

Referee/Reviewer #1

We would like to thank the anonymous referee #1 for the careful reading and valuable comments, which we address point-by-point.

In the following, the reviewer comments are in *italics*, the answers in plain text and the proposed changes / new text in [blue](#). References to Sections or Figures in our answers refer to the discussion version of the manuscript.

The manuscript by Krautwurst et al. deals with an airborne campaign to characterise methane emissions from two landfills close to the Madrid city. The MAMAP2DL and CHARM-F instruments (pushbroom imaging spectrometer and active lidar, resp.) were flown over the landfills to derive maps of methane column concentrations, which were used to estimate emission rates.

The manuscript is very well written and presented, the methods are sound, and the results are very solid. On the downside, perhaps the level of novelty is not great, given that the high methane emissions from those landfills are well known, and the two instruments and the corresponding processing methods are already described in a number of peer-reviewed publications. For example, I miss some synergistic application of the two instruments.

Having said that, I recommend publication of this manuscript in ACP because of the growing interest in the development of methods for the monitoring of methane emissions and of the great technical quality of the study.

Thank you for the encouraging words. We note that there is only one peer-reviewed publication about the Madrid waste treatment areas' emissions of methane covering the period 2018 to 2020 [Tu et al., 2022]. With the data presented in our paper using different sensors at a different time (summer 2022), the magnitude of the emissions is emphasized once again and indicates consistently high values. Furthermore, as stated in our comment to Line 43 of Referee#2, the CH₄ emissions of the Pinto landfill should have dropped by a factor of almost 40 from 2021 to 2022 according to the reporting.

We agree with the reviewer that both measurement principles and processing methods are well established in the community and have extensively been used in the past to quantify greenhouse gas emissions. However, to our knowledge, this is the first study which combines active and passive remote sensing observations for methane emission quantification. We emphasize that the analysis of the measurements was made independently and that 'only' the final products such as CH₄ concentration anomalies or the emissions of methane are used in further comparisons and analysis. We contend that having two independently characterized simultaneous methane emission data products is the optimal synergetic approach.

Nevertheless, for future work, it may be worthwhile to combine information collected by active and passive instruments already on a CH₄ column retrieval level. However, the focus of this study was to quantify the emissions of the two landfills and to assess whether they are as high as previously indicated by satellite (and ground-based) observations.

#####

Specific comments:

Below I am listing a number of minor points to be addressed at the authors' discretion.

P1, L18: the definition of the ERF is probably not needed

Agreed. The sentence has been amended accordingly.

It has an effective radiative forcing of $\sim 0.54 \text{ W m}^{-1}$ or one quarter of that of CO₂ (Forster et al., 2021).

#####

P2, L28: "is produced"?

Agreed and amended accordingly.

#####

P3, L56-57: thermal imagers can also be "passive remote sensing imaging instruments"

Agreed and amended accordingly.

Recently, passive remote sensing imaging instruments exploiting solar electromagnetic radiation in the near and short wave infrared have been deployed.

#####

P4, L115: "The non-operating ..." verb missing?

Agreed and amended accordingly.

Additionally, it contains landfill sites such as the non-operating Valdemingómez landfill...

#####

P5, Fig 1 caption: "Spain" → "Iberian Peninsula"

Agreed and amended accordingly.

#####

P7, Fig 2 caption (and elsewhere): I had never heard the term "ground scene size". I think is referring to "ground sampling distance" or "pixel size"?

We would refrain from using the term "pixel size", as this can sometimes be confusing when also talking about the sensor (chip) or FPA (Focal Plane Array) itself, which in our case has 384 x 288 pixels with a specific size in the μm range. The term "ground scene size" has a long legacy (e.g. in Afe et al., 2004, or Gerilowski et al., 2011) and is also used by other groups and in related fields (e.g., Lin et al, 2018,

or Ren et al., 2022). In our case, it expresses the size of the two dimensions of an observation through the atmosphere at the ground, which are defined by the used optical fibers of the optical fiber bundle within the instrument, the exposure time, and an additional co-adding of observations along the flight direction.

#####

P13, Eq. 4: please consider to use shorter variable names / subscripts for the emission rates F

Thank you for bringing this up. In fact, there were also long internal discussions on the subject among co-authors, going back and forth between even longer subscripts or just one letter subscripts. We have opted for an intermediate solution to allow the reader to better understand the meaning of the different emission rates F without having to search for them in the text or in the separate table.

#####

P15, L374: the “different opening angles of the two instruments” are provided as the main reason for the difference in the flux estimates by the two instruments. Can we expect that factor to be more important than potential differences in the column concentration retrievals (there are some in Fig. 6), and the different atmospheric paths sampled by the two instruments?

