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Synergistic retrieval of H₂O vapor in Mars' atmosphere: the path to a systematic 3D exploration of H₂O vapor

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Summary. Understanding the contemporary water cycle on Mars is a major goal in Mars' climate research. Our study has been conducted with the motivation of optimizing the scientific return of nadir observing instruments which have performed water vapor analysis at various wavelengths on Mars. First, we have evaluated the theoretical performances of jointly analyzing water vapor retrieval in both Thermal Infrared (TIR) and near-Infrared (NIR) ranges (i.e. less than 3 μm). We then proved, by applying our method to actual Mars Express data, that a simultaneous retrieval in the TIR and NIR of the water vapor abundance is susceptible to provide a very strong constraint on the shape of the water vapor profile. Up to now, only a column-integrated abundance has been derived from nadir observing instruments whereas it appears now possible to derive a second information on water vertical confinement, opening the path to a 3D exploration of water vapor on Mars.

Introduction. A Synergistic retrieval of trace gases (such as CO or CH₄) in the Earth atmosphere has proven very effective for constraining the vertical partitioning of these gases and might be used to identify potential sources at the surface [1,2]. Guided by this innovation, we have decided to apply a similar approach to the retrieval of water vapor when observed a nadir looking mode on Mars. A number of orbital assets have accomplished the detailed exploration of the nadir column abundance of water vapor on Mars, allowing the continuous monitoring of the water vapor temporal and horizontal distribution for almost 15 consecutive terrestrial years [3,4,5]. This dataset so far has only delivered an information on the vertically integrated amount of water, yet this information was obtained with a variety of instruments operating at different wavelengths. Indeed, it is possible to "see" water vapor through its absorption/emission in the thermal infrared with the Planetary Fourier Spectrometer (PFS) and through its absorption in the NIR domain with three different instruments (SPICAM, OMEGA and PFS). We undertook an examination of the contribution of a NIR / TIR synergy to the restitution of water vapor in the atmosphere of Mars. This approach is an important task in view of cross-comparing the various climate series

which have been produced for water vapor to date. Our work was divided in two stages: first, establish the theoretical relevance of this method for currently operating instruments on Mars, and second test and validate the performances predicted at completion of the first stage.

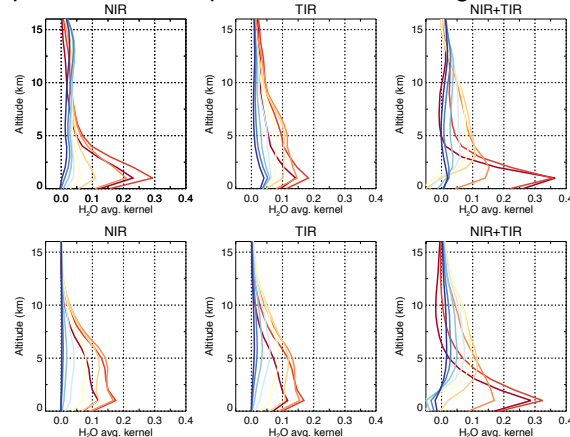


Figure 1: averaging kernels of water vapor in various configurations (from left to right: NIR from SPICAM, TIR from PFS TIR ranges, and synergy NIR+TIR).

NIR-TIR Synergy methodology. The work presented below is limited to the cases of the SPICAM and PFS-LW instruments. We relied on an instrumental model that we designed according to the spectral resolutions and mean SNR of the different sensors. Synthetic spectra were produced from atmospheric modeling extracted from a Martian climate database. A direct model has been developed to account for molecular absorption and aerosol scattering. It enabled us to estimate the sensitivities of the radiances to the various geophysical parameters. We have implemented a statistical approach to combine these sensitivities with the noise models of each instrument and to estimate errors and resolutions on the vertical steam and temperature profiles. It emerged from this study that the number of pieces of information on the vertical profile of water vapor is around 1 for NIR bands below 1 for TIR bands taken independently. The synergy of the entire band offers an increase by about 50%. This increase is highly dependent on the aerosol opacity estimated in the TIR. It has also been demonstrated that the sounded portions of altitude are different between the NIR bands,

which give access to the layer immediately above the surface, while the TIR band is sensitive to the highest altitudes (> 10 km).

On this basis, we have undertaken a statistical characterization of an estimator of the water vapor column and we have evaluated its robustness with respect to the *a priori* knowledge of aerosols. A preliminary approach allowed us to show that the synergy, in order to be significant, requires to have spectra averages to increase SNR. The synergy is shown to render information from an atmospheric portion that extends from the surface up to more than one height scale (see Figure 1), and also reduces the error on the column-integrated abundance estimate. It requires a prior knowledge of aerosols in order to limit estimation bias.

NIR-TIR Synergy Validation. The dataset used for testing and validating has been established from spectra acquired during Martian Year (MY) 27 by the SPICAM-IR and PFS-LW spectrometers. It consists of an ensemble of L1 products (calibrated spectra with wavelength assignment) selected specifically for this study. Each product corresponds to an ensemble of collocated spectra satisfying the following criteria: (i) a high quality of the individual measurements; (ii) a good geographical and seasonal coverage of the final dataset encompassing various dust or water ice cloud opacity situations; and (iii) a low error modeling due to surface inhomogeneity (albedo and emissivity). The results obtained with these tests (see Figure 2 for an example) using actual data confirmed the predictions of our theoretical investigation: the number of independently retrieved parameter increase when adding NIR and TIR together, by an amount of more than 20%, reaching >50%. This characteristic offers an optimized reassessment of the experimental data on Mars' atmospheric water collected from the orbit in a nadir-looking mode. Because the latter is the prime mode of observations of the instruments used to explore Mars, the corresponding data volume and its space-time coverage by far outmatch those of data collected in dedicated viewing geometry like solar occultations or limb staring and thus offers a rich and exciting opportunity to study a yet unexplored "territory" of Martian observations.

Conclusion. We have defined and implemented a Bayesian approach to estimate water vapor in the Mars atmosphere from NIR and TIR spectra obtained in nadir geometry. An analysis of the measurements information content showed that, on average, the spectral synergy allows the increase of retrieved information on

water vapor (which can be represented by the number of independent parameters) by 20 or 50% depending on the reference case (NIR or TIR). We also demonstrated that the NIR/TIR synergy makes it possible to give a more reliable estimate of the total column while unbiasedly estimate the partial column in the first 5 km of the boundary layer, an atmospheric region long remained unexplored although being known for hosting key mechanisms controlling the fate of volatiles on Mars. Using synergy, the scientific return of nadir observations of current and future missions at Mars can be fully optimized.

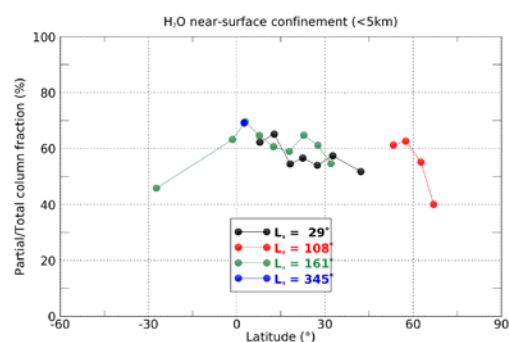


Figure 2: Plot showing the relative vertical partitioning of water as deduced from the NIR+TIR synergistic method. The quantity displayed, expressed in %, is the 5-km partial column ratioed with the total column abundance of water. Higher ratio values indicate stronger confinement of water near the surface.

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