

AIRMO – In-Orbit Demonstration of a Microsat Mission for GHG Measurements by Means of a Pushbroom Spectrometer and Elastic Microlidar:

Impact of Aerosol Lidar Soundings on Methane Enhancements

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Abstract

The AIRMO IOD mission, AIRMOSAT1, targeted for first flight in Q4 2027, combines a SWIR pushbroom grating spectrometer, a co-aligned single-line-of-sight micro-lidar and an RGB camera. The spectrometer provides a 20 km field of view at approximately 30 m spatial resolution, while the lidar measures aerosol backscatter to constrain aerosol layer height (ALH), width (ALW) and optical depth (AOD). These parameters are expected to reduce aerosol-induced bias in methane retrievals. Raw radiances are processed to Level-2 methane column concentrations (XCH₄), Level-3 plume enhancements (Δ XCH₄) and Level-4 emission rates. This is particularly relevant over the global dust belt, where mineral aerosol extinction can bias solar-reflectance retrievals if omitted from the radiative-transfer model (RTM).

We test whether a single lidar sounding at swath centre remains beneficial even though aerosol properties vary spatially and the lidar may not sample the background. An end-to-end simulator generated top-of-atmosphere radiances for mineral-dust scenes, followed by Level-2/3 retrievals using either a non-scattering RTM (NSRTM) or a constrained scattering RTM (SRTM). A Monte Carlo simulation of 2000 random observation, albedo and aerosol conditions was performed. The lidar-constrained SRTM reduced the mean absolute Level-3 error from 2.56 ppb to 0.49 ppb. The fraction of cases with errors ≥ 5 ppb decreased from 13.5% to 0.4%. ALH accuracy of a few hundred metres and AOD uncertainty below about 50% are sufficient for effective correction. The benefit is most relevant for weaker plumes (≤ 100 kgCH₄ h⁻¹).

1 Introduction

Sub-kilometre satellite imaging spectrometers such as EnMAP, EMIT, GHGSat, MethaneSAT and CarbonMapper enable detection and quantification of atmospheric methane and CO₂ plumes from point sources. AIRMO-Space aims to extend this capability through a 12-satellite constellation providing Level-2 XCH₄, Level-3 plume enhancements and Level-4 emission fluxes, with a target sensitivity of 25 kgCH₄ h⁻¹.

Aerosols can introduce significant retrieval bias by scattering and attenuating the reflected solar signal. Proxy approaches using co-retrieved gases such as CO₂ can compensate in some conditions, but rely on assumptions about spatially homogeneous proxy distributions. A physics-based solution is to use a scattering RTM constrained by aerosol optical depth and vertical structure.

ALH and ALW can be estimated from the oxygen A-band, but uncertainties of order 1 km can remain. A co-aligned pulsed micro-lidar is therefore planned to measure aerosol backscatter directly.

The central question is whether a single lidar profile at swath centre can improve the differential plume enhancement Δ XCH₄ despite unresolved aerosol variability outside the lidar footprint.

2 AIRMO E2E Methodology and Observation Geometry

The mission concept uses a staring lidar co-aligned with the pushbroom spectrometer. The lidar probes the swath centre while the spacecraft moves along track using forward-motion compensation (FMC). The effective integrated scene is approximately 6 $\times$ 20 km, whereas the lidar footprint is much narrower. Consequently, the sounding may sample the plume but not the adjacent background, or vice versa. Figure 1 illustrates the across-track and along-track geometries and a representative simulated scene.

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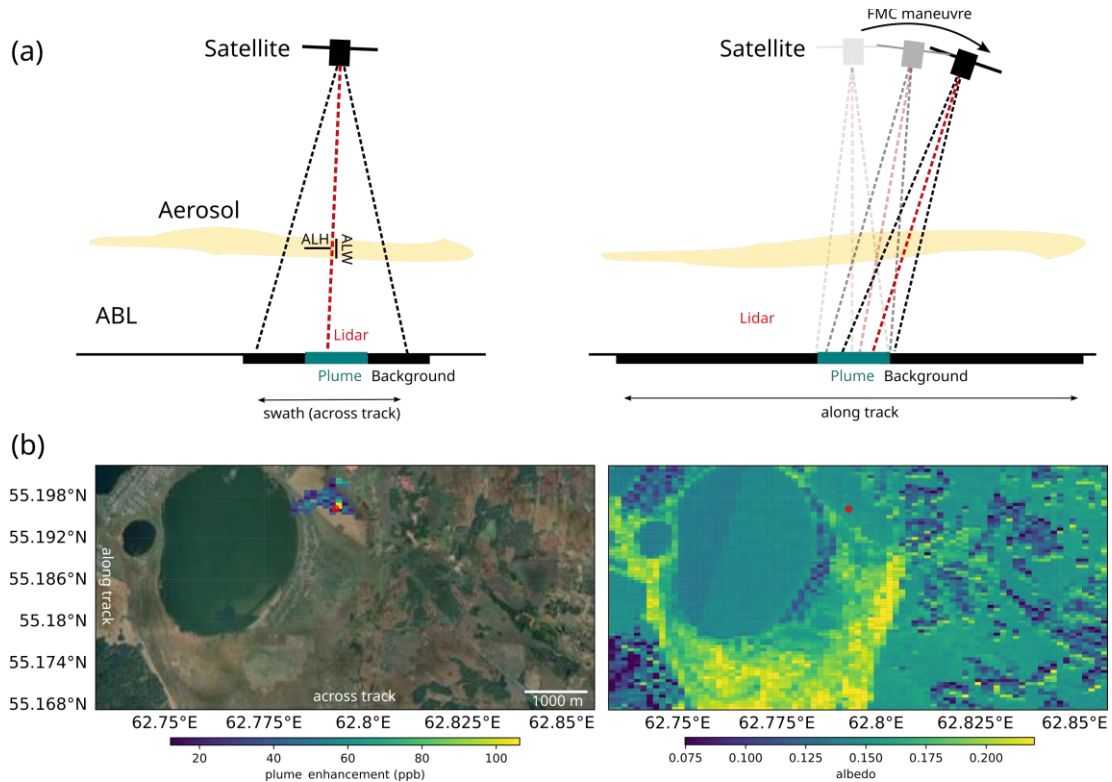


