

# Spaceborne Measurements of the Column Averaged Methane Dry Air Mole Fraction

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**Abstract.** Methane is the second most important anthropogenic greenhouse gas in the terrestrial atmosphere. Thus any attempt to understand its impact on climate change requires knowledge of its sources and sinks, which may be derived from high precision satellite measurements. A possible OCO-like [Miller et al., 2007] spaceborne measurement of methane by using reflected sunlight from the ground in the near infrared bands of methane at 4100 – 4300 cm<sup>-1</sup> and 5900 – 6100 cm<sup>-1</sup> is discussed. It is shown that by making use of the reflected sunlight, the sensitivity peaks at the surface, thus allowing better observations of the sites of methane's sources and sinks.

## Introduction

Methane is the second most abundant anthropogenic greenhouse gas in the Earth's atmosphere [IPCC, 2007], accounting for ~4 – 9% of the greenhouse effect on Earth. Thus any attempt to understand and quantify climate change requires knowledge of methane's sources, sinks and distribution within the atmosphere. Unfortunately current Earth-based methane sensor networks such as those operated by NOAA are geographically sparse and prone to spatial bias. Both of these issues are shortcomings that a space-based observation program would be perfectly suited to remedy.

Recently, a global map of methane has been reported from the SCIAMACHY measurement (Figure 1), but which has led to great controversies whether there are aerobic sources of methane [Frankenberg et al., 2008]. Obviously, independent satellite measurement is tempted.

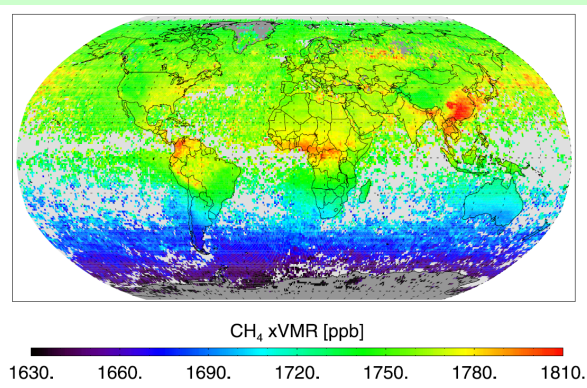


Figure 1. SCIAMACHY column averaged mixing ratios of methane gridded on 1°x1° in 2004. Adapted from Frankenberg et al. [2008].

The aim of this work is to investigate the precision to which spaceborne measurements of atmospheric methane can be made. This is achieved through the use of MODTRAN [Berk et al., 2004] forward models to generate synthetic spectra and inverse models to simulate information retrieval from virtually observed spectra. Although coverage would be greatly increased by a satellite mission it is important to also maintain the quality of data, thus the level of precision attainable when measuring methane abundance from space is of direct relevance to the feasibility of a potential mission for spaceborne monitoring of this important greenhouse gas.

It is worth noting that while TES (Tropospheric Emission Spectrometer) is currently orbiting the Earth and is capable of measuring methane, it uses thermal IR emission and thus its sensitivity peaks in the middle and upper troposphere. We show that by using reflected sunlight, the sensitivity peak is shifted down towards the surface, thus allowing better retrieval.

## Choice of CH<sub>4</sub> bands

There are two choices of spectral regions for methane observations in the solar absorption region. The many absorption bands between 4100 and 4300 cm<sup>-1</sup> is one choice and the one band near 6000 cm<sup>-1</sup> is the other (Figure 2). Other spectral regions in the solar absorption region contain methane absorptions that are too weak to be useful.

