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Martian surface-atmosphere properties obtained with the ExoMars infrared instrument TIRVIM and HP^3 on InSight

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ABSTRACT

ESA's ExoMars program comprises two missions including the Trace Gas Orbiter (TGO), launched in 2016, and a rover and surface platform, to be launched in 2022. The main scientific objectives of the program are to investigate the Martian environment and climate and search for past or present signs of life. For this purpose, a suite of three infrared spectrometers for remote sensing (Atmospheric Chemistry Suite, ACS) is in use on TGO. One of these instruments is a Fourier transform spectrometer, TIRVIM (Thermal IR V-shape Interferometer Mounting in honor of Vassili Ivanovich Moroz), operating in nadir, limb or solar occultation mode between 1.7 and 17 µm. On ExoMars22's surface platform the spectrometer FAST (Fourier for Atmospheric Species and Temperature) will study the atmosphere and surface at the landing site in the same wavelength range as TIRVIM on TGO. This paper presents the objectives of TIRVIM and FAST. It summarizes selected results of the determination of temperature profiles and dust content in the lower atmosphere of Mars based on radiative transfer modeling of TIRVIM data. Synergetic analyses of TIRVIM spectra and InSight (NASA) *in situ* measurements of temperature and pressure at InSight's landing site in Elysium Planitia enable improvements of procedures to retrieve parameters from TIRVIM observations. First results on surface temperature obtained from these different datasets together with the measurements to be expected in the future from FAST offer a unique opportunity to compare *in situ* and IR remote sensing measurements.

Keywords: Planetary remote sensing, Mars environment and climate, IR Fourier spectroscopy, radiative transfer.

1. INTRODUCTION

With the successful operation of the Trace Gas Orbiter (TGO) on the ExoMars16 mission, which is currently acquiring data at Mars, a new program has begun to explore the atmospheric and climatological conditions that will provide insights into the history and planetary evolution of our neighboring planet. This is a joint international effort led by ESA and the Russian Space Agency with broad international participation. One of the key experiments of TGO is the experimental suite ACS (Korablev et al., 2018[1]). ACS is a set of three spectrometers designed to observe Mars at infrared wavelengths. The main objective of ACS is the study of atmosphere and climate of Mars. It includes the spectrometers NIR (Near InfraRed), MIR (Mid InfraRed) and TIRVIM. TIRVIM is a Fourier-transform spectrometer operating in a spectral range from 1.7 to 17 µm at maximum spectral resolution of 0.13 cm^{-1}. TIRVIM enables to observe Mars in three observation geometries: nadir, limb and occultation mode. It monitors atmospheric temperature, dust and cloud features from the surface to approximately 60 km altitude (Ignatiev et al., 2018[2]). The present paper focuses on some results

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obtained in the nadir mode enabling to study atmospheric aerosols and surface properties. Radiative transfer models and retrieval methods are used to derive vertical temperature profiles from spectral features in the 15 µm CO_2 band and dust opacities from absorption features near 9.5 µm. At wavelengths with minimal atmospheric opacity (e.g. near 7.7 µm), the surface temperature can be determined.

In November 2018, the NASA lander InSight reached Mars' surface close to the equator (4.5°N, 135.6°E) in the wide plain Elysium Planitia. InSight mainly explores the planet's inner structure and thermal balance, but it is also equipped with temperature, pressure and wind sensors (Banerdt et al., 2020[3], Banfield et al., 2020[4]). Thus, it offers the unique opportunity to compare *in situ* data with results obtained from remote sensing measurements like those of TIRVIM.

It is always challenging to infer surface data from global remote sensing observations. Locally acquired data are very important references, therefore. It is rarely possible to combine such observations in planetary exploration. Synergetic analyses of TIRVIM spectra and InSight measurements have been recently performed allowing correlations of surface temperature results for different diurnal and seasonal environmental conditions. The paper reports on the first results of these combined studies.

2. RADIATIVE TRANSFER APPROACH AND TEMPERATURE RETRIEVAL

A spectra search routine has been applied to the TIRVIM data archive that selects all measurements at latitudes between 4 and 5°N and longitudes between 135 and 136°E in the UTC time interval December 01, 2018 to March 03, 2019 corresponding to the L_S interval [298.6°, 352.1°]. The quantity L_S (areocentric longitude of the Sun) characterizes the seasons on Mars. $L_S = 0°$ (180°) marks spring (fall) equinox on the northern hemisphere. 19 spectra have been found in total that match the given criteria, but only seven of them significantly differ with respect to season and local time. They are visualized in Fig. 1 in terms of brightness temperature, which is obtained from radiation spectra using Planck's law. The corresponding L_S and LT (local time) values are given in Table 1.