The different viewing geometries or opening angles of the instruments result in observations of different but overlapping air masses below the aircraft. This can, however, only partly explain the observed difference in the column, for example if an air mass has highly varying methane column amounts over short distances, as indicated in the manuscript. Differences also arise from different atmospheric light paths. For the passive remote sensing MAMAP2DL measurement, the sun first passes through the entire atmosphere at a given angle before being reflected from the ground towards the aircraft. In comparison, light from the CHARM-F lidar is emitted from the instrument itself on board the aircraft, being reflected and scattered at the ground before passing through the atmosphere and being collected again at the aircraft. Furthermore, differences could also originate from the different column retrievals, e.g., how they deal with variable surface reflectivity etc. However, the extent to which each factor contributes would require a dedicated study.

We have slightly expanded the paragraph in the main text accordingly.

These differences may be due to (a) different but overlapping opening angles of the two instruments and the resultant spatial resolution of the ground scene widths of 110 m and 10 m, respectively, or (b) different paths through the atmosphere of the electromagnetic radiation used to measure methane absorption, or (c) differences in the algorithms used to retrieve the columns, e.g. how they deal with variable surface reflectivity etc.

#####

P23, L533: *I don't think that is true. For example, Frankenberg et al. mapped methane missions with the AVIRIS-NG (optical) and HyTES (thermal) imaging spectrometers*
<https://doi.org/10.1073/pnas.1605617113>

Thanks for pointing that out. While writing this paragraph, we were addressing only the two different remote sensing techniques, “active” and “passive”, and not two different passive remote sensing instruments. We have amended the sentence accordingly.

This was the first time that emissions were observed and quantified simultaneously by two different and independent active and passive remote sensing techniques.

#####

P24, L562: “influence”

Agreed and amended accordingly.

#####

References:

Afe, O. T., A. Richter, B. Sierk, F. Wittrock, and J. P. Burrows: BrO emission from volcanoes: A survey using GOME and SCIAMACHY measurements, *Geophys. Res. Lett.*, 31, L24113, doi:[10.1029/2004GL020994](https://doi.org/10.1029/2004GL020994), 2004.

Lin, C., Tang, S., Zhang, L., and Guo, P.: Focusing High-Resolution Airborne SAR with Topography Variations Using an Extended BPA Based on a Time/Frequency Rotation Principle. *Remote Sensing*, 10(8), 1275, <https://doi.org/10.3390/rs10081275>, 2018.

Ren, Y., Tang, S., Dong, Q., Sun, G., Guo, P., Jiang, C., Han, J., and Zhang, L.: An Improved Spatially Variant MOCO Approach Based on an MDA for High-Resolution UAV SAR Imaging with Large Measurement Errors. *Remote Sensing*, 14(11), 2670, <https://doi.org/10.3390/rs14112670>, 2022.

Tu, Q., Hase, F., Schneider, M., García, O., Blumenstock, T., Borsdorff, T., Frey, M., Khosrawi, F., Lorente, A., Alberti, C., Bustos, J. J., Butz, A., Carreño, V., Cuevas, E., Curcoll, R., Diekmann, C. J., Dubravica, D., Ertl, B., Estruch, C., León-Luis, S. F., Marrero, C., Morgui, J.-A., Ramos, R., Scharun, C., Schneider, C., Sepúlveda, E., Toldano, C., and Torres, C.: Quantification of CH₄ emissions from waste disposal sites near the city of Madrid using ground- and space-based observations of COCCON, IASI, Atmospheric Chemistry and Physics, 22, 295–317, <https://doi.org/10.5194/acp-22-295-2022>, 2022.

Referee/Reviewer #2

We would like to thank the anonymous referee #2 for the careful reading and valuable comments, which we address point-by-point.

In the following, the reviewer comments are in *italics*, the answers in plain text and the proposed changes / new text in **blue**. References to Sections or Figures in our answers refer to the discussion version of the manuscript.

This manuscript by Krautwurst et al. (2024) shows the first use of both active lidar and passive remote sensing on aircraft to estimate landfill methane in Madrid with verification using in situ instruments. The manuscript is generally well written and thoroughly explains the instrumentation and methodologies used. The described research reflects important work to compare instrument capabilities, especially for complex emission sources like landfills. There is growing interest in tracking emissions reductions, and the work by Krautwurst et al. will be valuable for establishing the methodologies available for accurate quantification of methane emissions.

The manuscript currently provides thorough description of instruments, retrievals, and flux estimates, and I recommend publication. The main recommended revision is to add some discussion of how sources on the landfill were identified. Currently, there is little discussion of how sources at the facility were geolocated and attributed and the uncertainties in these methodologies. As the identification of the sources at the landfill is a major conclusion, there needs to be some additional text added to the body of the manuscript explaining how this was done. Detailed comments:

See our answers to the comments below.

#####

Line 34: Is this EU number for landfills? Solid waste? Or total waste sector? And can the actual reported number be added in addition to the relative 24% (as this would allow comparison to other regions of the world)?

The 24% are representative of the total waste sector (IPCC category: 5). Solid waste disposal (IPCC category: 5A) would account for 18 %.

