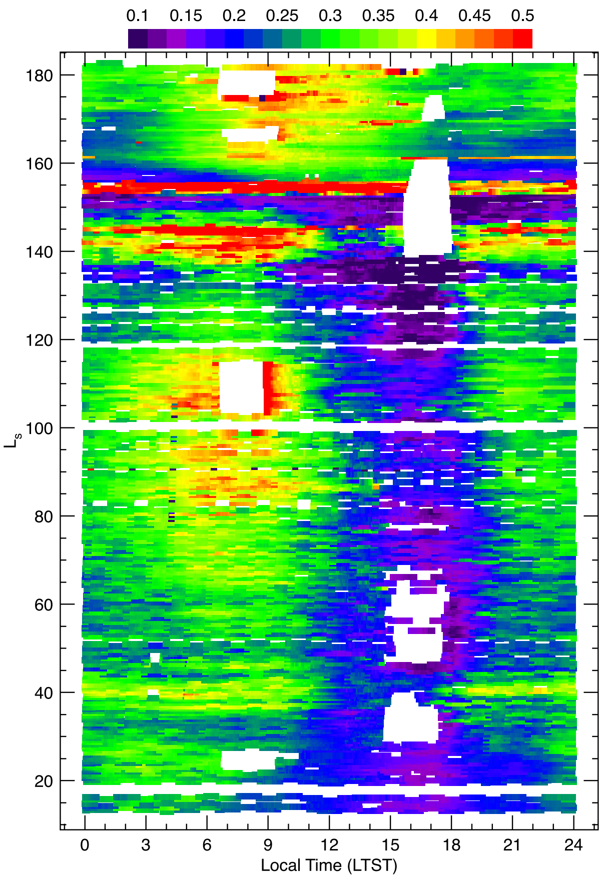

Figure 1. The seasonal and diurnal variation of aerosol optical depth retrieved from TIRS observations.

The red band in Figure 1 at L_s=153° shows an early-season regional dust storm. Figure 2 shows the complex time history of aerosol optical depth during this January 2022 event. Here, the sol numbers label midnight LTST. During the active period of this dust event between sols 313 and 317 (5–9 January 2022, Ls=153°–156°) there were numerous spikes in aerosol optical depth with several exceeding unity (at 9 μm). These spikes in aerosol (dust) optical depth occurred preferentially during the day but appear equally in both the morning and the afternoon.

Returning to Figure 1, the latest retrievals shown are from the season where it is expected that dust is becoming the dominant aerosol over water ice clouds. These observations taken after the regional dust storm show a higher overall baseline of aerosol optical depth (likely caused by dust), but with some water ice clouds still present. The local time variation also appears to shift with the diurnal maximum moving later toward the middle of the day, and there appears to be more sol-to-sol and diurnal variability in general.

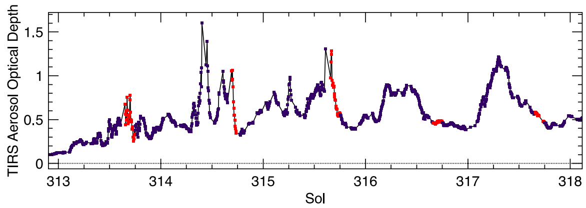

Figure 2. The detailed time history of aerosol (dust) optical depth retrieved from TIRS observations during the January 2022 regional dust storm. The red points indicate times when the Sun was within the field of view of TIRS and are therefore less reliable.

Summary: Observations taken by MEDA/TIRS onboard the Perseverance rover enable total aerosol optical depth to be retrieved systematically as a function of local time and season, including both during the day and the night. The retrieved values show clear seasonal and diurnal variations in aerosol optical depth. For water ice clouds, the two dominant patterns involve the seasonal growth and decay of the aphelion cloud belt and a consistent diurnal pattern with greatest cloud optical depth between 6:00 and 9:00 LTST. A large regional dust storm in January 2022 highlights the utility of nearly constant retrievals of aerosol optical depth for better understanding the complex evolution of dust opacity during the active portion of a storm. Systematic TIRS observations continue as part of the baseline set of MEDA observations on the Perseverance rover promising exciting new information to come about the diurnal variation of dust during the upcoming perihelion season.

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