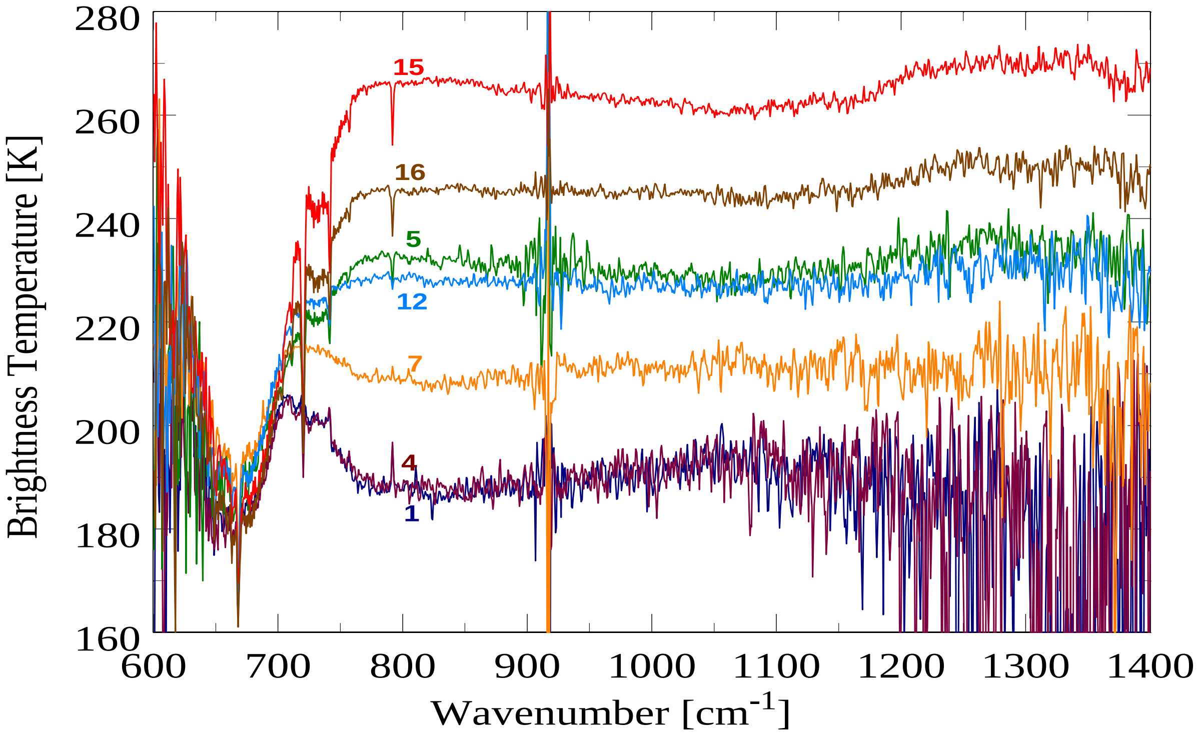

Figure 1. Selected brightness temperature spectra obtained from TIRVIM radiation measurements at different seasons and local times over the InSight landing site.

The selected TIRVIM spectra have been analyzed applying a radiative transfer simulation model (RTM) and a multi-range retrieval technique (MRR). Both RTM and MRR methods were originally developed for the analysis of measured spectra of Venus' atmosphere (Haus et al., 2013[5]) and adapted for the conditions on Mars. The RTM considers absorption, emission and multiple scattering by gaseous and particulate constituents. A uniform volume mixing ratio of CO_2 (95.32%) is used. Minor constituents like H_2O can be neglected for present investigations. Using the HITRAN 2016 line database (Gordon et al., 2017[6]) and Voigt line profiles (line wing cut at 10 cm^{-1}), look-up tables of quasi-monochromatic absorption cross-sections $\sigma(\upsilon,p,T)$ of CO_2 are calculated on the basis of a line-by-line procedure at different wavenumber resolution $(\Delta\upsilon)$ and for a variety of temperature (T) and pressure (p) values being representative for the Martian atmosphere at altitude levels between the surface and 100 km. The overall amount of dust in the Martian atmosphere is described by the total (altitude integrated) optical depth u_{vis} (opacity) at a reference wavelength λ_{vis} =0.55 µm. Mie scattering theory (Wiscombe, 1980[7]) for spherical particles is applied to derive the respective wavelength-dependent microphysical parameters (absorption and scattering efficiencies, single scattering albedo and phase functions) based on a modified Gamma particle size distribution function (Toon et al., 1977[8]) with a mode radius of 0.4 µm and the parameters α and γ equal to unity. Refractive index data are taken from Wolff et al., 2009[9]. They represent the current state of knowledge for use in the calculation of dust radiative properties on Mars. The reference atmospheric model assumes a decrease of dust particle number densities with increasing altitude using a synthetic scale height (H) profile that does not depend on atmospheric parameters. It linearly decreases from H=10 km at the surface to H=2 km at 100 km.