We have amended the sentence as follows:

... reported CH₄ emissions from waste (IPCC sector 5) are 97 Mt CO_{2,eq} yr⁻¹ (or 3.5 Mt yr⁻¹)¹ and still account for ~ 24 % (or ~ 18 % if only solid waste disposal, IPCC sector 5A, is considered) of the anthropogenic CH₄ emissions in the European Union in 2022 (EEA, 2024).

¹Converting CO_{2,eq} to CH₄ by using a factor of 28.

#####

Line 43: If not specified later in the manuscript, it would be helpful to know if the Madrid facilities, specifically, use IPCC-type methods.

We agree that some additional information on the landfill reporting may be useful. For example, the literature review revealed that the Pinto landfill changed its reporting methodology from 2021 to 2022, which may have been the reason for the almost 40-fold decrease in reported emissions over the same period.

We have added the information in Sect. 2.1.2, where the targets are described in more detail and with additional context in Sect. 4, where reporting in recent years is discussed.

According to the Spanish PRTR (Spanish-PRTR, 2025c), the combined annual reported 2022 CH₄ emissions for the two facilities "VERTRESA-URBASER, S.A. UTE (UTE LAS DEHESAS)"³ and "DEPOSITO CONTROLADO DE RESIDUOS URBANOS DE PINTO"⁴ are 0.2 t h⁻¹. Both sites are classified as "landfills" according to the European-Parliament (2006, Regulation (EC) 166/2006 E-PRTR, Annex I). We assume that these reported values are representative for the two investigated areas, which include landfills and waste treatment plants, as other listed sources would not contribute significantly to the emissions according to the Spanish PRTR (Spanish-PRTR, 2025c). According to the European-Commission (2006), both landfills appear not to use strict IPCC reporting methods. They report the methods 'OTH' (for other measurement or calculation methodology) and 'C' (for calculation) using 'issue factors', and 'CRM' (for measurement methodology by means of certified reference materials) and 'M' (for measurement) using 'electrochemical cells' for the Las Dehesas and Pinto landfills, respectively, in 2022. In addition, the reporting method for the Pinto landfill changed from 2021 to 2022, while 'OTH' and 'C' using 'an American EPA (Environmental Protection Agency) calculation model' was applied in 2021 instead of CRM as in 2022.

³E-PRTRSectorCode / Name: 5 / Waste and wastewater managements, mainActivityCode: 5.(d), landfills, EU-Registry Code: 003510000, PRTR Code: 3510 (Spanish-PRTR, 2025a).

⁴E-PRTRSectorCode / Name: 5/Waste and wastewater managements, mainActivityCode: 5.(d), landfills, EU-Registry Code: 001636000, PRTR Code: 1636 (Spanish-PRTR, 2025b).

Interestingly, the reported emissions of the Pinto landfill site decreased by a factor of almost 40 from 2021 to 2022, which could potentially be related to the change in reporting methodology (see Sect. 2.1.1).

#####

Line 63: Some discussion of the value of active remote sensing in comparison to passive remote sensing would be valuable.

Thank you for raising this important point. We have amended the paragraph from line 63 as follows:

Active remote sensing instruments are independent of sunlight because they use a laser as their own source of electromagnetic radiation. In contrast to airborne and satellite-borne passive instruments, they can measure during day and night, across all seasons and latitudes. They provide ranging capabilities resulting from the precise

measurement of the propagation time of the emitted light and, due to their narrow field of view, measure between clouds. IPDA (integrated-path differential absorption) lidars potentially provide highly accurate measurements without varying biases: the exceptions are those introduced by small differences in the scattering and reflectivity of the ground scene and any inaccuracies in the knowledge of the absorption cross-sections.

#####

Section 2.1.1: This description of CoMet 2.0 Arctic seems unrelated to the manuscript focus.

We agree and have deleted the paragraph as the information on the used instrumentation used is given later in Section 2 (and was partly outlined earlier). However, the information on the HALO aircraft has been moved to Section 2.1.

Below we describe the waste treatment facilities that were the targets of the research flights, and the flight strategy used to derive their methane emission rates. We then describe the instruments used, which were installed aboard the German research aircraft HALO (High Altitude and Long Range Research Aircraft, operated by the DLR, Deutsches Zentrum für Luft- und Raumfahrt, type: Gulfstream G550). The retrieval algorithms used to derive the CH₄ columns are explained next. This is followed by a description of the observed CH₄ columns. Finally, we derive the methane fluxes, i.e. the methane emission rates, using the plume cross-sections.

#####

Figure 1: A color key in the figure would be helpful.

It has been added.

#####

Line 121: Adding waste-in-place metrics for the 2 landfills and adding activity per year rates for both landfills (in the same units) would contextualize the landfills better.

We are not sure what the referee exactly means by “activity per year rates”. We assume that he is referring to the waste dumped over a certain period. We added these values for the VTP (and the Las Dehesas landfill) and the Pinto landfill site. We could, however, not find information or data on waste-in-place or the mass of waste material deposited.

