A Physics-Based Band-Ratio Algorithm for Methane Detection with PRISMA Satellite Data

Soo Chin Liew*, Li Tan, and Santo V. Salinas
Centre for Remote Imaging, Sensing and Processing, National University of Singapore,
Blk S17 Level 2, 10 Lower Kent Ridge Road, Singapore 119076, Singapore
*scliew01@gmail.com

Abstract**:** *Methane is a potent greenhouse gas (83 times warming potential of CO2 over 20 years), making its monitoring vital for climate action. Satellite sensors offer crucial advantages over ground methods by providing wide-area, high-resolution detection of its spatial and temporal distribution, often using short-wave infrared (SWIR). We simplified a complex, physics-based inverse modeling algorithm into a simple band-ratio method using selected SWIR bands. This method, validated with synthetic data and successfully applied to map a super-emitter site in Turkmenistan using PRISMA satellite data, demonstrates that physics-based insight can simplify quantitative methane retrieval.*

Keywords: Methane detection, hyperspectral data, PRISMA, physics-based modeling, band-ratio.

Introduction

Greenhouse gases, particularly methane, are primary drivers of climate change, with methane possessing a global warming potential 83 times higher than carbon dioxide over two decades. Consequently, monitoring methane's spatial and temporal distribution from both natural and human sources is crucial for climate modeling, prediction, and validating carbon reduction targets. Satellite sensors offer significant advantages over ground-based methods for this purpose, providing rapid, wide-area coverage, access to remote locations, global monitoring capabilities, high-resolution localized detection, and the ability to track emission trends over time. Satellites detect methane through two primary modes: measuring the absorption of sunlight by methane molecules using hyperspectral imaging in the short-wave infrared (SWIR) bands, or by analyzing natural thermal emission from Earth's surface in the mid-wave infrared (MWIR) band. While instruments like TROPOMI on Sentinel-5P offer global observations of methane emission, their spatial resolution is insufficient for localized sources. In a previous work presented in IGARSS 2024 (Liew et al. 2024), we introduced a physics-based inverse modeling algorithm using the linear matrix inversion technique for retrieving methane concentration of a near-ground methane cloud. In this paper we show that the physics-based algorithm may be simplified to a simple band-ratio method using appropriately selected SWIR spectral bands, for detecting and quantifying methane emissions from hyperspectral PRISMA satellite data. This method was validated using a synthetic dataset and successfully applied to a super-emitter site in Turkmenistan to map methane columnar density. This work demonstrates the importance of physics-based modeling in providing insights for retrieving quantitative information from a simple band-ratio algorithm.

Theory

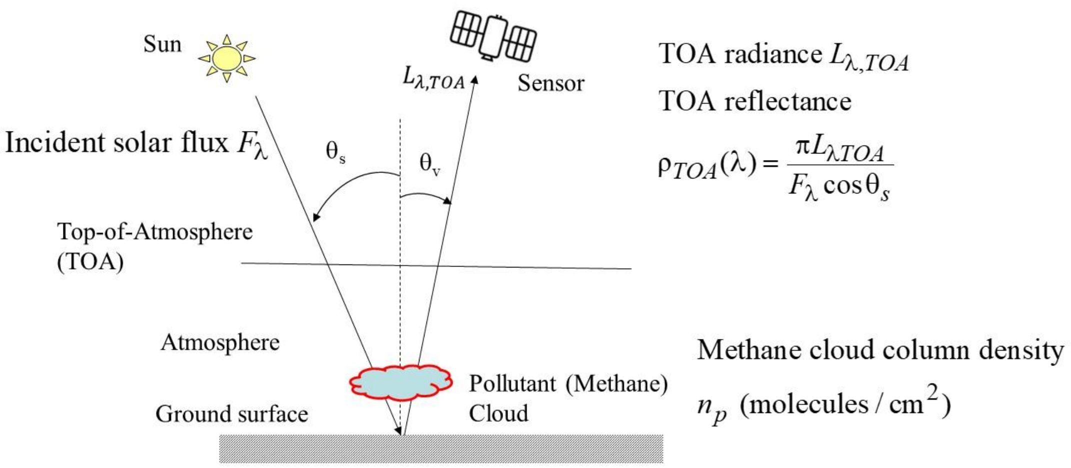


Fig. 1. Imaging geometry for detection of a methane cloud

The methane pollutant gas is assumed to be confined to a layer close to the ground surface. The top-of-atmosphere (TOA) reflectance is modeled by the equation

$$\rho_{TOA}(\lambda) = \rho_b(\lambda) T_{scat}(\lambda) T_b(\lambda) T_p(\lambda) + \rho_{scat}(\lambda) T_b(\lambda) \tag{1}$$