The 4100 – 4300 cm<sup>-1</sup> region contains a dense number of methane lines belonging to the  $\nu_2+2\nu_4$ ,  $\nu_1+2\nu_4$  and  $\nu_3+\nu_4$  bands; at 6000 cm<sup>-1</sup>, the  $2\nu_3$  band is the major component. On the basis of band strength alone the absorptions at 4200 cm<sup>-1</sup> are a clear choice. However, the absorptions at 6000 cm<sup>-1</sup> are less dense and the band strength is distributed among many fewer absorption lines. Therefore, there are some isolated lines in that band that have strong peak absorptions that are comparable to the absorptions in the stronger bands at 4200 cm<sup>-1</sup>. The absorptions in both spectral regions have absorptions that are about the right strength for accurate measurements of methane absorptions in a nadir observation. Another consideration is interference; the  $2\nu_3$  band is possibly the better choice on that basis, but in neither spectral region is that a serious consideration if high resolution observations are made.

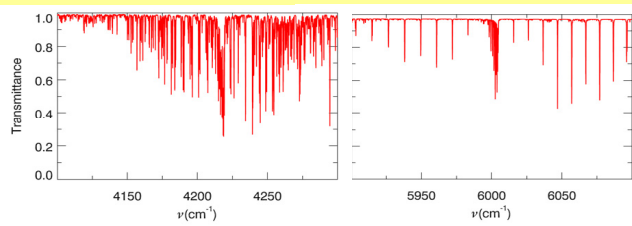


Figure 2. Transmittance of the methane bands in 4100-4300 cm<sup>-1</sup> (left) and 5900-6100 cm<sup>-1</sup> (right).

## Jacobians

The assessment of global sources and sinks of methane requires a remote-sensing that is sensitive at the surface. This can be achieved if the reflected sunlight is employed [Kuang et al., 2002]. We use MODTRAN [Berk et al., 2004] to simulate the total outgoing radiance at resolution 0.1 cm<sup>-1</sup> at the top of the atmosphere in the band regions 4100-4300 cm<sup>-1</sup> and 5900-6100 cm<sup>-1</sup>, where the thermal components are negligible. Since only methane will be perturbed in the calculation, we use a model atmosphere with methane as the only trace gas. To zeroth order, the resultant spectra are the reflected sunlight multiplied by the transmittance functions described above.

The Jacobians of the total outgoing radiance with respect to methane concentrations at different altitudes are calculated (Figure 3). The vertical profiles of pressure, temperature and methane are from the Mid-Latitude Summer Model Atmosphere [Anderson et al., 1986]. The surface is assumed to be Lambertian, with a constant albedo 0.13 (corresponding to an ocean surface). The derivatives are estimated by the 3-point Lagrangian interpolation method, with the perturbations -10%, 0% (i.e. unperturbed reference) and +10% applied at each wavenumber and altitude. Notice that the derivatives must be divided by the thicknesses of the atmospheric layers to cancel the air-mass column effect in the radiative calculations. Only the Jacobian of the strongest bands at 4218.3 cm<sup>-1</sup> and 6003.0 cm<sup>-1</sup> are shown in Figure 4. They are averaged over several "instrumental resolutions": 1, 5, 10 and 50 cm<sup>-1</sup>. Since the  $2\nu_3$  at 6003.0 cm<sup>-1</sup> is asymmetric, the center for the line window is shifted a bit to 6001.5 cm<sup>-1</sup> to capture other structures that are symmetric about the  $2\nu_3$  band.

Regardless of the instrumental resolutions, all Jacobians are peaked at the surface. These bands are therefore possible candidates for the measurement of methane concentrations near the surface level. Since there are a lot more methane lines in the 4100-4300 cm<sup>-1</sup> bands, the sensitivity has less variations with respect to the instrumental resolutions, even if the latter is very coarse. However, as far as high resolutions, e.g. <1cm<sup>-1</sup>, is concerned, the bands are very similar, and the retrieved quantities from these bands should be very close.

