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Simulation of source intensity variations from atmospheric dust for solar occultation Fourier transform infrared spectroscopy at Mars

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ABSTRACT

A Fourier transform spectrometer observing in solar occultation mode from orbit is ideally suited to detecting and characterizing vertical profiles of trace gases in the Martian atmosphere. This technique benefits from a long optical path length and high signal strength, and can have high spectral resolution. The Martian atmosphere is often subject to large quantities of suspended dust, which attenuates solar radiation along the line-of-sight. An instrument making solar occultation measurements scans the limb of the atmosphere continuously, and the optical path moves through layers of increasing or decreasing dust levels during a single interferogram acquisition, resulting in time-varying signal intensity. If uncorrected, source intensity variations (SIVs) can affect the relative depth of absorption lines, negatively impacting trace gas retrievals. We have simulated SIVs using synthetic spectra for the Martian atmosphere, and investigated different techniques to mitigate the effects of SIVs. We examined high-pass filters in the wavenumber domain, and smoothing methods in the optical path difference (OPD) domain, and conclude that using a convolution operator in the OPD domain can isolate the SIVs and be used to correct for it. We observe spectral residuals of less than 0.25% in both high- and low-dust conditions, and retrieved volume mixing ratio vertical profile differences on the order of 0.5–3% for several trace gases known to be present in the Martian atmosphere. These differences are smaller than those caused by adding realistic noise to the spectra. This work thus demonstrates that it should be possible to retrieve vertical profiles of trace gases in a dusty Martian atmosphere using solar occultation if the interferograms are corrected for the effects of dust.

1. Introduction

Solar absorption spectroscopy is affected by airborne aerosols, which absorb and scatter incoming solar radiation. These often take the form of thin clouds, water vapour, pollution, and smog. In the case of ground-based observations, these conditions may change during the day, and lead to biases in retrieved volume mixing ratios (VMRs) that may vary between measurements. While making remote sensing observations from orbit, the optical path observed by the instrument changes during acquisition, and if the line-of-sight passes through atmospheric layers with varying aerosol loading, the aerosol optical depth will change during acquisition.

The Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) is a high-resolution Fourier transform spectrometer (FTS) in near-polar, low-Earth orbit on the Canadian Space Agency's (CSA's) SCISAT, launched in 2004 [1]. It operates in solar occultation geometry, measuring the absorption of solar radiation along the atmospheric limb and yielding transmission spectra using observations of the un-occulted Sun and deep space. An ACE-FTS-like instrument would be ideally suited for detecting trace gases on Mars, where the atmospheric chemistry and the existence and distribution of trace gases are not well known. ACE-FTS has a wide spectral range (750–4400 cm^{-1}), allowing it to search for dozens of trace gases active in the infrared. It has a spectral resolution of 0.02 cm^{-1}, orders of magnitude better than current Mars missions [8,14], and capable of distinguishing isotopologues. Solar occultation geometry provides very high signal-to-noise ratios (SNRs) and long optical path lengths, and allows for self-calibration between each occultation.

A challenge of applying the ACE-FTS technique to the Martian atmosphere is the presence of suspended dust particles. Dust storms occur frequently on Mars, can be global in scale, and can elevate dust to altitudes above 50 km [17,9]. With ACE-FTS, the

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treatment of interference from aerosols involves the use of retrievals from altitudes with clear skies, or specific studies of cloud properties (e.g., [7,5]) or dust events (e.g., [21,6]). However, on Mars, the extent of the dust layers can be too large to discount, while the duration of dust events can last the majority of a proposed mission length [4,14], so retrieval algorithms for an ACE-FTS-like instrument at Mars must be able to derive trace gas VMR vertical profiles from a dusty atmosphere.

Keppel-Aleks et al. [12] proposed a now-widely-used technique to mitigate the effects of source intensity variation (SIV) for instruments in the Total Carbon Column Observing Network (TCCON) [25]. The Greenhouse gases Observing SATellite (GOSAT) Thermal And Near infrared Sensor for carbon Observation (TANSO) FTS uses a similar technique [15]. Both techniques Fourier transform a raw interferogram, apply a high-pass filter, perform an inverse Fourier transform, and divide the raw interferogram by the filtered interferogram. This requires knowledge of the DC signal level and cannot be applied to AC-coupled interferograms, which are commonly recorded to satisfy the requirements of specific analog-to-digital converters (ADCs) used on the ground (e.g., [24,19]) and from orbit (e.g., [1,13]). If operating an ACE-FTS-like instrument at Mars, DC coupling will be a necessary requirement to measure and mitigate changes in the incoming solar signal.

A solar occultation instrument tracks the centre of the solar disk as the spacecraft comes out of, or enters, the shadow of the planet. During an occultation, the location and altitude of the tangent point along the optical path changes continuously. ACE-FTS uses a double pendulum swing arm with a maximum optical path difference (OPD) of ±25 cm, and interferogram acquisition takes 2 s. How many interferograms are acquired during an occultation, and the altitude spacing between them, depends on the β angle (between the orbit plane and the vector from the Sun). With ACE-FTS, β angles between $\pm 20^\circ$ result in a mean tangent altitude spacing between measurements of 5.5–6 km above 20 km during an occultation.