Figure 1. Observation geometry and representative simulated scene. (a) Across- and along-track geometry of the co-aligned staring lidar and pushbroom spectrometer, including FMC. (b) Example 100 kgCH₄ h⁻¹ LES plume and corresponding Sentinel-2 albedo, re-gridded to the instrument sampling.

The plume enhancement is retrieved as the difference between plume and nearby background XCH₄. Therefore, aerosol effects matter not only through the absolute Level-2 bias, but through the inequality of the biases between plume and background. If both pixels have identical observation conditions and aerosol properties, the errors can largely cancel. In realistic scenes, different surface albedo and geometry can prevent such cancellation.

2.1 Simulation Strategy

An end-to-end simulation was performed in Monte Carlo mode. Each realization contains a plume and background pixel and includes: (1) top-of-atmosphere spectral simulation with variable aerosol layer height, width and AOD; (2) instrument spectral degradation; (3) Level-0 to Level-1b processing; and (4) Level-2 retrieval with either NSRTM or SRTM, followed by Level-3 Δ XCH₄. The Level-3 bias is the difference between retrieved and true enhancement and is consequently governed by the difference between plume and background Level-2 biases.

A simplified two-pixel configuration was selected to retain the radiative-transfer physics while allowing 2000 random realizations. The true enhancement was derived from a mass-balance plume model assuming a 160 m plume width and 1 m s⁻¹ wind, giving an example enhancement of approximately 30 ppb. Observation geometry, surface albedo and aerosol properties were independently randomized within representative ranges.

2.2 End-to-End Processing Chain

The scene-generation module (SGM) calculates SWIR top-of-atmosphere spectra using a scattering RTM that accounts for H₂O, CO₂ and CH₄ absorption and transported mineral dust. True aerosol profiles are based on representative AERONET conditions. Plume aerosol parameters are generated by perturbing the background profile, while plume and background albedos are drawn independently. ALH and ALW are constrained to physically representative ranges, AOD is varied between 0.02 and 1, viewing and solar zenith angles extend to 20° and 70°, and albedo spans 0.1–0.8.

