FAR INFRARED SPECTROSCOPIC PARAMETERS OF MARS ATMOSPHERIC AEROSOLS AND THEIR APPLICATION TO MCS RETRIEVALS IN HIGH AEROSOL CONDITIONS

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Introduction:

Limb sounding of thermal emission in the infrared wavelength range is a powerful technique for measuring dust and water ice aerosols in the martian atmosphere. It provides vertical profile information and, due to the long optical path, typically has a higher sensitivity compared with nadir viewing measurements. However, the limb path might become opaque in high aerosol conditions, preventing a limb sounding measurement from penetrating the atmosphere. While atmospheric opacities of aerosols in the far infrared are typically lower than in the mid-infrared, the spectroscopic parameters that control aerosol absorption in the far-infrared are often not well quantified.

Here we use limb measurements and atmospheric profile retrievals by the Mars Climate Sounder (MCS) to evaluate aerosol spectroscopic parameters in the far infrared. We derive empirical extinction efficiencies for dust and water ice around 32 μm and 42 μm, respectively. These far infrared extinction efficiencies will enable MCS limb retrievals of aerosol profiles in atmospheric conditions where mid-infrared retrievals are challenging, e.g. in dust storms or the aphelion cloud belt. We demonstrate that using the 32 μm channel of MCS for dust retrievals extends the retrievable altitude range in dust storm conditions by about a scale height.

MCS Instrument and Retrievals:

The Mars Climate Sounder [1] is a passive infrared radiometer onboard Mars Reconnaissance Orbiter (MRO), which views the martian atmosphere in limb, nadir, and off-nadir geometries. It has 5 mid-infrared, 3 far infrared, and one broadband visible/near-infrared channels. Each spectral channel uses a linear detector array consisting of 21 elements, which provides -10 to 90 km altitude coverage with 5 km vertical sampling when pointed at the Mars limb.

Profile retrievals from MCS radiance measurements use a modified Chahine method together with a Curtis-Godson approximation in the radiative transfer [2] and employ a single-scattering approximation to account for scattering in the limb radiative transfer [3]. Retrievals of temperature profiles use the MCS mid-infrared channels A1, A2, and A3 that cover frequencies within the 15 μm gaseous absorption band of CO_2. Water ice extinction retrievals are based on limb measurements of an absorption feature in channel A4 with a center frequency of 843 cm^{-1}. Water ice extinction is represented in the MCS radiative transfer through particles that follow a modified gamma-distribution with an effective radius of 1.41 μm [3] and spectroscopic parameters by Warren [4]. Dust extinction is retrieved from limb measurements using an absorption feature in channel A5 with a center frequency of 463 cm^{-1}. Dust extinction is represented through particles that follow a modified gamma-distribution with an effective radius of 1.06 μm [3]. Dust spectroscopic parameters are based on Wolff et al. [5] in the mid-infrared, augmented in the far infrared with the work by Hansen [6]. MCS measurements in the far infrared are currently only used for the retrieval of surface temperature in channel B1 at 316 cm^{-1} from nadir and off-nadir views. However, far infrared limb radiances in the channels B1, B2 and B3 are acquired simultaneously with radiances from the mid-infrared channels and the visible/near-infrared channel.

Analysis Approach:

Our analysis is based on the comparison of measured limb radiances in the MCS far infrared channels with calculated radiances for these channels. Radiances for the far infrared channels are calculated based on the retrieved temperature and aerosol profiles retrieved from the same measurements in the mid-infrared. Radiance profiles in a limb measurement can be described as

$$R_{m,c} = B(\nu,T_{eff}) \bullet (1 - e^{-k_{m,c} \bullet U}),$$

where the indices m and c stand for measured and calculated, respectively. B is the Planck function at the effective frequency ν and the effective limb temperature T_{eff}, k is the extinction coefficient and U is the aerosol amount. Our goal is an empirical quantification of k_m based on the measured and calculated radiances in the far infrared. The radiance calculation is based on the known quantity k_c. Under the simplifying assumption of an optically thin atmosphere, the desired extinction coefficient can be derived from the simple expression

$$k_m = k_c \bullet (R_m / R_c).$$

We focus on altitudes close to where the line-of-sight of the limb view becomes opaque in the A channels in the mid-infrared. As the extinction efficiency is significantly lower in the far infrared, the limb path in the B channels should still be sufficiently optically thin. For each limb profile we select the two lowest detectors used for aerosol retrievals in the A channels. In order to be able to attribute the extinction to a particular aerosol type we select scenes where only one aerosol type (either dust or water ice) is dominant.