The latter [VTP] is a waste treatment complex that accepts around 1,222 kt (Madrid, 2022) of waste, of which around 140 kt were deposited at the Las Dehesas landfill site in 2022 (Spanish-PRTR, 2025a), ...

It [Pinto] opened in 1987, is still operational with around 53 kt of waste being dumped in 2022 (Spanish-PRTR, 2025b), ...

#####

Line 125: Clarify if, for readers unfamiliar with EPRTTR, there is potential for the facility reported numbers to be missing methane sources. For example, are some sources not reported due to regulatory limitations, or should we expect the reported number to be comparable to measurements?

Very good point. For CH₄ emissions from landfills, operators have to report their emissions if they emit more than 100 tCH₄/year or receive more than 10 t/d or have a capacity of more than 25 kt [European Parliament, 2006]. Other source types also have specific thresholds or reporting requirements, which can be found in European Parliament [2006]. As a result, potential CH₄ sources, e.g., emitting smaller amounts of CH₄ than specified in the Regulation, are not covered by reporting. Just for clarification, the sentence in line 125 refers to additional sources over the Pinto landfill or the VTP (such as waste treatment plants or biogas plants), not over the entire measurement area. Outside the coloured areas (Fig. 1), there are some additional CH₄ sources according to the Spanish PRTR that we could interfere with our observed plume [Spanish-PRTR, 2025], but their emissions are too small to contribute significantly to the calculated emission rate, if they emit CH₄ at all. Furthermore, our data does not indicate a significant contribution from these potential sources either, or any other sources unknown to PRTR, except for the northeastern most signal discussed in Sect. 3.4.2.

The question as to whether we would expect the measurements to give similar emission rates to those reported is tricky. If the regulations and therefore the reporting are correct, we would expect similar values. However, as we know, reporting, especially when based on bottom-up methods, can yield uncertain estimates. However, in this case, we expected higher values than reported based on the ESA web story released the year before.

We have added the reporting regulations to the introduction, where we introduce the (E-)PRTR (Line 43):

Landfill facility emissions must be reported to the authorities (E-PRTR) in the European Union to comply with the objectives of EU directives if they meet certain criteria, such as emitting more than 100 kt CH₄ yr⁻¹ or receiving more than 10 t d⁻¹ or having a total capacity of more than 25 kt (European-Parliament, 2006).

#####

Line 132: Further information on winds would be valuable in this section. For example, visuals showing the wind speeds and directions over time and space for the study area (can be added to Appendix rather than body of text). Some discussion of topography may also be valuable. For example, is it possible that the second landfill location is a topographic low and the methane from upwind is just pooling there?

We agree and have added a reference in line 132 to the temporally and vertically resolved winds in the measurement area shown in Fig. D2 in Appendix D. The topography in this area shows some variability. Based on SRTM, the surface elevation along the entire flight path over Madrid is around 500 to 1000 m a.s.l. with a mean of around 670 m a.s.l. and a 1-sigma standard deviation of 80 m. Based on Google Earth topography, the highest elevation areas are tentatively located at the eastern and western locations of the flight pattern and have no direct influence on the

plume. The surface elevation around the landfills and the observed plume signal is much less variable, ranging between 550 and 700 m a.s.l. Between the Pinto landfill and the VTP, there is a small valley (about 70 m lower than the surroundings) with a steep increase at the start of the VTP and then remaining relatively stable between 600 and 650 m a.s.l. until the position of the northernmost leg. The most likely location for methane accumulation, if any, would be upwind of the VTP, but there is no evidence for this in our measurements. It is likely that the high solar insolation has already transported the main plume to higher altitudes.

We have added some context concerning the topographical situation around the landfills to the manuscript in Sect. 2.1.2 and a statement on the pooling in Sect. 3.3.

... (Fig. D2 in the Appendix D1 shows time-resolved wind profiles for the time measured in the measurement area).

The topography around these landfill sites shows some variability, ranging from about 550 to 700 m a.g.l. with a small valley between the two sites and a steep rise just south of the VTP, according to Google Earth.

Furthermore, the retrieved column anomalies in Fig. 5 as well as the cross-sectional fluxes in Fig. 7 show no sign of accumulation of CH₄ as, for example, in the valley between the two landfills (see Sect. 2.1.1 for a brief discussion of the local topography).

#####

Line 297: It's unclear what the authors are defining as a "plume" versus "enhancement" and how this relates to the differentiation between "flux" and "emission rate".

In general, we retrieve from the measured spectra the CH₄ column anomalies relative to the local background. These may be positive or negative. Positive anomalies or deviations are called "enhancements". If these enhancements (visible in multiple ground scenes) are caused by a CH₄ source, are connected and have a plume-like shape, they are also called a "plume". Such plumes are always CH₄ enhancements, but a CH₄ enhancement does not have to be a plume. In Eq. 1, we then integrate over contiguous CH₄ enhancements or "plumes", along a straight line (i.e. a cross-section) to calculate the mass flow rate of CH₄ molecules or the flux through this cross-section. If this flux can be associated with a source, we refer to it as the methane emission rate of that source (see also line 291ff).

