Journal of Quantitative Spectroscopy & Radiative Transfer 209 (2018) 137–149

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Spatial Heterodyne Observations of Water (SHOW) vapour in the upper troposphere and lower stratosphere from a high altitude aircraft: Modelling and sensitivity analysis

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ARTICLE INFO

Article history:
Received 30 November 2017
Revised 18 January 2018
Accepted 19 January 2018
Available online 31 January 2018

Keywords:
Remote sensing
Water vapour
Radiative transfer

ABSTRACT

A spatial heterodyne spectrometer (SHS) has been developed to measure the vertical distribution of water vapour in the upper troposphere and the lower stratosphere with a high vertical resolution (~500 m). The Spatial Heterodyne Observations of Water (SHOW) instrument combines an imaging system with a monolithic field-widened SHS to observe limb scattered sunlight in a vibrational band of water (1363 nm–1366 nm). The instrument has been optimized for observations from NASA's ER-2 aircraft as a proof-of-concept for a future low earth orbit satellite deployment. A robust model has been developed to simulate SHOW ER-2 limb measurements and retrievals. This paper presents the simulation of the SHOW ER-2 limb measurements along a hypothetical flight track and examines the sensitivity of the measurement and retrieval approach. Water vapour fields from an Environment and Climate Change Canada forecast model are used to represent realistic spatial variability along the flight path. High spectral resolution limb scattered radiances are simulated using the SASKTRAN radiative transfer model. It is shown that the SHOW instrument onboard the ER-2 is capable of resolving the water vapour variability in the UTLS from approximately 12 km – 18 km with ±1 ppm accuracy. Vertical resolutions between 500 m and 1 km are feasible. The along track sampling capability of the instrument is also discussed.

1. Introduction

It is widely accepted that the distribution of water vapour in the Upper Troposphere and Lower Stratosphere (UTLS) region is strongly linked to climate related processes [1–3]. Indeed, the chemical and radiative properties of water vapour have a strong influence on the overall composition and structure of the region. While the basic dynamical processes that govern the transport of water vapour throughout the UTLS are understood, important questions remain. For example, dynamical coupling between the stratosphere and troposphere via Stratospheric Tropospheric Exchange (STE) and the subsequent changes to distributions of the trace species, such as water vapour and ozone, are believed to result in a radiative feedback in the UTLS. This feedback has been shown to influence the formation of the Tropopause Inversion Layer (TIL) [4], a layer of enhanced static stability just above the tropopause that provides a barrier to vertical motions. Detailed structure has also been observed in the Tropical Tropopause Layer (TTL) that is not well understood. In addition, radiative feedback mechanisms associated with water vapour have been identified as a major source of uncertainty in current climate models.

Resolving these questions requires instruments capable of resolving spatial variations in the vertical distribution of the water vapour near the tropopause [4]. These variations have scales on the order of ~500 m [4]. Currently, the highest vertical resolution space based observations of UTLS water vapour are achieved using limb viewing sensors. Limb viewing satellites in a low-earth orbit provide the best combination of vertical resolution and global coverage. For example, the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) [5,6], the Atmospheric Chemistry Experiment (ACE) [7], the Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY (SCIAMACHY) [8] and the Microwave Limb Sounder (MLS) on NASA's EOS Aura satellite [9] all provide between 3 and 5 km vertical resolution observations of the water vapour profile in the UTLS.

Limb observations are also conducted from stratospheric balloon and high altitude aircraft. For example, aircraft observations from the Gimbaled Limb Observer for Radiance Imaging of the Atmosphere (GLORIA) instrument [10,11] have provided measurements of the UTLS water vapour profile (as well as other important trace species) with a vertical resolution of <500 m in the 4 km – 20 km range [12]. It was shown that appropriate flight patterns can

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https://doi.org/10.1016/j.jqsrt.2018.01.026
0022-4073/

be chosen to facilitate three dimensional tomographic retrievals [13]. On the other hand, limb measurements from stratospheric balloons provide similar vertical resolutions and allow the in situ variability of the water vapour profile to be examined [14].

The Spatial Heterodyne Observations of Water (SHOW) instrument is a Canadian-led instrument concept that was initially developed at York University and is being further developed at the University of Saskatchewan in collaboration with ABB and the Canadian Space Agency (CSA) [15]. The instrument is being designed to provide high vertical resolution (< 500 m) observations of the UTLS water vapour profile from a satellite platform. This is achieved by combining an anamorphic imaging system with a spatial heterodyne spectrometer (SHS) [16,17] to observe limb scattered radiation in a narrow passband within a vibrational band of water (1363 nm–1366 nm) centred at ∼1364.5 nm. Vertically resolved images of the water vapour spectra are obtained for each limb image. These images are then inverted to obtain vertically resolved measurements of the water vapour profile using standard inversion techniques [18].

A prototype instrument has been developed and tested as part of a CSA advanced space studies project and the performance of this design has been validated in the lab [15] using a water vapour cell to mimic several expected atmospheric water vapour pressures in the 8–40 km altitude range. The performance of the instrument was shown to be acceptable for the measurement of atmospheric water vapour using limb-scattered sunlight. In 2014, the SHOW instrument flew on a stratospheric balloon launched from Timmins Ontario [19]. The instrument operated for several hours at a float altitude of 37 km. These observations were used to validate the instrument configuration and demonstrate the technical readiness of the instrument technique for further study.