Results:

Dust. For the analysis of dust we focus on the dusty season of the Mars year. We chose the time period of L_s=210°-330° of MY29 (Feb.-Aug. 2009). MCS measurements provide dense, nearly continuous coverage during this time period and included off-nadir measurements for surface temperature retrieval. Dust was the predominant aerosol in this time period, with regional dust storms but no global dust storms occurring. For every successful profile retrieval during this time period, measured and calculated radiances for the MCS far-infrared channels were binned separately for the day- and nightside parts of the orbit into bins of 20° latitude and 15° L_s. Ratios between measured and calculated radiances were determined for the detectors in the B channels that correspond to the lowest altitudes for which an aerosol retrieval in the mid-infrared was possible. For the analysis we required a minimum altitude of 5 km to exclude potential surface contaminations of the limb measurement.

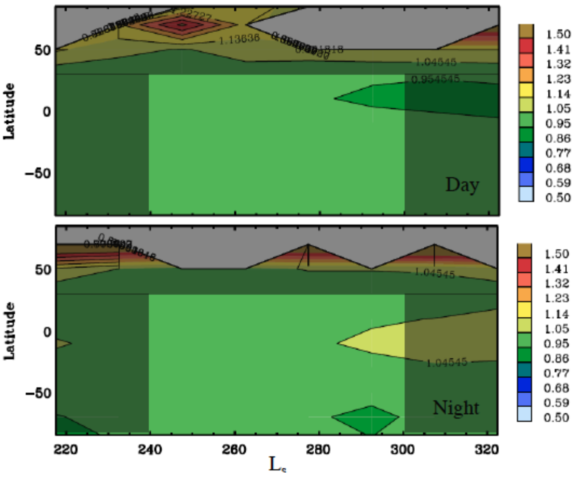

Figure 1: Ratio between the measured and calculated radiances in the MCS B1 channel for the detector that corresponds to the lowest altitude at which a mid-infrared aerosol retrieval was possible. Data is from MY 29 and is separated into daytime (top) and nighttime (bottom). Radiances were binned in 20° latitude and 15° L_s. A minimum altitude of 5 km was required. Data from the non-shaded areas were used to calculate extinction efficiencies.

Fig. 1 shows results of this analysis for MCS channel B1, which is the far infrared channel most sensitive to dust. Ratios between measured and calculated radiances are very homogeneous between the south polar region and the northern mid-latitudes throughout the considered time period. In addition, the radiance ratios are very close to 1, suggesting that the extinction efficiencies for dust in the original formulation of the radiative transfer [3] are quite accurate. Only at high northern latitudes the ratios are more variable, and several bins are unpopulated because of ice being the dominant aerosol or because of the aerosol retrieval reaching below the minimum altitude.

Channel	Center Frequency	Extinction Efficiency
A5	463 cm^{-1}	0.3506
B1	316 cm^{-1}	0.1766

Table 1: Dust extinction efficiencies for MCS channels A5 from [3] and B1 from this work.

We chose a latitude range between 90°S and 30°N and an L_s range between 240° and 300° (non-shaded area in Fig. 1) to derive an average radiance ratio in the MCS B channels. As the radiance ratios on the day- and nightside parts of the orbit are very similar we derived a single value representative of both day and night. The average ratio is 0.994. Multiplication of this factor with the original extinction efficiency used in the calculation of the radiances [3] yields an empirical extinction efficiency of 0.1766 (Tab. 1).

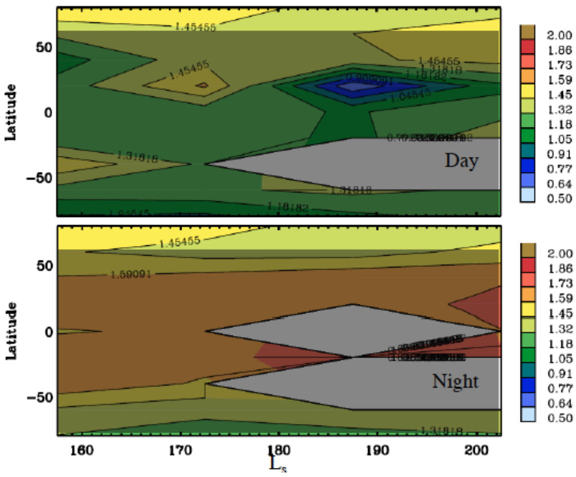

Figure 2: Ratio between the measured and calculated radiances in the MCS B2 channel for the detector that corresponds to the lowest altitude at which a mid-infrared aerosol retrieval was possible. Data is shown for the north polar hood conditions of MY 29, separated into daytime (top) and nighttime (bottom). Radiances were binned in 20° latitude and 15° L_s. A minimum altitude of 5 km was required. Data from the non-shaded areas were used to calculate extinction efficiencies.

