Transport processes of dust and water in the Martian atmosphere revealed by the MMX Infrared Spectrometer (MIRS): Fast retrieval code for aerosol and gaseous profiles for limb-sounding

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Abstract:
The MMX infrared spectrometer (MIRS) aims to clarify the temporal evolution of the atmospheric species and aerosols to reveal the rapid transport processes with a relatively high spatial resolution (typically 2-10 km) at the timescale of hours, thanks to its equatorial orbit. To process such a huge spectral dataset for each map, a pre-calculated look-up table of synthetic spectra is created to retrieve physical parameters. We also prepare a new fast retrieval code, JACOSPAR, for the limb-geometry dataset, to reduce the huge computation cost, and address the complexity of full light scattering processes in spherical geometry. This study applies for the first time simultaneous limb retrievals for both dust and water ice clouds. Under standard dust conditions, the dust and water-ice cloud effective radius and number densities were successfully obtained at an altitude range roughly below 40 km.

Introduction:
The MMX infrared spectrometer (MIRS) is an imaging spectrometer onboard the MMX JAXA mission. MMX (Martian Moon eXploration) (Kuramoto et al., 2022, EPS) is scheduled to be launched in 2024 with a sample return from Phobos to Earth in 2029. MIRS will remotely provide near-infrared (IR) spectral maps in the range from 0.9 to 3.6 micron with a spectral resolution better than 20 nm for the Martian atmosphere, in addition to those of Phobos and Deimos (Barucci et al., 2022, EPS; Ogohara et al., 2022, EPS).

Mars observation by the MMX Infrared Spectrometer (MIRS):
The equatorial orbit of MMX offers some advantages for global mapping of the Martian atmosphere. Being placed on the same orbit as Phobos around Mars, at altitudes ~6000 km, the spacecraft will have a ~7 hr orbit around Mars, allowing it to complete a global mapping of Mars. The well-controlled scanner system of MIRS enables the specific pointing of the instrument, thus allowing MIRS to obtain wide spatial coverage in hourly timescale. The spacecraft's slewing capabilities in combination with the instrument's scanner will also be used during observations of Mars to maximize the coverage of the MIRS from low to mid-latitudes within an hour, or to obtain an almost global mapping of the sunlit hemisphere up to ~60° N/S latitude with several orbits. These provide the first opportunity to follow the temporal evolution of the atmospheric species (CO_2, H_2O, CO) and aerosols

(dust and clouds) to reveal the rapid transport processes with a relatively high spatial resolution (typically 2-10 km). Time-resolved pictures of the atmospheric phenomena should be an important clue to understanding both the processes of water exchange between the surface/underground reservoirs and the atmosphere and the drivers of efficient material transport to the upper atmosphere. Different observation strategies will be possible to maximize either temporal or spatial coverage of MIRS monitoring of the Martian atmosphere from 30' time resolution observation of a limited zone to complete coverage in a few orbits.

Retrieval tools for MIRS observations:

One of the challenges to process such a high spatial resolution data will be its large data volume. For a typical observation by MIRS, approximately 10^6 spectra are acquired for each map. Common retrieval techniques, such as retrievals using line-by-line calculations with exact values for geometric and atmospheric parameters for each spectrum, will be computationally too expensive. To solve this issue, we have been developing a pre-calculated look-up table of synthetic spectra. This method prepares a series of synthetic spectra that are calculated in advance at tabulated grid values of geometric and atmospheric parameters (such as surface pressure, solar zenith angles, emission angles, atmospheric temperature, surface albedo, aerosols abundance, etc). Forget et al. (2007) and Spiga et al. (2007) demonstrated that this method is robust and fast to retrieve surface pressure with MEx/OMEGA data. We have applied this method to other molecules such as water vapour and carbon monoxide.

MIRS will also perform limb observations to obtain information on the Martian atmosphere at high vertical resolution, to better understand the Mars atmosphere which is a considerably mutually coupled system between the surface, the lower and upper atmospheres, and the space environment.

Fast retrieval code for aerosol and gaseous profiles in the Martian atmosphere for limb-sounding observation:

Limb-sounding observations are still largely unexploited, due to their huge computation cost, and complexity of full light scattering processes in spherical geometry. On the other hand, limb-sounding is essential for understanding the mutual coupling system of the Martian atmosphere between the lower and upper atmosphere, as done by MCS onboard MRO (e.g., Heavens et al., 2018). In this study, we present a new retrieval code used to invert the limb observations using a Bayesian approach (Rodgers, 2000), to retrieve the vertical profiles of dust and water ice density and their particle size.