where T_{scat}, T_b, T_p are, respectively, the atmospheric transmittance terms due to scattering, absorption by ambient gases and absorption by pollutant cloud, ρ_b is the background surface reflectance and ρ_{scat} is the atmospheric path reflectance due to scattering. In this equation, the TOA reflectance $\rho_{TOA}(\lambda)$ is measured by the satellite sensor. The atmospheric transmittance terms T_{scat}, T_b can be calculated using a radiative transfer code such as MODTRAN (Berk et al. 2014). The surface reflectance ρ_b is unknown while the transmittance due to the pollutant layer T_p is modeled by,

$$T_p(\lambda) = e^{-Mn_p\sigma_p(\lambda)} \approx 1 - Mn_p\sigma_p(\lambda) \tag{2}$$

where M is the airmass factor, $\sigma_p(\lambda)$ is the absorption cross-section (cm^2 per molecule) of the pollutant and n_p is the pollutant column density (molecules per cm^2). The airmass factor is determined by the imaging geometry while the absorption cross-section can be obtained from existing databases such as HITRAN (Gordon et al. 2022).

Suppose that the TOA reflectance is measured at two wavelengths, λ_1 in an absorption band of the pollutant molecule, λ_0 outside the absorption band. The band ratio of the two TOA reflectance is,

$$r = \frac{\rho_1}{\rho_0} = \frac{\rho_{b1}T_{s1}T_{b1}(1-Mn\sigma_1)+\rho_{s1}T_{b1}}{\rho_{b0}T_{s0}T_{b0}(1-Mn\sigma_0)+\rho_{s0}T_{b0}} \tag{3}$$

Where the subscripts 1 and 0 refer to the measurements at λ_1 and λ_0, respectively. In principle, this equation may be inverted to obtain the pollutant concentration n in terms of the band ratio r,

$$n = \frac{(\rho_{b1}T_{s1}T_{b1} - r\rho_{b0}T_{s0}T_{b0}) + (\rho_{s1}T_{b1} - r\rho_{s0}T_{b0})}{M(\sigma_1\rho_{b1}T_{s1}T_{b1} - r\sigma_0\rho_{b0}T_{s0}T_{b0})} \tag{4}$$

provided all the terms on the righthand side are known. The challenge is that the background surface reflectance is an unknown at both the absorption and non-absorption wavelengths. In our previous work, we model the surface reflectance by a cubic polynomial and the inverse solution is solved by a least square fitting technique. However, if $\lambda_1 \approx \lambda_2$, then the inverse solution (Eq. 4) may be simplified to,

$$n \approx \frac{(1-r)}{M(\sigma_1 - r\sigma_0)} \tag{5}$$

by making the below four assumptions:

Assumption 1: $\rho_{b1} \approx \rho_{b0}$

Assumption 2: $\rho_{s1} \approx \rho_{s0}$; $T_{s1} \approx T_{s0}$

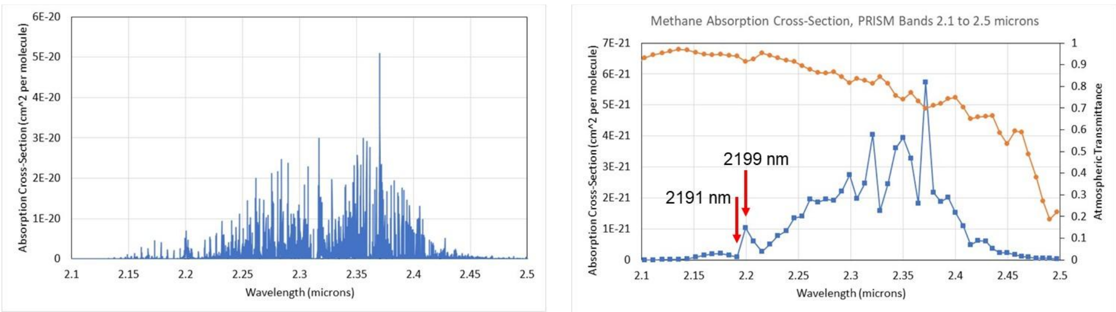
Assumption 3: $\rho_{s1} \ll \rho_{b1}T_{s1}$

Assumption 4: $T_{b1} \approx T_{b0}$ (6)

Since the surface reflectance usually does not change very much over a short wavelength range, Assumption 1 is generally valid, unless the surface contains some substance that also absorbs at the absorption band of methane. Assumption 2 is also generally valid since for atmospheric scattering, $\rho_{s1} \approx \rho_{s0} \approx 0$ and $T_{s1} \approx T_{s0} \approx 1$ at the short-wave infrared region. Assumption 3 is valid if the background surface is sufficiently bright such that $\rho_{s1} \ll \rho_{b1}T_{s1}$. The last assumption 4 holds if the atmosphere does not contain other gases that absorb at wavelengths near the absorption band of methane. Thus, if these 4 assumptions are valid, the methane concentration can be calculated from the band ratio directly.