Water ice. From preliminary analyses it became clear very quickly that radiance ratios for water ice dominated scenes depended more strongly on atmospheric conditions than for dust. Hence we separately considered regions and seasons where the atmosphere became too opaque due to water ice to allow a mid-infrared limb retrieval close to the surface. These conditions are found during the aphelion cloud belt and the north polar hood. Clouds in the south polar hood are typically not sufficiently opaque to prevent a mid-infrared limb retrieval at low altitudes.

For conditions representative of the north polar hood we chose the time period of L_s=150°-210° of MY29 (Nov. 2008-Feb. 2009). This corresponds to the formation period of the polar hood [7]. Mid-winter conditions were not considered to avoid contamination of the analysis by CO_2 ice that can form in the center of the polar vortex [8]. Analyses during the dissipation period of the polar hood (L_s=330°-30°) yielded results that were very similar to the ones from the formation period, giving us confidence that the derived quantities are representative throughout the polar hood period.

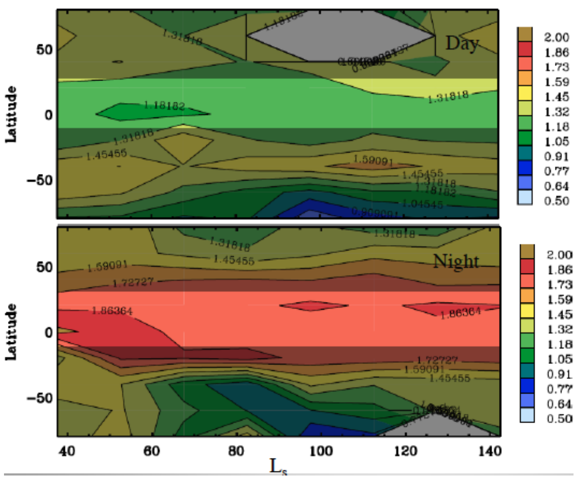

Figure 3: Ratio between the measured and calculated radiances in the MCS B2 channel for the detector that corresponds to the lowest altitude at which a mid-infrared aerosol retrieval was possible. Data is shown for conditions during the equatorial cloud belt in MY 30, separated into daytime (top) and nighttime (bottom). Radiances were binned in 20° latitude and 15° L_s. A minimum altitude of 10 km was required. Data from the non-shaded areas were used to calculate extinction efficiencies

The calculation of radiance ratios was done in the same way as for dust, only here it was required that the water ice opacity was higher than the dust opacity at any altitude considered in the analysis. The results are shown in Fig. 2 for channel B2, which covers a frequency band where water ice extinction has a maximum. Radiance ratios in the north polar region are very homogeneous over the considered time period. No significant differences between the day- and nightside parts of the orbit are observed, which is to be expected at very high latitudes. Considering a region between 70°-90°N we derive an average radiance ratio of 1.41. The higher extinction efficiency in the far infrared suggests that the average particle size at low altitudes in the polar hood is likely somewhat larger than assumed in the particle size model [3]. Multiplying this factor with the original extinction efficiency used in the calculation of the radiances [3], we derive an empirical extinction efficiency of 0.2901 (Tab. 2).

For the analysis of conditions found during the aphelion cloud belt we chose the time period of L_s=30°-150° of MY30 (Dec. 2009-Sep. 2010). The analysis was done in the same way as for the north polar hood. Only the minimum altitude was raised to 10 km.

Channel	**Center Frequency**	**Extinction Efficiency**
A4	843 cm^{-1}	0.7730
B2 (equatorial belt, day)	254 cm^{-1}	0.2531
B2 (equatorial belt, night)	254 cm^{-1}	0.3756
B2 (polar north)	254 cm^{-1}	0.2901

Table 2: Water ice extinction efficiencies for MCS channels A4 from [3] and B2 for various atmospheric conditions from this work.

