Mapping ethylene plumes using satellite high-resolution imaging spectrometers that exploit the SWIR spectrum

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Ethylene (C_2H_4) is an important volatile organic compound that has a negative impact on human health, but space-based monitoring of plumes from this gas remains largely unexplored. Here, we demonstrate, for the first time, that ethylene point-source emissions can be detected and quantified using shortwave infrared (SWIR) imaging spectroscopy, overcoming the spatial limitations of existing thermal infrared observations. As a proof of concept, we apply a matched filter approach to EMIT data and retrieve two ethylene plumes from industrial facilities in Saudi Arabia and Iraq. The emission rate of the first source is consistent with IASI measurements, whereas the second reveals a previously unreported hotspot, highlighting the potential of SWIR imaging spectrometers for high-resolution monitoring of ethylene sources.

Introduction

Ethylene (C_2H_4) is a volatile organic compound that contributes to air pollution as a precursor of tropospheric ozone and formaldehyde, which ultimately has an impact on human health[1]. It is emitted into the atmosphere from biomass burning, urban activity, and industrial processes, and its production is expected to increase[2].

Franco et al.[3] used satellite-based thermal infrared (TIR) measurements from the IASI instrument[4] and identified over 300 ethylene anthropogenic hotspots. Most of these emissions originated from industry, primarily from the metallurgy, coal, and chemical sectors. Bottom-up emission inventories largely underestimate industrial emissions, and in some cases do not include them. These findings highlight the limitations of current inven-

tories and underscore the importance of space-based emission monitoring for supporting effective environmental policies. Even though IASI could identify and quantify all these hotspots, its coarse spatial resolution ($>$ 12 km) is not sufficient to attribute emissions to their corresponding point sources in large industrial hubs. Instruments with finer spatial resolution are required for this task.

While ethylene absorption lines in the TIR spectrum are available in public databases, measurements of its absorption in the shortwave infrared (SWIR) are only reported in the literature[5]. From Sharpe et al.[6], we obtained the ethylene cross section spectrum in the 1550–2500 nm spectral range. Figure 1 compares the absorption cross sections of ethylene and methane (CH_4), showing features of comparable magnitude. Several satellite imaging spectrometers currently cover this spectral region while providing relatively high spatial resolution. Among these is EMIT[7], which has a pixel size of 60 m. Since methane plumes can be detected with this instrument[8,9], the detection of ethylene plumes may also be feasible, potentially improving the attribution of emissions to individual point sources.

[Figure 1 about here.]

In this study, we combine the cross section spectrum from Sharpe et al.[6] with EMIT observations to assess the feasibility of detecting and quantifying ethylene point source emissions from space. To demonstrate this capability, we characterize two plumes originating from industrial areas in Iraq and Saudi Arabia.

Methods and materials

We acquired L1 data from the EMIT instrument, which are publicly available through the mission data portal. The matched filter method[10] was then applied to derive ethylene concentration-path-length enhancement (α) maps, expressed in ppm·m. These maps were subsequently used to identify and quantify point-source emissions.

Following Roger et al.,[11], multiple iterations and supervised radiance thresholding were added to the basic matched filter implementation. The unit gas absorption spectrum (K) required by this methodology was derived from high-resolution radiance spectra (0.1 nm). Optical depth spectra were first computed using the HITRAN 2024 line-by-line database[12] and the ARTS radiative transfer model[13], and subsequently converted into radiance spectra using libRadtran[14]. A sea-level surface elevation and a midlatitude summer atmospheric profile from the RFM model[15] were assumed. To account for ethylene absorption, the cross section spectrum from Sharpe et al.[6] was incorporated into the atmospheric optical depth generated by ARTS. Several radiance spectra were then simulated for different values of α. For simplicity, an infinite ethylene lifetime was assumed,

and the same α values used for ammonia (NH_3) in Roger et al.,[11] were adopted. The K spectrum was generated following Foote et al.,[16], already accounting for the convolution to the instrument spectral response function and the specific acquisition geometry. We used the 2000–2450 nm spectral range to characterize ethylene, as it contains the strongest absorption features of this gas. In addition, K spectra for CH_4, NH_3, CO_2, and H_2O were generated using the same setup as in Roger et al.[11], to enable assessment of potential ethylene false positives through comparison with retrievals of other gases.