The MRR simultaneously processes information from different spectral ranges of an individual TIRVIM spectrum. It iteratively optimizes several atmospheric and surface parameters until the simulated spectrum well fits the measurement for all utilized spectral ranges. Atmospheric temperature profiles are retrieved from radiation signatures in the short-wavelength wing of the strong 15 µm CO_2 band (12.35-15.38 µm, 650-810 cm^{-1}) applying a radiative transfer inversion technique (Smith, 1970[10]). The required initial temperature model constrains the derived profile in the vicinity of the upper retrieval boundary near 60 km. It can be extracted from existing well-known meteorological databases (e.g. Mars-GRAM, Mars Climate Database), but it can also be provisionally derived from a measured spectrum itself. Silicate dust opacities are determined from absorption (or emission) features near 9.5 µm (1050 cm^{-1}). A quantification of atmospheric water ice is possible near 12 µm (830 cm^{-1}) but was not performed so far.

3. RESULTS

Fig. 2 shows a comparison of measured and simulated (optimum fit) brightness temperatures for spectra 1, 5 and 15 (cf. Fig. 1). A repeated three-point smoothing was applied at wavenumbers larger than 850 cm^{-1} to suppress the partly strong noise. The smoothing does not affect the dust opacity retrieval. Under day time conditions, the surface temperature TS can be directly determined from brightness temperature averages at wavelengths with minimal atmospheric opacity (e.g. near 7.7 µm, 1300 cm^{-1}). Night time spectra are quite noisy in this range and TS is rather obtained from averaged signatures near 800 cm^{-1}. Retrieved TS values are indicated by broken lines in Fig. 2. The retrieved temperature altitude profiles for the three cases are shown in Fig. 3. Note that retrieval results above 50-55 km are strongly constrained by respective initial temperature profiles.

The Heatflow and Physical Properties Package (HP^3) on InSight includes an infrared radiometer primarily sensitive to the wavelength range of 8 to 14 µm (Spohn et al., 2018[11]). Self-calibration ensures a temperature measurement uncertainty of typically 3 K, except during a period in the late afternoon when the uncertainty can be as high as 6 K (Mueller et al., 2020[12]). The instrument observes two spots on the surface. Data of the spot farther from the lander have been used here, which is unaffected by the lander shadow. The instrument monitors the seasonal surface temperature variation by taking hourly measurements during most sols. The hourly measurements are interpolated to the local time of the TIRVIM observations.

Table 1 compares the surface temperature determined from remote sensing TIRVIM measurements and *in situ* InSight (HP^3 temperature) data. Retrieved dust opacities are additionally given.

