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Usage of differential absorption method in the thermal IR: A case study of quick estimate of clear-sky column water vapor

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ABSTRACT

The concept of differential absorption has been widely used in UV and shortwave remote sensing. This study explores how to extend such concept to the thermal-IR for fast estimation of the total column water vapor (CWV) from clear-sky IR radiances. Using Atmospheric Infrared Sounder (AIRS) radiances as a case study, double difference of radiances at two pairs of pre-selected AIRS channels can be used to suppress the influence of continuum absorption and to highlight contrasts due to weak water vapor line absorptions. To take emission into account, another two AIRS channels are used as surrogates of surface temperature and lapse rate in the lower troposphere. As a result, a three-dimensional look-up table (LUT) can be constructed based on training data sets. Such LUT enables us a fast estimate of CWV directly from the spectral radiances without any *a prior* information or formal retrieval. The performance of the method is tested using synthetic AIRS radiances based on reanalysis as well as actual sounding profiles. It is also tested against AIRS L2 cloud-cleared radiances and CWV retrievals. The comparisons show that the mean bias of this method is within ± 0.07 cm and the root-mean-square fractional error is about 33%.

1. Introduction

The concept of differential absorption has been widely used in the UV and visible remote sensing. The most known example of such concept would be the differential optical absorption spectroscopy (DOAS) instrumentation [1], which makes use of different absorption dependences on frequency to discriminate different absorbers in the measurements. Another classical application of this concept is the World Meteorological Organization (WMO) standard procedure of using Dobson spectrophotometer to measure total column ozone concentration, which utilizes two pairs of UV wavelengths to eliminate the atmospheric scattering effect and hence to derive the total column ozone concentration [2]. Other applications include that Frouin et al. [3] estimated total column water vapor by differential absorption of two spectral channels near 0.94 μm; Noël et al. [4] proposed a DOAS approach to retrieve water vapor as well as other trace gases from Global Ozone Monitoring Experiment (GOME). Unlike the UV and visible regions where the emission from terrestrial atmosphere can be simply ignored, infrared (IR) region is featured with significant contribution from atmospheric emission as well as absorption. Therefore, to apply the concept of differential absorption in the thermal IR is not as straightforward as in the shortwave and emission needs to be taken into account.

Total column water vapor (hereafter, CWV), defined as the vertical integration of atmospheric water vapor mass, is an important thermodynamic quantity. It is closely related to the radiation balance and the convective stability of the Earth's atmosphere [5,6]. CWV is also crucial for

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the atmospheric correction in the remote sensing of surface parameters [7,8]. In certain cases of remote sensing of atmosphere, the classification of scene types also depends on CWV, e.g., the scene type defined and used by Cloud and Earth's Radiant Energy System (CERES) to define its angular distribution model [9]. Currently retrieval of CWV can be done at different spectral regions. For the visible and near-IR, Frouin et al. [3] estimated CWV using differential absorption of two channels near 0.94 μm. In the microwave, Prabhakara et al. [10] obtained CWV over the oceans from NIMBUS-7 microwave measurements by differencing the brightness temperatures at the 21 GHz and 18 GHz channels. Alishouse et al. [11] retrieved CWV from the Special Sensor Microwave/Imager (SSM/I) by regressing brightness temperatures of four SSM/I channels. The CWV retrievals from SSM/I have been widely used by the climate communities [9,12]. For the thermal IR, CWV can be derived from retrieval of water vapor vertical profiles based on hyperspectral sounding such as Atmospheric Infrared Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), and Cross-track Infrared Sounder (CrIS) [13–15]. A split-window technique has been used by many researchers to retrieve CWV in the thermal-IR without explicit retrieval of water vapor vertical profile [e.g., 16–22]. This technique utilizes a linear assumption that atmospheric attenuation of the surface infrared emission is linearly proportional to the radiance difference between two split-window channels (i.e., 11 μm and 12 μm). The split-window technique was originally designed to remove the effect of water vapor in surface temperature retrieval [23]. When used for CWV retrieval, this technique can suffer from large uncertainties when the CWV is large (the linear slope between CWV and the ratio at two split-window channels can have a bias up to 20% for CWV >4 cm) [24]. Such large uncertainty is due to the breakdown of the linear assumption.