We went through the document and unified the terminology where appropriate.

#####

Figure 5: It would be helpful to separate 5a-b from 5c-d and provide more explanation of what 5c-d is meant to show. Keys for the color outlines are needed. Were the 5c-d enhancements the highest enhancements of all observed methane, or just those above the landfills? Why do the shapes of enhancement regions vary and how were they delineated? This comment relates to the above comment about providing more details on how source locations were identified on the landfills.

We are not quite sure why 5a-b should be separated from 5c-d. 5c actually belongs to 5a (as does 5b) – all subplots show MAMAP2DL observations, in one form or another. You could separate 5d (showing CHARM-F observations) from 5a-c, but then you would lose the direct comparison between the MAMAP2DL and CHARM-F columns. Presumably, the reviewer is referring to 5b-c when talking about the isolated enhancements.

The shown enhancements are the highest for all observations, i.e., not limited to landfills. There are no enhancements larger than ~8% downwind of the Pinto landfill and no enhancements larger than 4% downwind of the VTP.

The basic assumption for the source identification based on the observed column enhancements is that just above or very close to a potential source, the CH₄ is most concentrated as it has not yet dispersed (horizontally), leading to the highest observed column anomalies. Of course, by chance, high column concentrations could also be observed elsewhere because of turbulent transport, but if the highest column anomalies during multiple overflights point to the same region, there is a high probability that this region is acting as a source. In addition, the observed column enhancement is also modulated by the actual wind speed at which the CH₄ is released into the atmosphere, leading to smaller CH₄ columns (also at the source) for higher wind speeds, and by the strength of local turbulence.

The colour of the outlines is less important and should only show that the observations belong to different legs (i.e., the yellow one belongs to the flight leg in wind direction actually not shown in Fig. 5 but in the Appendix in Fig. A1, a).

With respect to the question “... shapes of enhancements vary”: As mentioned above, the different colour contours indicate different legs, which were acquired during different overflights at different times. In reality, two different observations of an emission plume will never give the same concentration measurements or the same plume shape due to turbulence, which is spatially and temporally variable. Therefore, even for an idealised emission source (with constant emissions, which may not need to be the case for the landfills studied), the plume (location, shape, enhancements) will change from overflight to overflight. In addition, the position of the emission may also vary with the activity across the landfill.

Regarding the question “... delineated”: MAMAP2DL provides approx. square ground scene sizes. In Fig. 5b-c only those ground scenes are shown that are above a certain threshold as defined in the caption.

We have amended Sect. 3.1 and the caption of Fig. 5 accordingly.

They were selected by analysing the flight legs (those flown perpendicular to the wind direction as well as those flown in wind direction) over the landfills to find the ground scenes with the highest column enhancements (only ground scenes above a certain threshold are shown, see Fig. 5 for more details). The assumption is that the CH₄ is most concentrated just above or very close to a source, as it is not yet dispersed (horizontally), leading to the highest observed column enhancements. However, there is a residual uncertainty associated with this method, as by chance, high column enhancements could also be observed further away due to turbulent transport. Columns are also modulated by the prevailing wind speed at the time of release into the atmosphere

and by local atmospheric turbulence. Both can change during a measurement flight. However, if the highest column anomalies during multiple overflights point to the same region, there is a high probability that this region is acting as a source.

The CH₄ plumes clearly begin over these areas of the Pinto and Las Dehesas landfills (see Figs. 5 and A1 and discussion on the step-wise increase of the fluxes in Sect. 3.3). However, we cannot exclude that other parts, closed cells of the landfills or facilities located in these waste treatment areas, also contribute (weakly) to the observed CH₄ plume, but are partly masked by CH₄ released further upwind. For example, in the north western part of the VTP, there are also hot spots identified (two ground scenes outlined in yellow in Fig. 5, b) from the along wind leg (Fig. A1, a), which could be advected there or released from the waste treatment plants (PLANT OF BIOMEIZATION La Paloma and Las Dehesa) immediately to the south. However, as a second overflight (Fig. A1, b) shows no enhancements, it is probably the former.

#####

Line 354-357: These two sentences are confusing and contradictory. The authors point out a source but then say it may not be that source and could be any part of the landfill. Is this due some aspect of method uncertainty (e.g., geolocation of source, wind direction, identification of enhanced pixels)?