In this scheme, the forward model, JACOSPAR, is a full radiative transfer code that accounts for multiple scattering of the sunlight photons by the atmospheric aerosols, to model the radiances with high precision (Iwabuchi, 2006; Mahieux et al., 2019). We aim to retrieve vertical profiles for dust and water ice cloud effective radius and number density, which all show clear absorption and/or scattering structure in the considered wavelength region. JACSOPAR uses the backward the Monte Carlo and dependent-sampling method to efficiently calculate multiple wavelength regime (Marchuk et al., 1980). It calculates the scattering for a given number of wavelength values and interpolates the radiance at the other wavelengths. JACOSPAR accounts for the instrumental field of view in its calculations. JACOSPAR also computes precise analytical Jacobians relative to the radiances with respect to the absorption and scattering extinction profiles. They are used to derive the Jacobians to the aerosols number density and effective radius, which are used in the Bayesian algorithm. We compute the aerosol's single scattering albedo, phase function and extinction coefficients using the Mie theory (Wiscombe, 1980), for altitude constant modified-gamma size distribution taken from Kleinbohl et al. (2009), using the refractive index of dust and water ice from Wolf and Clancy (2003) and Warren (1984), respectively. We implemented the Bayesian algorithm approach developed by Rodgers (2000) using the Levenberg-Marquardt method. Based on the a priori atmosphere obtained from the GEM-MARS (Neary et al., 2018), we fit the logarithm of the different aerosol's number densities and effective radius, assuming temperature and pressure conditions obtained from Mars Climate Database (MCD) (Millour et al., 2018) for the latitude, longitude, time and local solar time observation mean value. This is the first time such an algorithm is applied to the limb retrievals for both dust and water ice simultaneously. Although the gaseous profiles can also be retrieved by this method, this will be done in near-future development. Here we focus on the retrievals of aerosols number density and effective radius.

The forward model was validated by comparing it with other existing codes. The comparison implied that the derived radiances agree within 3 % in the nadir-geometry case, and within 1 % in the limb-geometry case. The retrieved accuracy and the sensitive altitude range were evaluated by the synthetic spectra given by known profiles of dust and water ice. Under standard dust conditions, the dust and water ice effective radius and number densities were successfully obtained for altitudes below ~40 km (Figure 1). In this case, the retrieved number densities of dust and water ice were distributed within roughly ~10^{-2} /cm^3 accuracy (~100%) of the true values. The retrieved effective radius of dust and water ice also show good agreements within ~20% of the true values. The code needs further evaluation under various atmospheric conditions to study the sensitive altitude range and accuracy of the retrieved parameters. In addition, the effect of surface albedo needs to be evaluated. We will discuss the comparison with the recent study by D'Aversa et al. (2022). This code is intended to be applied to the inversion of the NOMAD (Vandaele et al., 2015) onboard ExoMars TGO limb observations, in addition to MIRS onboard MMX.

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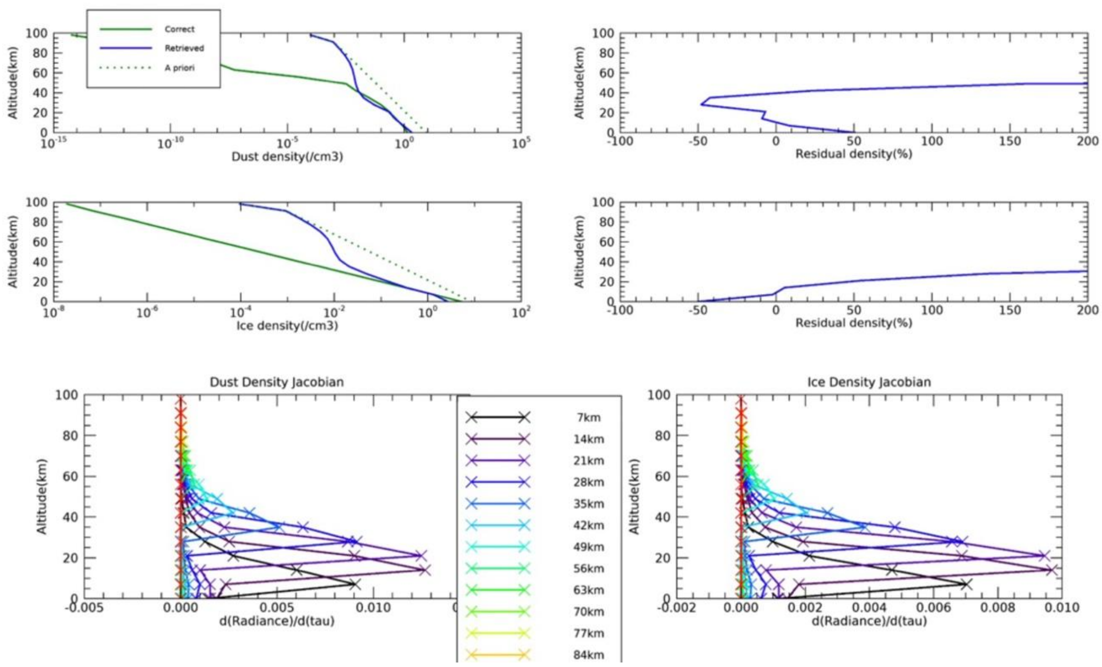

Figure 1. Comparison of dust and water ice clouds number density between (i) true value, (ii) a priori, and (iii) retrieved profiles (top). Jacobian profiles of dust and water ice clouds number densities (bottom).