Methods

The above band-ratio inversion method is tested on the PRISMA hyperspectral satellite. The absorption cross-section of methane is shown in Fig. 2. As shown in this figure, the methane absorption peak located at PRISMA Band 42 (2199 nm) and the adjacent non-absorption Band 43 (2191 nm) are used to calculate the band ratio. Although there are other stronger absorption peaks in this wavelength range, they are not ideal as they are at the edge of the atmospheric transmittance window and there is no distinct non-absorption band near to the stronger peaks.



$$\sigma_1 = 1.03327\times10^{-21}\ \text{cm}^2 / \text{molecule}$$
$$\sigma_0 = 0.08250\times10^{-21}\ \text{cm}^2 / \text{molecule}$$

Fig. 2. Absorption cross-section of methane. Left: Line by line absorption cross-section retrieved from HITRAN. Right: Absorption cross-section at PRISMA bands from 2.1 to 2.5 micrometers at 10 nm spectral resolution.

A synthetic dataset of top-of-atmosphere (TOA) reflectance is generated to test the band-ratio inverse model for retrieval of the methane gas column density. The TOA reflectance is computed using the forward model equation (1). The atmospheric transmittance T_s, T_b are computed with MODTRAN6 for a standard atmosphere with randomly varying precipitable water from 0 to 5 cm. The background surface reflectance ρ_b is a random linear mixture of a vegetation component and a non-vegetation component, both randomly drawn from a spectral library. The transmittance term due to absorption by pollutant molecules is computed with the full exponential form of the equation (2). The methane column density n_p varies randomly from 0 to 10000 ppmm (parts per million – meter). At 300 K and 1 atm pressure, the molecular density of the regular gases in the atmosphere is about 2.4×10^{25} molecules/m^3. Thus, the molecular density of 1 ppmm of pollutant is about 2.4×10^{19} molecules/m^3.

Results and Discussions

The results of methane concentration retrieval on the synthetic data set using the band-ratio method are shown in Fig. 3. It is noted that there is an offset of about 8383.4 ppmm due to the presence of background methane in the standard atmospheric model.

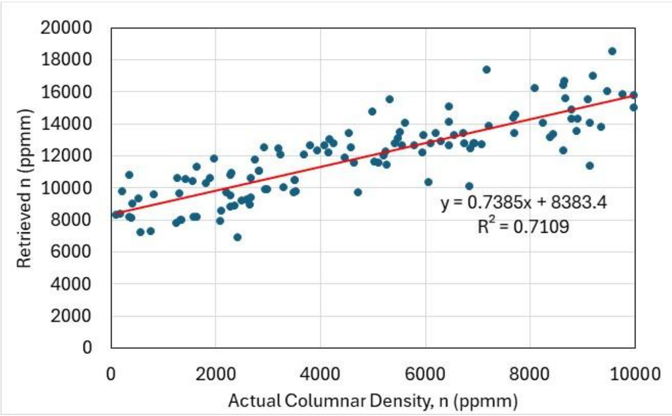


Fig. 3. Results of methane density retrieval using the band-ratio method.

There is a high correlation between the retrieved and the actual methane density (R^2=0.71). Ideally, the slope of the scatterplot should be one. The deviation could be due to an error in the conversion factor when converting from molecular density to ppmm. It could also be due to deviations from the four assumptions.