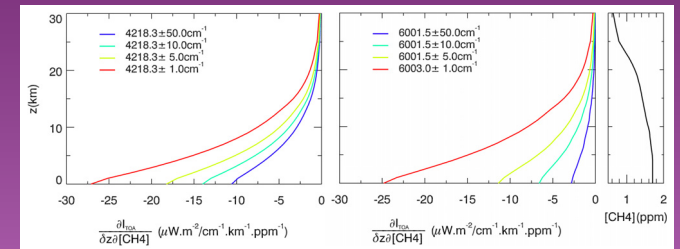


Figure 3. Jacobians of the strongest methane bands in the mid-latitude summer model atmosphere. Left: 4218.3 cm<sup>-1</sup>; middle: 6003.0 cm<sup>-1</sup>. The reference methane profile is shown on right.

## Information content

On one hand, the measurement accuracy of a channel is always limited by the signal-to-noise ratio of the instrument; on the other hand, according to the Bayesian theory [Rodgers, 2000], the covariances of the underlying atmosphere would also limit the retrieval accuracy. One way to characterize the usefulness of a channel is from its information content.

For a single channel, the total variance of a measurement at wavenumber  $\nu$  is given by

$$\sigma_v^2 = \int dz' \int dz K_\nu(z) K_\nu(z') S_\nu(z, z') + \sigma_{SNR}^2 \quad (1)$$

where  $K_\nu(z)$  is the Jacobian at  $\nu$ , and  $\sigma_{SNR}$  is the instrumental error. The channels are assumed to be independent of each other; here we assume that  $\sigma_{SNR} = 400$ , typical of the OCO measurement.  $S_\nu$  is the covariance matrix of the methane concentration [CH<sub>4</sub>]. We assume that  $S_\nu$  can be described with a Markov process such that it takes the form

$$S_\nu(z, z') = \alpha^2 \exp\left(-\frac{|z-z'|}{h}\right) \quad (2)$$

where  $h = 7\text{km}$  is the typical scale height and we take  $\alpha = 0.2$  [CH<sub>4</sub>]. We can then define the degree of freedom  $d_\nu$  and Shannon information entropy  $H_\nu$  as

$$d_\nu = 1 - \frac{\sigma_{SNR}^2}{\sigma_v^2}, \quad H_\nu = \log_2 \left| \frac{\sigma_v}{\sigma_{SNR}} \right| \quad (3)$$

Table 1 summarizes  $d_\nu$  and  $H_\nu$  for the channels and the respective resolutions in Figure 3. As discussed above, there are less bands around 6000 cm<sup>-1</sup>, and thus it is more prone to the instrument noises than the 4100 – 4300 cm<sup>-1</sup> bands.

band	4218.3 ± Δν cm <sup>-1</sup>				6003.0 ± Δν cm <sup>-1</sup>			
Δν	1	5	10	50	1	5	10	50
$d_\nu$	0.996	0.974	0.946	0.896	0.952	0.75	0.482	0.143
$H_\nu$	3.994	2.641	2.109	1.631	2.188	1.001	0.475	0.111

Table 1. Degrees of freedom and Shannon information content of the proposed measurement of methane using the bands and resolutions shown in Figure 3.

## Future work

Our next goal is to determine the precision of methane measurement from inverse modeling [Butler et al., 2004] such that the determination of sources and sinks become feasible. Based on the information content, we will determine which of the two bands we have discussed above are suitable for making the measurement.

## References

Anderson et al., AFGL atmospheric constituent profiles (0-120 km). In *Technical Report AFGL-TR-86-0110*, AFGL (OPI) (1986); Berk et al., Proc. SPIE, Vol. 5571, 78 (2004); Bulter et al., *Atmos. Chem. Phys.*, 4, 2561(2004); Frankenberg et al., *GRL*, 35, L15811 (2008); IPCC, *Fourth assessment report* (2007), [www.ipcc.ch](http://www.ipcc.ch); Kuang et al., *GRL*, 29, 1716 (2002); Miller et al., *JGR*, 112, D10314 (2007); Rao et al., *Spectroscopy of the Earth's Atmosphere and Interstellar Medium* (1992); Rodgers, *Inverse methods for atmospheric sounding: theory and practice* (2000).