During 2016–2017, the SHOW instrument configuration was optimized for integration on NASA's ER-2 aircraft by ABB Ltd in collaboration with the University of Saskatchewan [20,21]. From July 17–21, 2017, the SHOW instrument flew aboard the ER-2 aircraft from the Armstrong Flight Research Centre (AFRC), located at (34N, 118W), on several engineering and science flights. The data that was acquired during these flights is currently being processed and the results from these flights will be presented in a different publication.

In this paper, we focus on the simulation of limb scatter observations, conducted from a high altitude aircraft with SHOW. These simulations and the subsequent examination of the retrieval sensitivity provides the ability to assess and refine the retrieval technique and determine the expected sensitivity to water vapour variability from a high altitude aircraft. A simulated 3D water vapour field has been provided by Environment and Climate Change Canada (ECCC) from the GEM-MACH (Global Environmental Multi-scale - Modelling Air quality and CHemistry) forecast model [22] to represent realistic variations in the water vapour profile along the flight path of the aircraft.

The paper provides an overview of the SHOW measurement technique and describes the forward model that is used to simulate limb scattered radiance and the instrument model used to simulate the realistic measurements. The retrieval technique is described and its application to SHOW limb measurements is discussed. The forward model, instrument model and retrieval implementation form a full model of the measurement process. This model is used to examine sensitivity of SHOW retrievals using realistic measurements. Finally, observations are simulated along a hypothetical flight path where the ER-2 flies at a constant altitude of 22 km and a constant speed of 800 km/h. These simulations are used to examine the spatial and temporal sampling capabilities of the instrument. It is shown that the sensitivity and sampling capability achieved by the instrument will allow for the small-scale gradients in the vertical distribution of the water vapour profile near the tropopause to be resolved.

2. SHOW ER-2 limb imaging configuration

The SHOW viewing geometry and mounting inside the ER-2 aircraft wing-pod are shown in Fig. 1(a) and (b) respectively. The optical layout of the instrument is shown in Fig. 1(c). The field of view looking out the wing pod window is ∼4° in the vertical (4° downward from the boresight tangent) and 5° in the horizontal. This geometry is achieved by tilting the instrument downward inside the wing pod. The Figure shows a nominal aircraft altitude of 20 km and an example line of sight corresponding to the ∼8 km tangent point. In practice, the aircraft altitude and pitch varies as a function of time and the lines of sight are defined using the aircraft attitude information.

The SHOW instrument combines an SHS with an anamorphic imaging system, operating in limb viewing mode, in order to obtain vertically resolved limb images of the water vapour absorption spectra in a narrow spectral window from 1363 nm to 1366 nm with an un-apodized spectral resolution of ∼0.03 nm. The configuration and operation of an SHS is quite similar to a traditional Fourier Transform Spectrometer (FTS) such as a plane mirror Michelson (with a beam splitter and two plane mirrors) interferometer; however, the plane mirrors are replaced with fixed, tilted diffraction gratings. In the case of the SHS, a wavenumber dependent shear is introduced between the wave fronts exiting the interferometer. An image of the associated wavenumber dependent Fizeau fringes is formed by imaging the plane of the gratings onto a detector array. The gratings are operated in the Littrow configuration so that the fringes are heterodyned about the Littrow wavelength. A more detailed description of the SHS approach is given in [16].

The SHOW fore optics have an anamorphic design so that the limb is imaged in the vertical and defocused in the horizontal to provide a homogeneous scene in the interferogram dimension. This configuration has been chosen so that spatial variations in the horizontal limb radiance do not influence the spectral content recorded in the horizontal dimension at the detector. The SHOW aft optics and SHS are configured so a spatial heterodyned interferogram is imaged conjugate to the vertically resolved image of the limb at the detector. This provides a one-to-one mapping of tangent altitude to each row, i.e. each interferogram.

An example forward modelled SHOW limb measurement is shown in Fig. 2. The interferogram row corresponding to the tangent altitude at 16.45 km is shown in Fig. 2(a). The full interferogram image is shown in Fig. 2(b) where each interferogram row corresponds to a particular tangent altitude at the limb. The vertical intensity profile in the interferogram image is associated the variation of the limb scattered radiance with altitude. Each interferogram row is processed separately using analysis and calibration techniques similar to those applied in FTS to obtain the water vapour spectra corresponding to each tangent altitude. The associated spectrum corresponding to the tangent altitude at 16.45 km is shown in Fig. 2(c). The target wavelength region from 1363 nm to 1366 nm is isolated using a narrow band filter located in the aft-optics. The shape of the filter transmission profile (shown as the dotted line in Fig. 2(c)) as a function of wavelength is evident in Fig. 2(c) and (d). The lower wavelength cut-off corresponds to the Littrow wavelength of the device. The slight increase in intensity above the transmission filter on the left hand side of the profile is due to aliasing of spectral information from the left side of Littrow into the right side of Littrow, which will be discussed in more detail in Section 3.2. The modelled limb image of the water vapour spectrum, shown in Fig. 2(d), is obtained by applying this process to each interferogram row. In practice, the resulting spectrum is