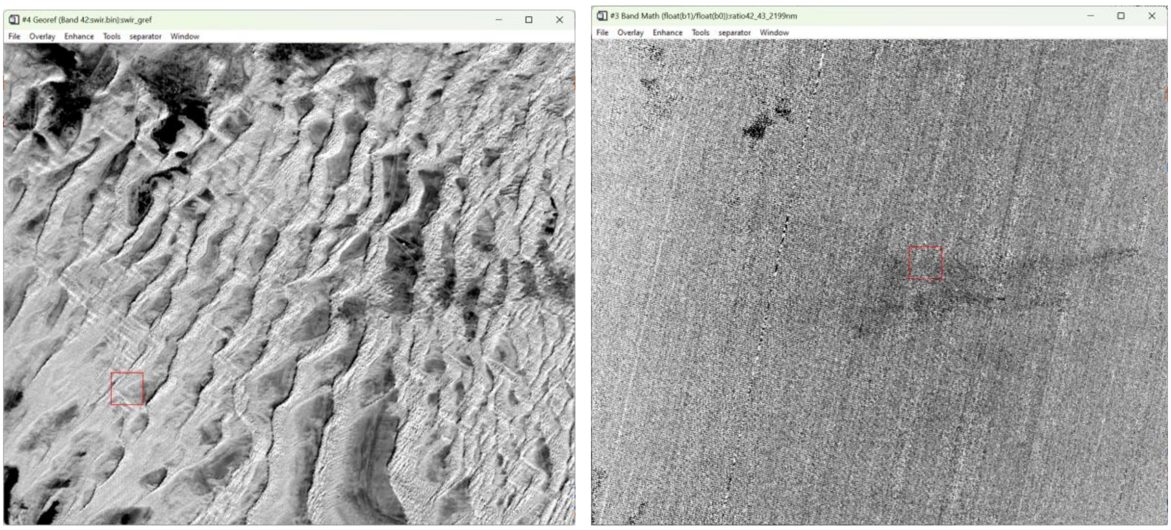


Fig. 4. Left: Grey scale image of PRISMA Band 42 (2199 nm). Right: Band ratio image (Band42/Band43). Dark plumes indicate presence of methane.

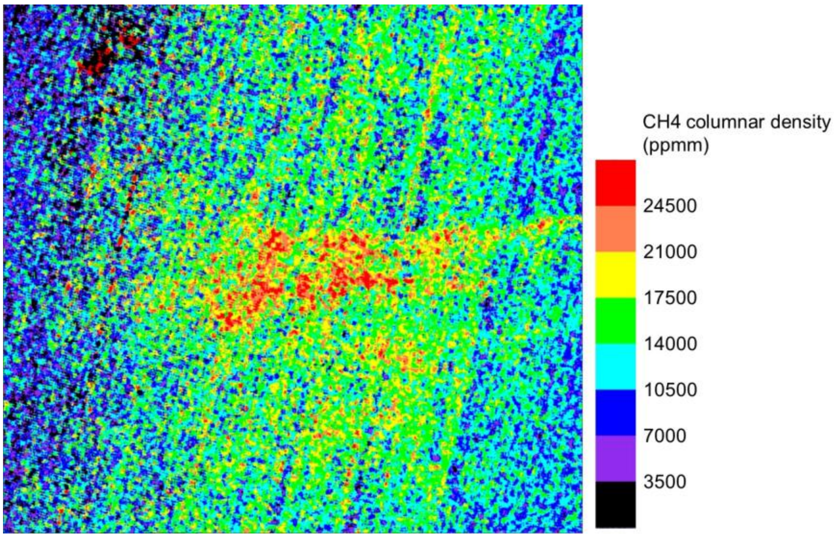


Fig. 5. Methane columnar density map derived from PRISMA data using the band-ratio method.

The band ratio method is applied to a PRISMA scene of a known methane super-emitter at Turkmenistan (Scene Centre: 53.71721E, 39.36565N, Date: 2021-01-23, 07:29 UT). Fig. 4 shows the grey scale image of Band 42 and the band ratio image (Band 42/Band 43). The methane columnar density map calculated from the band ratio is shown in Fig. 5. Though not supported by ground measurements, the results indicate the feasibility of the band-ratio method in detecting intense methane plumes using the PRISMA satellite data.

Conclusions

We have demonstrated the application of a simplified band-ratio model in mapping methane columnar density using the PRISMA hyperspectral satellite data. We simplified a complex, physics-based inverse modeling algorithm into a simple band-ratio method using selected SWIR bands. We have validated this method with a synthetic data set and successfully applied to map a super-emitter site in Turkmenistan. This work also demonstrates that physics-based insight can simplify a complex model for quantitative methane retrieval.

Acknowledgements

We thank the Italian Space Agency (ASI) for providing the PRISMA data for our research. This work is an extension of a research project funded by Singapore Office for Space Technology and Development (OSTIn) under the Space Technology Development Programme Grant (S21-19004-STDP).

References

A. Berk, et al. (2014). MODTRAN6: a major upgrade of the MODTRAN radiative transfer code. Proc. SPIE 9088, Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XX, 90880H.

I. E. Gordon, et al. (2022). The HITRAN2020 molecular spectroscopic database, Journal of Quantitative Spectroscopy and Radiative Transfer 277, 107949.

S.C. Liew, L. Tan, S. V. Salinas (2024). Inverse modeling for methane detection with hyperspectral satellite sensors, IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium, Athens, Greece, July 2024, pp. 347-350. DOI: 10.1109/IGARSS53475.2024.10640627.