Atmospheric ethylene concentrations were set to zero, as ambient concentrations are typically negligible[17]. Furthermore, ethylene emissions were assumed to be in the first 500 m above the surface within our reference atmosphere, where a pressure of P = 1 atm and a temperature of T = 294 K were assumed. However, the cross section spectrum from Sharpe et al.[6] was measured under conditions of P = 1 atm and T = 298.1 K. To assess the impact of this temperature difference, we performed a test using methane as a reference gas. Methane cross section spectra were generated with the HAPI tool[18] using P = 1 atm and temperatures of T = 294 K and T = 298.1 K. Following the procedure described above, the corresponding K spectra for the methane case were generated and compared, revealing no significant differences due to this difference in temperature. A similar behavior is therefore expected for ethylene, indicating that the resulting K spectrum is sufficiently accurate for the consistent detection and quantification of ethylene plumes.

Ethylene plumes are quantified using the IME method[19,20], which provides the emission rate (Q) in t h^{-1}. This methodology requires the effective wind speed (U_{eff}), an empirical parameter that relates Q to the mass and spatial extent of the plume. U_{eff} was obtained using a calibration approach similar to that of Guanter et al.,[21], based on the WRF-LES simulations presented by Gorroño et al.[22] and located in Zenodo[23]. This calibration was adapted to the molar mass of ethylene and to the EMIT instrument by considering the typical noise levels of ethylene retrievals. The lower and upper bounds of the noise range were derived from the same regions used by Roger et al.,[11] for NH_3, and the same emission-rate range was adopted. The resulting calibration is $U_{eff} = 0.48 \cdot U_{10} + 0.59$, where U_{10} is the wind speed at 10 m above the surface, obtained from the GEOS-FP product[24]. Note that emission rate uncertainty is calculated as in Roger et al.,[25].

Results and discussion

In Figure 2, we show ethylene plumes originating from two different sources. One of these emissions (left panel) is located in Yanbu, Saudi Arabia, and is associated with a single source. This source is part of an ethylene hotspot identified by Franco et al.,[3] as a large petrochemical hub. The higher spatial resolution of EMIT allows us to better constrain the potential emission sources to a much smaller area within the petrochemical complex. An analysis of high-resolution RGB imagery from Google Earth suggests that the plume

originates from a flare stack. We estimated an emission rate of Q = 3.2 $\pm$ 0.9 t h^{-1}, which agrees with the one deduced from IASI with Q = 0.72 (0.36–4.28) t h^{-1}. A second plume was detected over another petrochemical complex in Iraq (right panel). This plume also appears to originate from a flare stack, and an emission rate of Q = 3.7 $\pm$ 1.3 t h^{-1} was estimated. This region was not previously identified as an ethylene hotspot by Franco et al.,[3]. Possible explanations include differences in acquisition dates between the IASI observations and our measurements. The study of Franco et al.,[3] covered the period from 2008 to 2020, whereas the plume detected over Iraq was observed in 2023. Changes in industrial activity may therefore have occurred during this period.

[Figure 2 about here.]

Additional visual inspection of the CH_4, CO_2, NH_3, and H_2O retrievals was carried out to assess whether the ethylene plumes shown in Figure 2 could be false positives. Part of this assessment is illustrated in Figure 3, where the ethylene retrieval is compared to that of methane. Note that the analyzed sources are marked with red dots. We observe no correlation with other gases, which increases confidence in the ethylene plumes.

[Figure 3 about here.]

Imaging spectrometers with characteristics similar to those used in this study, including the AVIRIS family[26], EnMAP[27], PRISMA[28], GF-5 AHSI[29], and Tanager-1[30], are promising candidates for ethylene plume detection. Upcoming missions such as CHIME[31], as well as future Carbon Mapper instruments, are also expected to provide valuable capabilities for the detection and quantification of ethylene emissions.

Data and code availability

- Code for retrievals, plume delineation, and quantification is available at `https://github.com/jarojuan96/HS_tool`. The repository also contains lookup tables of radiance spectra for ethylene, CH_4, CO_2, NH_3, and H_2O. Additional updates related to ethylene retrievals have been implemented for this study relative to Roger et al.[11].

- L1 data from EMIT are open to the public and is available through the Earthdata Search portal:
`https://www.earthdata.nasa.gov/data/catalog/lpcloud-emitl1brad-001`

Acknowledgements

This research is partly funded by the Spanish Ministry of Science, Innovation and Universities (Grant PID2023-148485OB-C21/C22 funded by MCIU/AEI/10.13039/501100011033 ERDF, EU).

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Competing interests: The authors declare no competing interests.