This is a good and important point. To unambiguously identify sources over landfills, one would need ground scene sizes in the sub-metre range. Based on the plume shape alone (assuming at least some wind to have a reasonable transport of CH₄ away from the source in one direction), the source of the emissions could usually be identified. For MAMAP2DL, the ground scene size is about 110 m, and the accuracy of the orthorectification has also been estimated to be about one ground scene size (see Sect. B4) limiting the exact geolocation capabilities. For the Pinto landfill in the south, the start of the plume, and therefore at least 'one source', is in the south-eastern part of this landfill, as shown in Figs. 5a and A1 a, b. This is also supported by the already available argumentation in Sect. 3.3, line 381ff, discussing the step-wise increase in fluxes over the landfills. However, it cannot be excluded that other parts of the landfill are also emitting CH₄, which would then be covered/masked by the previously emitted CH₄. The same reasoning applies to areas outside the landfill, but is much less likely if no potential sources on the ground can be identified. Analysing the CH₄ column anomalies at the VTP (Fig. A1), there is again a plume starting in the south-eastern part, which corresponds to the highest observed enhancements (yellow outlined ground scenes in Fig. 5, b) and is over the active landfill. However, there is also a cloud of enhanced CH₄ over the north-western part with smaller enhancements. This cloud could have been advected from the active landfill part, but could have also originated at this location from the waste treatment plants located there.

Overall, there is strong evidence that the active parts of the landfills contribute significantly to the observed emissions, but it can neither be confirmed nor refuted that there are also contributions from other parts of the waste treatment areas. See also the comment to Fig. 5 above for more detailed adaptations in the manuscript.

#####

Figure 7: The flux estimates above the Pinto landfill seem to show that the passive remote sensing is seeing a combination of background and enhancement from landfill whereas active lidar is only seeing the enhancement. Is this the influence of the narrower instrument view? Some discussion on the potential interpretation difficulties if the active lidar "misses" the enhancement when there are steep gradients (and/or need for tight flight patterns to avoid this) would be valuable.

We thank the reviewer for highlighting this important aspect. We agree, and indeed this point has been discussed in the literature in the context of both methane and carbon dioxide emission quantification (e.g., Krautwurst et al., 2021; Wolff et al., 2021). In particular, Wolff et al. (2021) showed that under turbulent atmospheric conditions, the spatial distribution of enhanced concentrations within a plume can be highly heterogeneous. As a result, individual overflights may intersect either strongly enhanced or only weakly enhanced sections, depending on the local variability. This can lead to significant differences in the retrieved fluxes/emission rates despite constant emissions, unless results are averaged over multiple plume crossings.

To address this potential limitation, we have added a brief discussion to the Introduction section of the revised manuscript.

However, Wolff et al. (2021) showed that under turbulent conditions, the spatial distribution of enhanced concentrations within an exhaust plume may be highly heterogeneous. As a result, a single overflight may sample sections with stronger or weaker enhancements purely as a result of the local variability. In some cases, the true emission signal only emerges after averaging over a high number of overflights.

To account for this potential limitation, in the analysis, we combine active lidar with passive imaging spectrometry, both designed to capture atmospheric CH₄ column gradients. Thus, we obtain both high-precision transects and spatial context, which supports a more robust interpretation of the observed CH₄ column enhancements. Moreover, these remote sensing measurements are complemented by auxiliary in situ measurements of CH₄, CO₂ and 3D winds in support of the remote sensing data.

There, we now explicitly state that one motivation for the synergistic deployment of active lidar and passive imaging spectrometry in our campaign is to overcome the interpretation challenges arising from plumes having spatial inhomogeneities. The combination enables the analysis to benefit from the high-precision transects of the lidar while using the wide swath of the imaging spectrometer to provide spatial context and thereby support a more robust interpretation of the observed CH₄ column enhancements.

As the reviewer also correctly notes, the narrower field of view of CHARM-F limits its spatial sampling. Specifically, CHARM-F measures a single ground scene approximately in the middle of the MAMAP2DL swath, which itself consists of 28 cross-track ground scenes. In the case of the Pinto landfill observations discussed in Figure 7, this difference is further influenced by the flight pattern: the flight legs were deliberately designed so that, during the first leg (blue), CHARM-F sampled upwind of the landfill to assess potential background conditions, while MAMAP2DL already partially covered the source area. Conversely, the second leg (green) directly overflew the Pinto landfill

with CHARM-F, while the MAMAP2DL swath still included parts of the upwind background. This difference in spatial coverage is now briefly discussed in the manuscript (line 393). Specifically, we added the following text about Fig. 7:

The first two flight legs were deliberately designed so that, in the blue leg, CHARM-F sampled background conditions upwind of the Pinto landfill, while MAMAP2DL already partially covered the source area. Conversely, during the green leg, CHARM-F measured directly over the Pinto landfill, whereas the MAMAP2DL swath still included parts of the upwind background.

#####

Section 3.4.2: Would it not be possible for the other methane sources in the region to be significantly contributing but not be individually detectable? For example, the enhancement from a single smaller source may not be detectable over that source but as multiple of these sources emit in your domain, could their combined methane lead to detectable enhancements downwind if the winds are stable? It would be valuable to provide some metrics (e.g., emission rate) of the expected potential contribution of the other methane sources in the domain.