Based on above facts, we are motivated to explore to what extent the concept of differential absorption can be used to estimate CWV in the thermal-IR. The continuum absorption is only slowly varying with frequency while water vapor line absorption varies much faster with frequency. This is analogous to the slow varying atmospheric scattering and fast varying ozone line absorption with respect to frequency in the case of column ozone concentration retrieval from Dobson spectrophotometer. However, the existence of atmospheric and surface emission complicates the problem. This study investigates to what extent the differential absorption concept can be applied to CWV retrieval in the presence of such complexity. It is not aimed to outperform currently available sophisticated retrievals algorithms, such as those implemented in the AIRS, IASI, and CrIS operational retrievals, but rather an exploration of applicability of such technique in the thermal-IR.

The rest sections are arranged as follows. Section 2 describes the datasets and the forward model used in this study. The proposed method for quickly estimating CWV based on differential absorption concept is presented in Section 3, and the results and comparisons with other CWV data sets are delineated in Section 4. Further conclusions and discussions are presented in Section 5.

2. Datasets and forward modeling

AIRS is an infrared grating array spectrometer aboard NASA's Aqua satellite launched in 2002 [25]. AIRS measures upwelling radiances at the top of atmosphere (TOA) in 2378 channels of three bands: 3.74–4.61 μm, 6.20–8.22 μm and 8.8–15.4 μm. The spectral resolving power ($\lambda/\Delta\lambda$) is 1200. AIRS scans from -49° to 49° with a nadir-view ground footprint of 13.5 km. Its noise equivalent delta temperature (NEDT) is $\sim$0.1 K or better for a 250 K target blackbody [26]. AIRS operational algorithm derives Level-2 (L2) cloud-cleared radiances on the 45-km ground footprint, and then uses such cloud-cleared radiances to retrieve temperature and humidity [27]. AIRS humidity retrievals have been extensively validated [28–30]. It has been shown that AIRS tropospheric humidity (up to 200 hPa) retrieval achieves an average accuracy of $\sim\pm 10\%$ with RMS of 20–35% with 2-km vertical resolution.

ECMWF ERA-Interim reanalysis [31] is used in this study to construct the algorithm for estimating CWV. ERA-interim is the latest generation of ECMWF reanalysis. The dataset has a spatial resolution of 1.5° latitude by 1.5° longitude and 37 vertical levels up to 1 hPa. 6-hourly temperature and humidity profiles in January, April, July, and October 2005 are fed into radiative transfer model to generate synthetic AIRS radiances and then used to construct the look-up tables (LUTs) for estimating CWV as detailed in Section 3. ERA-Interim reanalysis from another time period (four months in 2008) is also used as one step in the validation of the LUTs approach in Section 4.

For validation of our algorithm, we also use the Thermodynamic Initial Guess Retrieval (TIGR2000 v1.2) data set, which has been provided by the Laboratoire de Météorologie Dynamique and widely used by atmospheric retrieval community [32]. TIGR consists of 2311 actual atmospheric profiles measured by radiosondes from 1968 to 1989, among which 872 profiles were from the tropics, 742 profiles from the mid-latitudes, and the rest 697 profiles from the Polar regions. About 53% of TIGR profiles are over ocean. The data set contains temperature, water vapor and ozone profiles on 43 levels up to 0.0026 hPa, as well as surface temperature and surface pressure. Temperature profiles between 37 hPa and 0.05 hPa and water vapor profiles between 380 hPa and 0.05 hPa are from a monthly climatology of ERA-Interim reanalysis.[1] Between 0.05 hPa and 0.0026 hPa, the data are based on extrapolation of ACE-Scisat Instrument level 2 outputs [33]. Given the change of specific humidity with altitude, such filling values above 37 hPa have little effect on the CWV. Because of its representation of global atmosphere, TIGR data has been frequently used in the development of retrieval algorithms [34].

A fast and accurate thermal radiative transfer model, PCRTM version 2.1 [35], is used as forward radiative transfer model in this study. The PCRTM is a principal-component based radiative transfer model to simulate radiances at thousands of channels by predicting a few

[1] More relevant information can be found at http://ara.abct.lmd.polytechnique.fr/index.php?page=tigr.