List of Figures

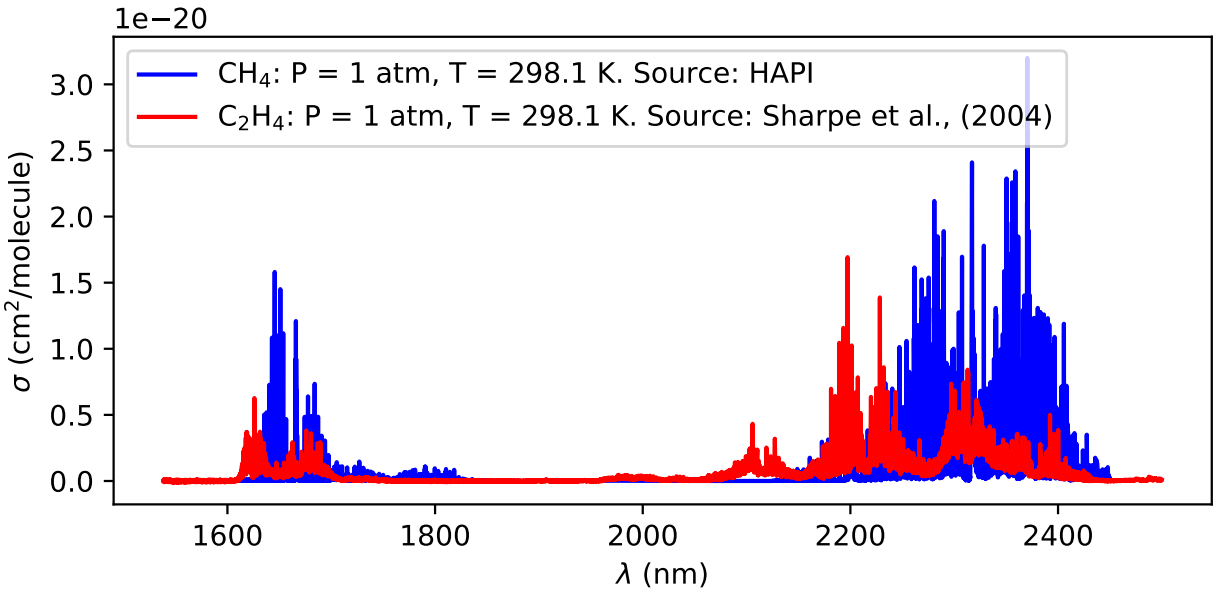

Figure 1: Cross section spectra of methane (blue) and ethylene (red) at P = 1 atm and T = 298.1 K.

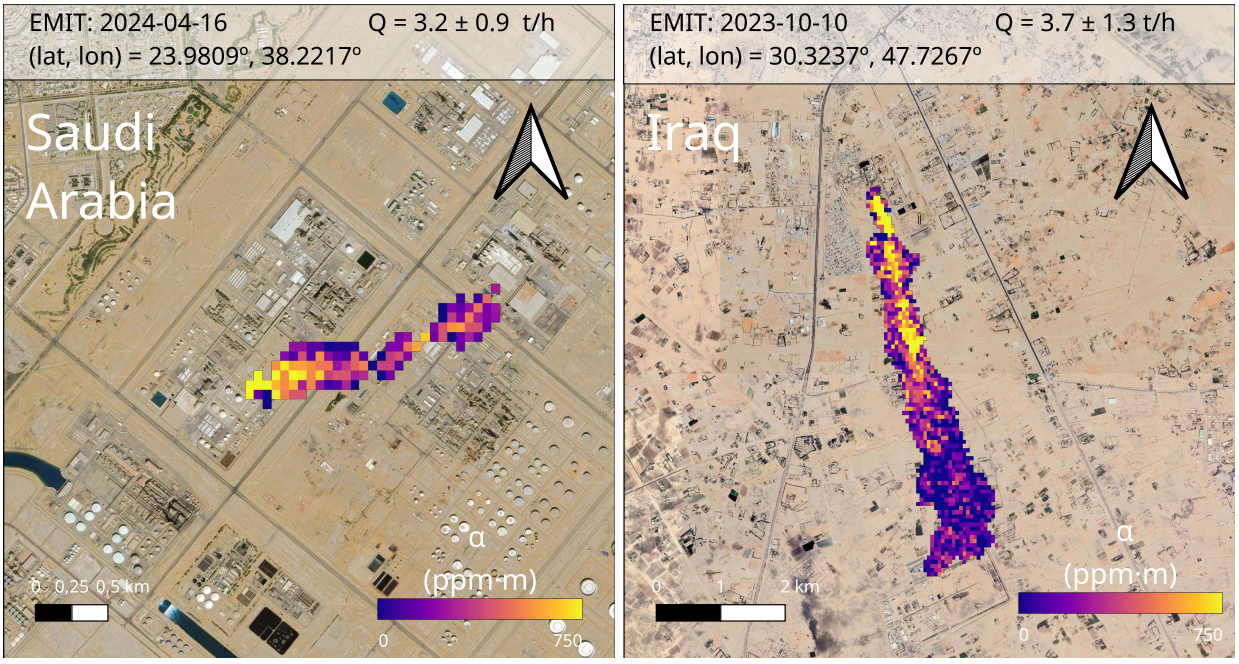

Figure 2: Examples of two ethylene plumes overlaid on high-resolution Google Earth images (© Google Earth; data provider: Airbus). From left to right, we find a plume in Saudi Arabia and another one in Iraq. Both plumes were characterized using EMIT data and were originated from industrial sources. Details of the ethylene concentration-path length enhancement levels, acquisition date, source coordinates, and emission quantification can be found for each plume.