We agree with the reviewer that weak sources, if present in very large numbers, can contribute to the observed emission rate. However, to contribute significantly to the calculated emission rate, the sources would have to be within the range of observed CH₄ enhancements and not outside in the background area. We have attempted to estimate these (additional) emissions by analysing the CH₄ emissions reported in EDGAR v8.0 (Crippa et al., 2023) over the entire area covered by our measurement flight, by aggregating all the emissions reported in EDGAR in that area. Figure 1 shows the CH₄ emissions according to EDGAR in the area, where our meas-

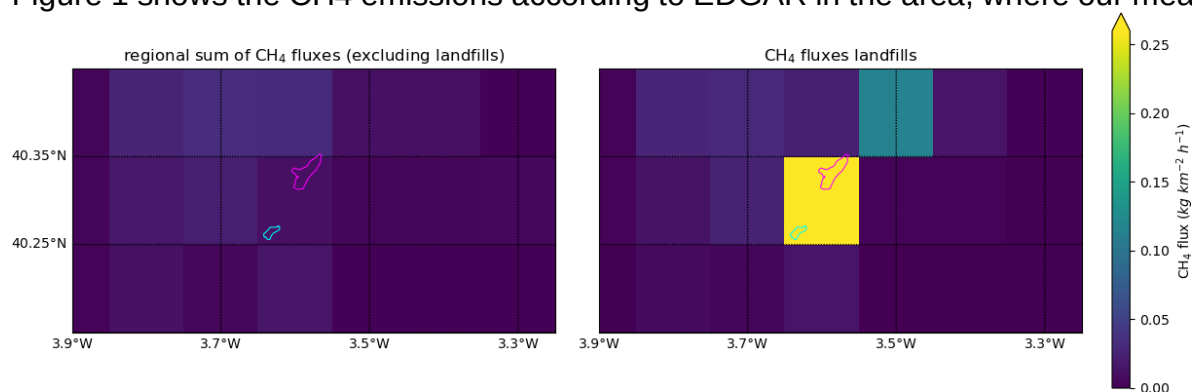


Figure 1: The coloured contours show the position of the Pinto (south) and VTP (north) waste treatment areas. Left: Excluding landfills yielding emissions of ~2 t/h. Right: All CH₄ emissions yielding ~6 t/h.

urements were acquired. All categories are shown except for the 'solid waste landfills' (4A, 4B) sectors, as this is the one we are targeting in our analysis. The sum of the emissions is about 2 t/h (left) or about 15% of our total estimated emission rate. If these emissions are located within our plume region, they would add to the landfill emissions, but if they were only in the background region, they would actually reduce the landfill emissions, as a higher background would then be removed from the landfill plume

signal. Alternatively, if they were evenly distributed between the plume and the background area, then they would have a negligible effect. Please also read the comment above to “Line 125” and the additional sources mentioned according to the Spanish PRTR.

We have amended Sect. 3.4.2 accordingly with a short paragraph.

Furthermore, there is the possibility, that other CH₄ sources located in the measurement area could affect the observed emission rates. Depending on whether these sources are in the plume area or the background area, they either contribute to the emissions or reduce them. If they were evenly distributed around the area, the effect on the estimated emission rate would be negligible. We estimated this effect by analysing the CH₄ emissions reported in EDGAR v8.0 (Emission Database for Global Atmospheric Research, Crippa et al., 2023). We aggregated all CH₄ emissions in our measurement area except for the source categories 4A and 4B (solid waste disposal and biological treatment of solid waste), which are our targets. Consequently, the resulting impact on our estimated emission rates could be approximately up to 2 t h⁻¹ at maximum or around 15 % of our total emission rate estimated according to EDGAR v8.0. Additionally, no other sources stand out in our column observations.

#####

Line 448: This seems like a very important potential limitation of these methodologies, so it would be valuable to move the discussion of the wind changes into the body of the paper rather than the Appendix. A visual showing the potential location of these "puffs" in comparison to the mapped "plumes" would be helpful for understanding the impact this wind direction change could have on the calculated fluxes (this visual does not necessarily need to go in the body of the text though).

Certainly, the mass balance approach is strictly applicable only for constant and persistent wind conditions. We are well aware of these limitations and are therefore currently carrying out model simulations to elucidate the evolution of the wind field. However, this is beyond the scope of this paper at hand and will be the subject of a subsequent paper that is currently in preparation. For this reason, we would like to leave this discussion to the forthcoming publication. In the manuscript at hand, we believe that we have at least mentioned all the possible reasons that could lead to deviations between “real” and “mass-balance derived” emissions rates.

#####

Line 499: Why does the unpredictability of locations impact process-based modeling? In some cases, landfill operators have well documented information on which cells are being filled at different points in time. For the Madrid landfills, is it that this information is not being collected or just not publicly available to researchers?

Our statement is not related to the process-based modelling or unpredictability of locations, but to the emissions which might be modulated by activities on the landfill. Usually, there is a lot of activity on weekdays, when waste is being added. In contrast, during weekends, less waste is shifted and less vehicles drive across the landfill, reducing the pressure on the subsurface waste and disfavour CH₄ release due to compression. Thus, CH₄ might be trapped more easily and is less likely to reach the atmosphere across the active area of the landfill on weekends (or during night, if no work is

done). Information on which cells are active or inactive is available and also included in the paper (see Sect. 2.1.2).