The results for channel B2 are presented in Fig. 3. We note that channel B2 has a cross-sensitivity to water vapor [1]. It is reasonable to assume that water vapor is close to saturation in atmospheric conditions with thick clouds, and this has been taken into account. It is very obvious that significant differences exist between the radiance ratios during day and night in the equatorial cloud belt. Focusing on the latitude band with the most intense cloud cover between 10°S and 30°N we derive an average radiance ratio of 1.23 on the dayside and 1.82 on the nightside. This suggests that while the assumed particle size model is quite reasonable on the dayside, particles on the nightside are likely to be larger than assumed. Further analysis shows that the average altitude where a cloud becomes too opaque for a mid-infrared retrieval on the nightside is about 13 km. On the dayside within the equatorial belt, lines-of-sight on average become opaque in the mid-infrared around 28 km. So the smaller particles on the dayside are associated with higher clouds than the larger ones on the nightside. The differences in terms of cloud altitude and particle size between day and night are likely related to tidal activity acting on the equatorial cloud belt.

Due to the large differences in radiance ratios we derive extinction efficiencies separately for day and night. Based on the averages between 10°S and 30°N over the considered time period we derive an average B2 extinction efficiency of 0.2531 on the dayside and 0.3756 on the nightside. The extinction efficiencies derived for water ice in the B2 channel under the various atmospheric conditions studied are summarized in Tab. 2.

Application to MCS Retrievals:

The empirically derived extinction efficiencies in the far infrared can be applied to MCS retrievals of aerosol profiles that make use of the MCS far infrared channels. For dusty conditions, Tab. 1 suggests that limb retrievals of dust in channel B1 should be possible at opacities about a factor 2 higher than in channel A5. For cloudy conditions Tab. 2 indicates that water ice limb retrievals in channel B2 should be possible at opacities a factor 2-3 higher than in channel A4.

Fig. 4 shows an example of a dust profile retrieval at low latitudes during a regional dust storm at L_s=215° of MY 31 (Nov. 2012). The limb retrieval based on channel A5 cuts off slightly below 20 km altitude as the line-of-sight becomes too opaque in the mid-infrared for a reliable retrieval. Adding two detectors from channel B1 extends the retrievable altitude range by about 10 km and into the lowest scale height of the atmosphere. The derived extinction efficiency ratio between A5 and B1 (Tab. 1) allows us to report the dust extinction profile at the A5 reference frequency even though the retrieval uses information from both mid- and far infrared channels.

Retrievals of this kind will be possible throughout the dusty seasons of the five Mars years covered by the MCS data set. In many cases profile retrievals will be possible that reach low enough altitudes such that vertical integration of the dust profile will yield a reliable column amount. In cases where this is not possible the extended altitude range of the far infrared profile retrieval will still aid a column retrieval based on nadir or off-nadir observations.

The far infrared extinction efficiencies quantified here enable limb profile retrievals of aerosols in high aerosol conditions where retrievals in the mid-infrared were not possible previously. In the dusty seasons they will allow us to study the growth and decay phases of regional or even global dust storms. In cloudy conditions they will be able to penetrate the clouds of the polar hood and the equatorial belt, giving us insight into their structure and temporal evolution on diurnal to seasonal time scales.

Acknowledgements:

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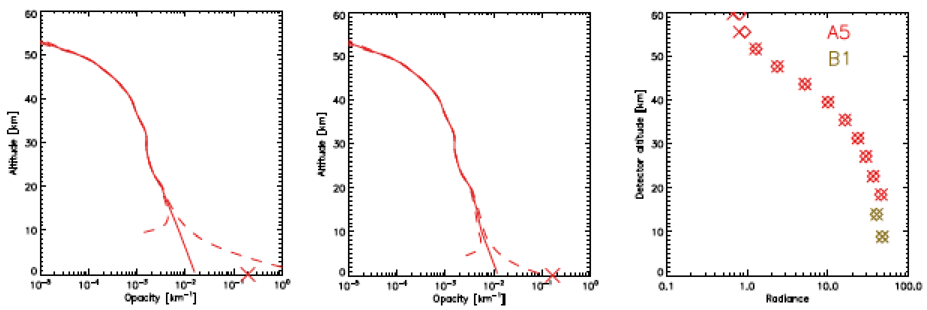

Figure 4: Limb retrieval of a dust extinction profile during a regional dust storm at L_s=215° of MY 31 (Nov. 2012) using only A5 detectors (left) and using a combination of A5 and B1 detectors (center). Dashed lines indicate error estimates. The right panel shows measured (crosses) and fitted (diamonds) radiances in the A5 and B1 detectors at the altitudes where they were used for retrieval.