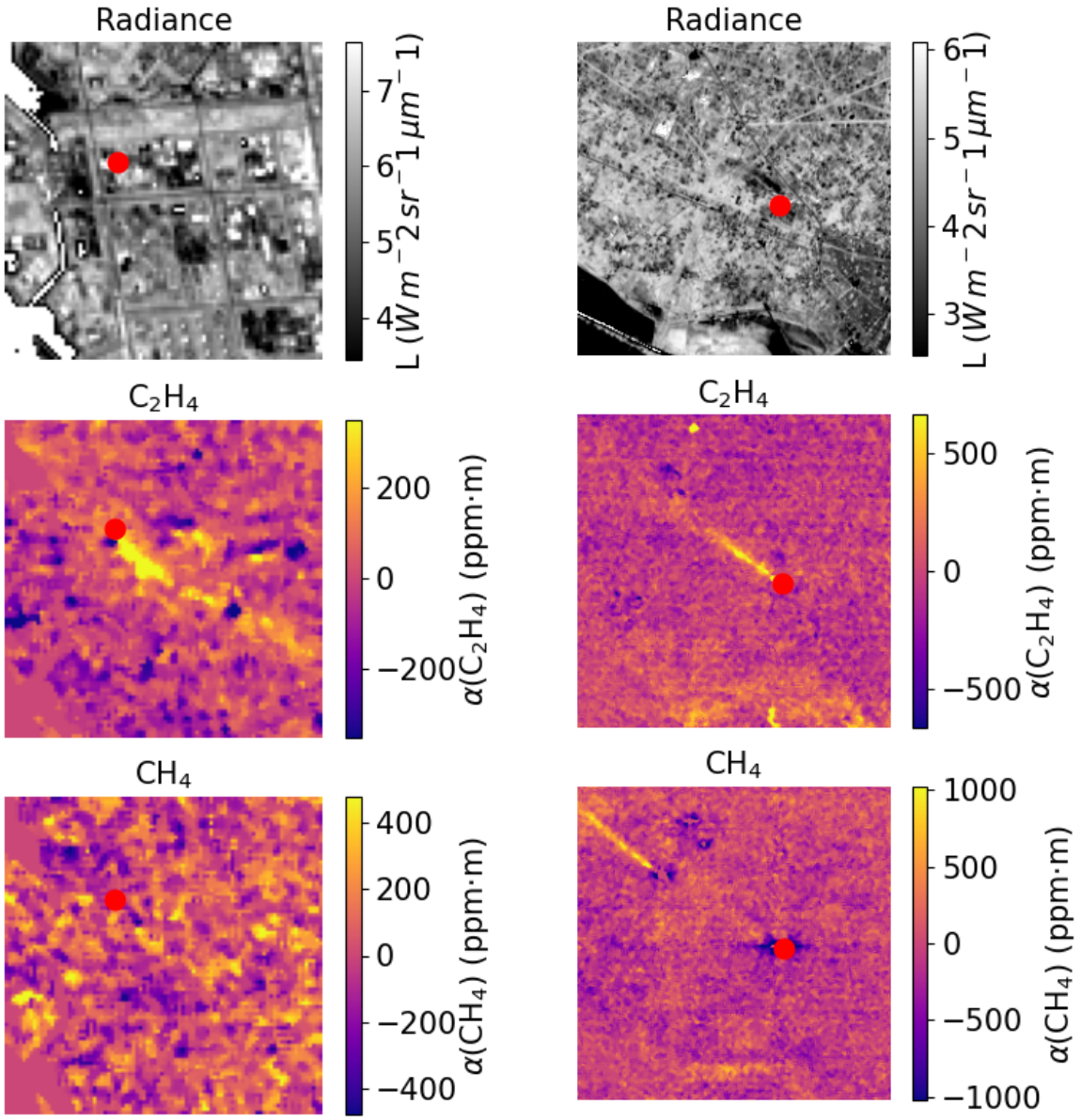

Figure 3: Analysis of potential ethylene emission correlation with other gas retrievals for the Saudi Arabia (top) and Iraq (bottom) plumes. Starting from the top: radiance reference band, ethylene, and CH_4 retrievals. The ethylene source is marked with a red dot in all the panels. Note that the plume orientation differs from that shown in Figure 2, where the retrievals are georeferenced.