On Mars, the amount of dust along the optical path can vary significantly over the altitude range tracked during a single interferogram acquisition (1–6 km, depending on β angle), especially at the boundary of a dust layer. We generated synthetic spectra to simulate Mars atmospheric conditions, transformed these spectra into interferograms, and added DC signals. To simulate continuous acquisition, each interferogram was perturbed using the interferograms and DC levels of the measurements from the previous and next tangent height. We then investigated three methods to recover transmission spectra and compared them to the original synthetic spectra.

In Section 2, we describe the creation of synthetic spectra for the Mars atmosphere, their transformation into interferograms, and the SIV perturbation applied. In Section 3, we present the SIV mitigation strategies we investigated, and in Sections 4 and 5 we discuss comparisons of spectra and gas retrievals between the original synthetic spectra and those influenced by SIVs.

2. Simulated spectra

Synthetic transmission spectra, with a range of 850–4320 cm^{-1} and resolution of 0.02 cm^{-1} were generated using the GGG software suite used for analysis of spectra from the MkIV balloon-borne FTS [22] and TCCON [25]. The full spectral range is divided into two channels representing an HgCdTe (MCT) detector between 850 and 2000 cm^{-1}, and an InSb detector between 1900 and 4320 cm^{-1}. *A priori* profiles were developed at NASA's Jet Propulsion Laboratory (JPL), based on Viking mission results [11,16], and hypothesized trace gas quantities and vertical distributions, and include two cases for dust loading (prior to an ACE-FTS Mars mission, these would likely be updated and incorporate global circulation model output). The vertical profiles of the mole fraction of atmospheric dust used to generate the synthetic spectra are shown in Fig. 1 for the high- and low-dust scenarios. Near the surface, the high-dust case contains around six times more dust particles, and the area most susceptible to SIVs, where the rate of change of dust loading with altitude is greatest, occurs near 60 km, compared to 20 km for the low-dust scenario. Other dust profiles were created to make stronger SIVs and are shown in Fig. 1. Two such profiles feature: (i) strong vertical stratification and (ii) a high-altitude detached layer, and are based on observations made by the Mars Climate Sounder on the Mars Reconnaissance Orbiter [17,10] and the Thermal Emission Spectrometer on Mars Global Surveyor [9]. These profiles greatly increase the rate of change of dust mole fraction with altitude, but results from their use do not differ strongly from the high-dust scenario as discussed in Section 5.

Enhanced dust produces broad spectral features characterized by a non-unity spectral baseline that varies with wavenumber. GGG uses a pseudo-line approach [23] to calculate the wavenumber-dependent attenuation due to dust from a set of laboratory-measured line strength parameters. Fig. 2 shows synthetic spectra simulating Martian atmospheric conditions for high-dust and low-dust conditions at an altitude where the rate of change of dust mole fraction is significant in both scenarios. In the high-dust case, three consecutive altitudes are shown, which illustrate the inherent problem of a real interferometer's scan beginning in the lower layer and ending in the upper layer. Also shown is a terrestrial spectrum from ACE-FTS at a similar pressure level.

These synthetic spectra are converted from transmission spectra to absorption spectra by: multiplication by the solar Planck function, addition of a Mars Planck function, and conversion of units to photons (using the field-of-view, aperture radius, throughput efficiency, integration time and spectral resolution). The spectra are multiplied by an instrument function and an efficiency function to simulate the active spectral range of the MCT and InSb detectors. Both functions were determined at JPL and based on the MkIV interferometer. The resulting spectra are then zero-filled from 0 cm^{-1} to the Nyquist frequency (3235.6 cm^{-1} for MCT and 6471.2 cm^{-1} for InSb). Each spectrum is inverse Fourier

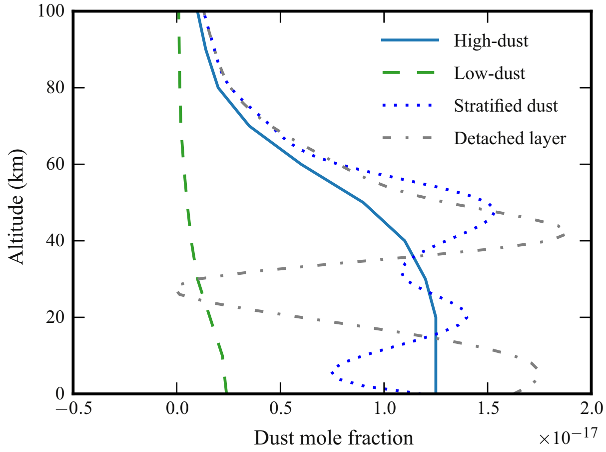

Fig. 1. Vertical profiles of the dust mole fraction used to generate synthetic spectra for the Martian atmosphere for high-dust (blue) and low-dust (green) conditions. The maximum rate of change of dust quantity with altitude occurs near 20 km in the low-dust case and near 60 km in the high-dust case. Also shown are scenarios that attempt to enhance the SIVs featuring strong stratification in the dust profile (grey), or detached layers of dust (grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)