#####

Line 525: It seems inaccurate to say the two landfill sites were "well separated" when the downwind site flux could not be isolated.

We meant that the separation of the landfills was sufficient to quantify the emissions from the upwind (Pinto) independently from the Las Dehesas/VTP area. In fact, because our measurements were performed in the least favorable conditions (with plume emitted by upwind source crossing over the downwind one), it is logical to assume that in the perpendicular wind situation would make independent estimation even easier. Thus, we believe that the areas are, in fact, well separated.

We have amended Line 525 accordingly.

The emissions from the two landfill sites were sufficiently separated for our methods by the two remote sensing instruments with an observed emission rate...

#####

Line 546-548: This implies confidence in the ability of these instruments to identify sub-facility locations of sources. If this is a major conclusion of this manuscript, it does not seem like there was enough explanation of the methodology for identifying source locations and the associated uncertainty in those locations in the body of the paper.

We have expanded the explanation of the source identification methodology and potential uncertainties and limitations as described in previous comments. (e.g., comment to "Fig. 5" and comment to "Line 354 - 357").

We have amended the statement taking the discussions above into account.

The determination of the exact source location is limited by a combination of the ground scene size of ~ 110 x 110 m², the accuracy of the orthorectification process itself being estimated to be better than 110 m, and modulation by local winds. The highest column enhancements and the 'start' of plumes, indicating the origin of the emissions, were observed over active parts of the landfills, ...

#####

Section 5: Given the mention of the coming satellite in the introduction, it may be valuable to have more discussion on how the information gained from this study can inform future methods for the satellite.

We have amended Sect. 5 as follows:

The methods used in this work are also applicable to planned satellite missions such as CO2M and MERLIN. Nevertheless, the generally coarser resolution on the ground will lead to a reduced sensitivity for emission rates, particularly for somewhat dispersed

sources. Also, the combination of active and passive remote sensing on a single satellite platform would show promise for the future, as the advantages of both methods can be synergistically exploited.

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References:

Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Riskey Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E., Commission, E., and Centre, J. R.: GHG Emissions of All World Countries – 2023, Publications Office of the European Union, Luxembourg, <https://doi.org/10.2760/953322>, release: EDGAR v8.0_GHG (October 2023). JRC EDGAR website: https://edgar.jrc.ec.europa.eu/dataset_ghg80, 2023.

European-Parliament: Regulation (EC) No 166/2006 of the European Parliament and of the Council of 18 January 2006 concerning the establishment of a European Pollutant Release and Transfer Register and amending Council Directives 91/689/EEC and 96/61/EC, available at <http://data.europa.eu/eli/reg/2006/166/2009-08-07>, <http://data.europa.eu/eli/reg/2006/166/2020-01-01>, and Annex I at https://converters.eionet.europa.eu/xmlfile/EPRTTR_AnnexIActivityCode_1.xml, last access: 24.03.2025, 2006.

Krautwurst, S., Gerilowski, K., Borchardt, J., Wildmann, N., Galkowski, M., SwolkieŃ, J., Marshall, J., Fiehn, A., Roiger, A., Ruhtz, T., Gerbig, C., Necki, J., Burrows, J. P., Fix, A., and Bovensmann, H.: Quantification of CH₄ coal mining emissions in Upper Silesia by passive airborne remote sensing observations with the Methane Airborne MAPper (MAMAP) instrument during the CO₂ and Methane (CoMet) campaign, Atmos. Chem. Phys., 21, 17345–17371, <https://doi.org/10.5194/acp-21-17345-2021>, 2021.

Spanish-PRTR: VERTRESA-URBASER, S.A. UTE (UTE LAS DEHESAS) (COD. PRTR: 3510), available at https://en.prtr-es.es/informes/fichacomplejo.aspx?Id_Complejo=3164, last access: 24.03.2025, 2025a.

Spanish-PRTR: DEPOSITO CONTROLADO DE RESIDUOS URBANOS DE PINTO (COD. PRTR: 1636), available at https://en.prtr-es.es/informes/fichacomplejo.aspx?Id_Complejo=1458, last access: 24.03.2025, 2025b.

Spanish-PRTR: Information point sources, available at <https://en.prtr-es.es/informes/Pollutant.aspx?ReportedYear=2022&contaminante=1&Comunidad=66>, last access: 24.03.2025, 2025c

Spanish-PRTR: Information point sources, available at <https://en.prtr-es.es/informes/Pollutant.aspx?ReportedYear=2022&contaminante=1&Comunidad=66>, last access: 24.03.2025, 2025c.

Wolff, S., Ehret, G., Kiemle, C., Amediek, A., Quatrevalet, M., Wirth, M., and Fix, A.: Determination of the emission rates of CO₂ point sources with airborne lidar, Atmos. Meas. Tech., 14, 2717–2736, <https://doi.org/10.5194/amt-14-2717-2021>, 2021.