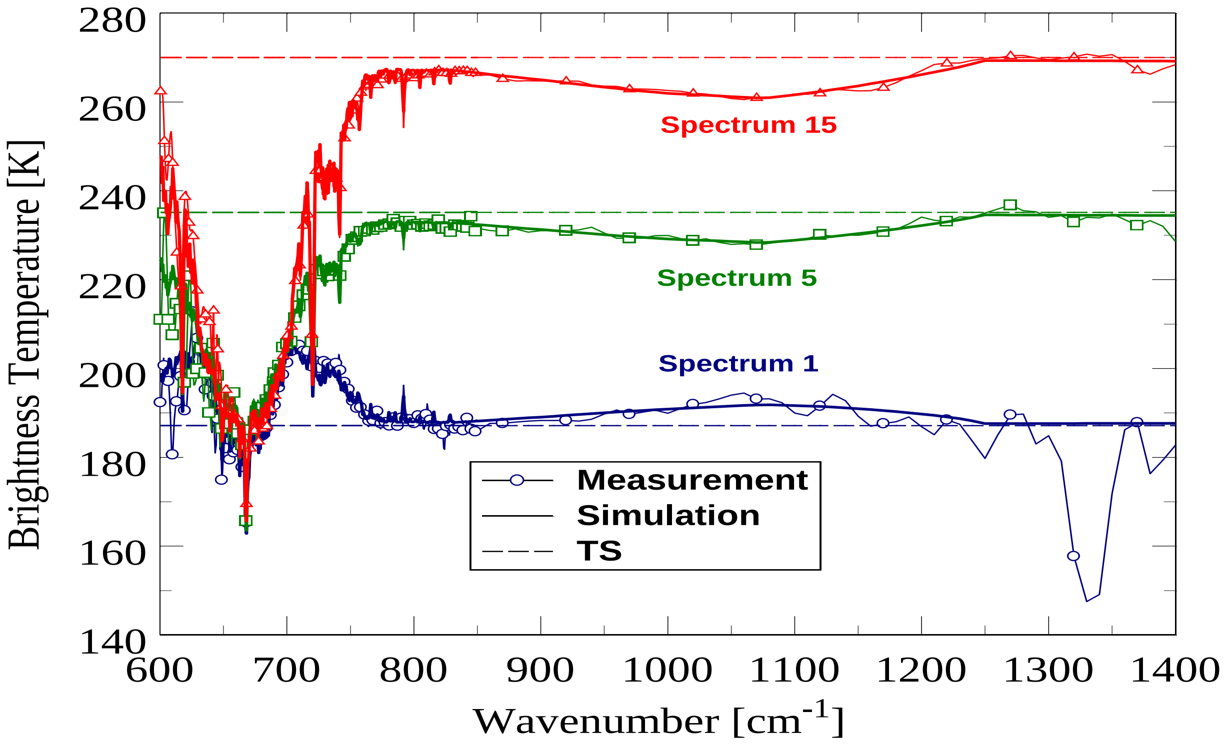

Figure 2. Comparison of measured and simulated brightness temperatures for TIRVIM spectra 1, 5 and 15 (see Fig. 1). TS is the derived surface temperature (cf. Fig. 3 and Table 1).

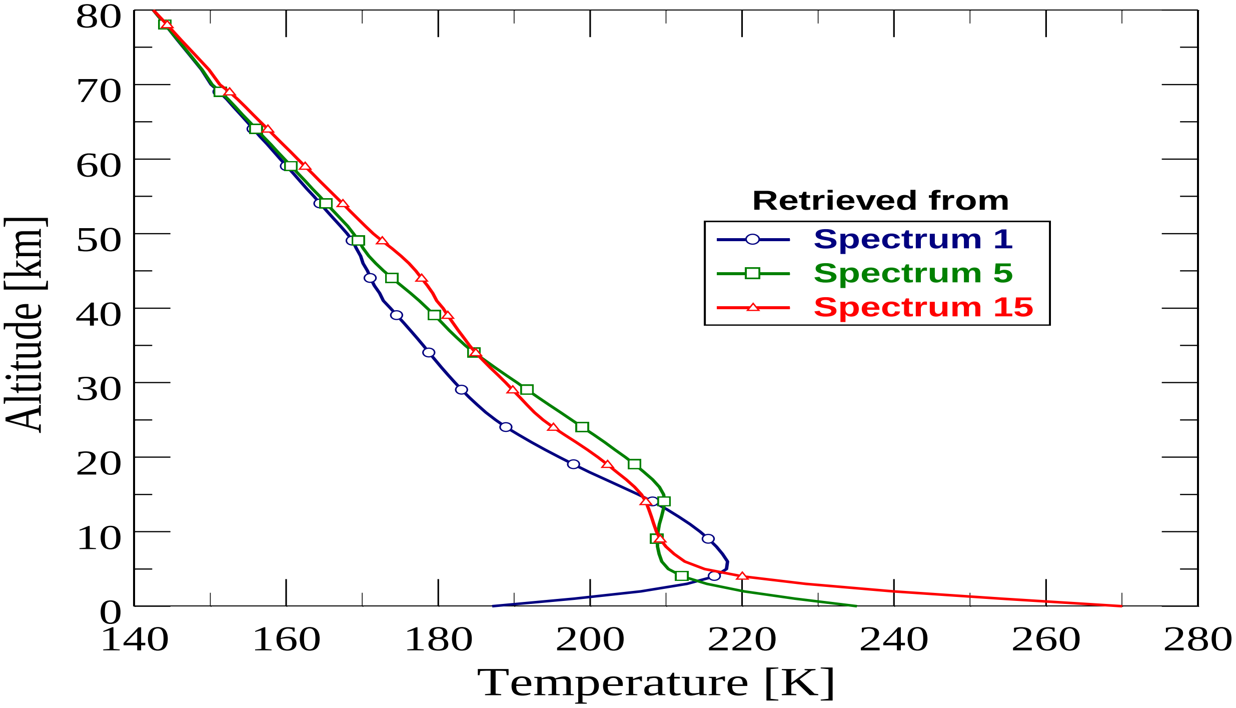

Figure 3. Retrieved temperature altitude profiles from spectra shown in Fig. 2.

Spectrum	L_S [°]	LT [h]	TS-TIRVIM [K]	TS-InSight [K][12]	u_{vis}-TIRVIM
1	311.8	1.31	187.1	192.1	0.32
4	315.9	23.64	188.0	195.5	0.34
5	323.1	8.89	235.1	237.3	0.74
7	329.1	18.26	208.3	218.1	0.84
12	333.0	16.63	230.9	240.8	0.94
15	345.5	11.32	270.0	276.1	0.53
16	349.2	9.68	250.1	254.9	0.45

Table 1. The utilized seven TIRVIM spectra. L_S: Areocentric longitude of the Sun, LT: Local time, TS: Surface temperature, u_{vis}: Dust opacity at 0.55 µm.

4. DISCUSSION

The agreement between surface temperature results obtained from TIRVIM and InSight data is quite good. TIRVIM values are somewhat lower. Deviations range from 2 K (spectrum 5) to 10 K (spectrum 12). Considering the limited number of seven investigated cases it would be inadmissible to deduce a clear trend however. There are mainly two reasons that may explain the differences. First, TIRVIM spectra were selected from a latitude/longitude rage of ±0.5° around the InSight landing site to ensure a sufficient number of appropriate spectra. As a consequence, most spectra do not exactly reflect the conditions at the landing site, the more so as the instrument's FOV is about 2.5° corresponding to 17 km at the surface. The spot observed by the HP³ radiometer is mostly representative of the surrounding region, with the exception of the surface albedo, which has been reduced by 35 % relative to the regional average albedo during the rocket-powered landing (Golombek et al., 2020[13]). Such a decrease in albedo corresponds to a surface temperature increase of 2 to 10 K, depending on time of the day. Second, the limited altitude resolution of retrieval results from remote sensing measurements makes it difficult to distinguish between real temperatures at the surface and some 100 m above. Temperatures on Mars at the surface and the lowest atmospheric layers above may differ significantly, especially during daylight hours when the surface strongly heats up. An altitude step of 1 km was used in the retrieval routine. Test calculations show that measured spectra cannot be fitted in the 15 µm band wing (as in case of Fig. 2) when InSight TS values are utilized in the TIRVIM retrieval routine. Deviations might also be due to calibration issues of either instrument.

5. CONCLUSION AND OUTLOOK

The radiative transfer approach enables reliable surface temperature retrieval from interferometric IR data like TIRVIM/ACS. The combination of these results with *in situ* measurements of Martian surface temperature, e.g. from HP^3 on InSight, is a good reference and also serves to verify the discussed method of temperature retrieval. Future IR measurements from the ground on Mars, as planned for the lander mission ExoMars 2022, with complex analyses of the Martian ground and the lower Martian atmosphere as seen from the ground, will lead to further improvements in linking such local *in situ* investigations with global orbital analyses. The infrared-transform spectrometer FAST (Fourier for Atmospheric Species and Temperature) experiment, which will operate on the ExoMars 2022 platform, will play a prominent role at this. The interferometer has an aperture of about 2.5 cm and operates in the spectral range between 1.7 and 17 µm with a best spectral resolution of about 0.05 cm^{-1} in the Sun tracking mode (Shakun et al, 2019[14]; Zelenyi et al., 2015[15]). The instrument is aimed at long-term thermal sounding of the Martian atmosphere and retrieval of the aerosol properties (dust and ice) as well as measurements of minor species by observing the Sun from the surface.

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