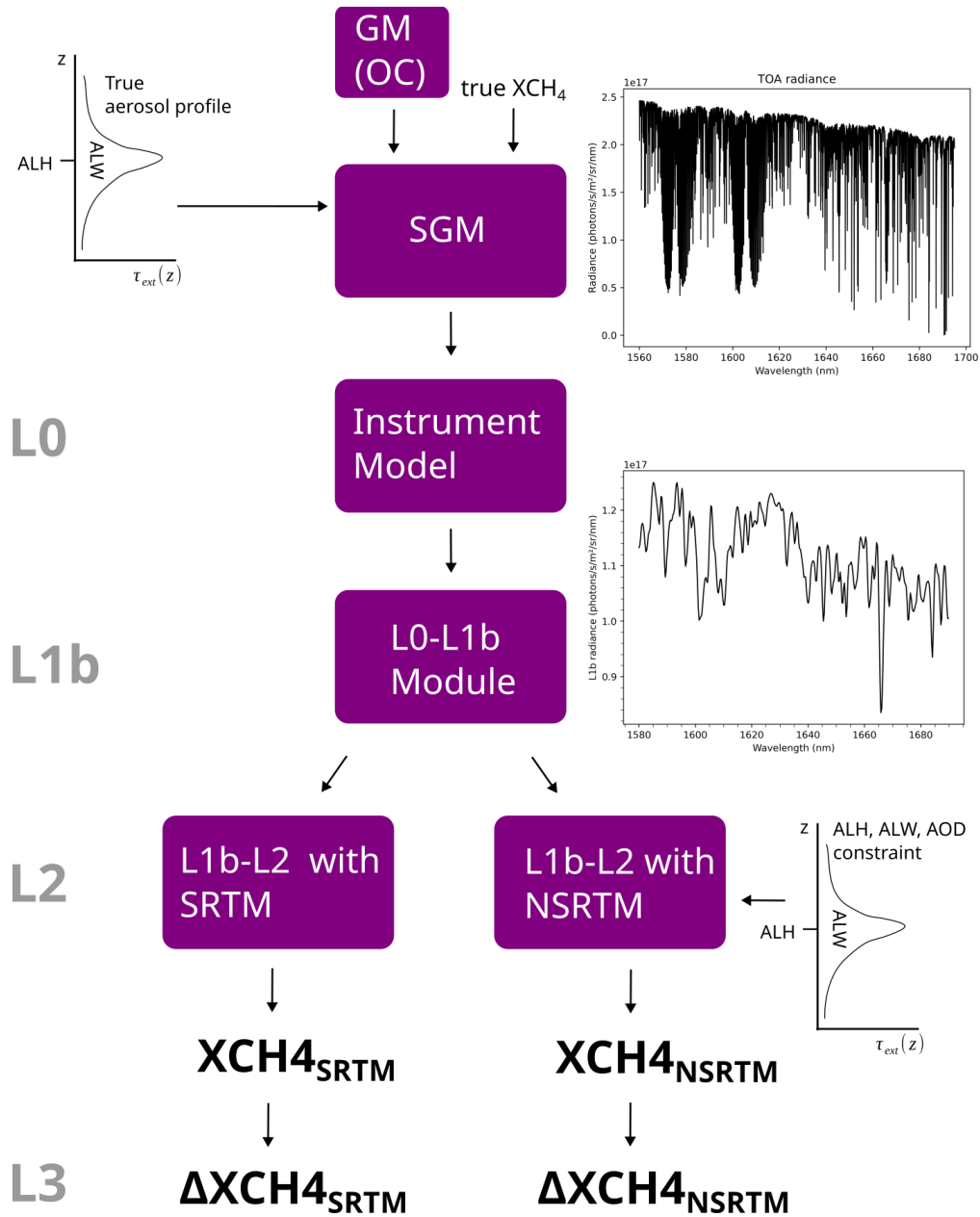


Figure 3. End-to-end simulation architecture: geometry/observation conditions, scene generation, instrument model, Level-0/Level-1b processing and Level-2 retrieval using scattering and non-scattering RTMs, followed by Level-3 enhancement.

The instrument model degrades the simulated radiance using the expected spectral response. Instrument noise and calibration errors were deliberately omitted so that the experiment isolates aerosol-scattering effects. The resulting Level-0 spectra are converted to calibrated Level-1b spectra and passed to the Level-2 forward model. For the SRTM case, the retrieval uses aerosol constraints from the lidar scenario; the NSRTM case ignores aerosol scattering.

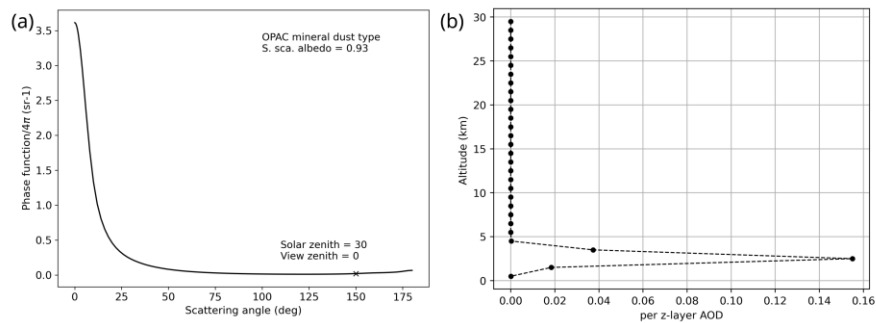


Figure 4. Aerosol phase function and example mineral-dust aerosol profile used in the simulations. GM/OC: geometry and observation conditions; SGM: scene generation module.

2.3 Aerosol Representation

The aerosol is represented as transported mineral dust, appropriate for the dust-belt regions targeted by the mission. The retrieval requires a parameterized aerosol profile. True ALH, ALW and AOD vary between Monte Carlo cases, while the retrieval is constrained by the lidar-derived profile and its assumed uncertainties. The experiment therefore tests whether useful correction is possible even when the lidar does not resolve all spatial variability.

The simulations also account for surface coupling and path-shortening effects. These effects become particularly important at low surface albedo and when plume and background albedo differ, because the relative contribution of scattered and directly reflected photons changes between the two pixels.

2.4 Aerosol and Observation-Condition Distributions

The Monte Carlo parameter space covers the range of observation and aerosol conditions expected during operational measurements. ALH and ALW are clipped to ≥ 300 m and ≥ 200 m, respectively, and AOD to 0.02–1. Observation and surface parameters are varied independently for plume and background to expose the conditions under which Level-2 bias cancellation fails.

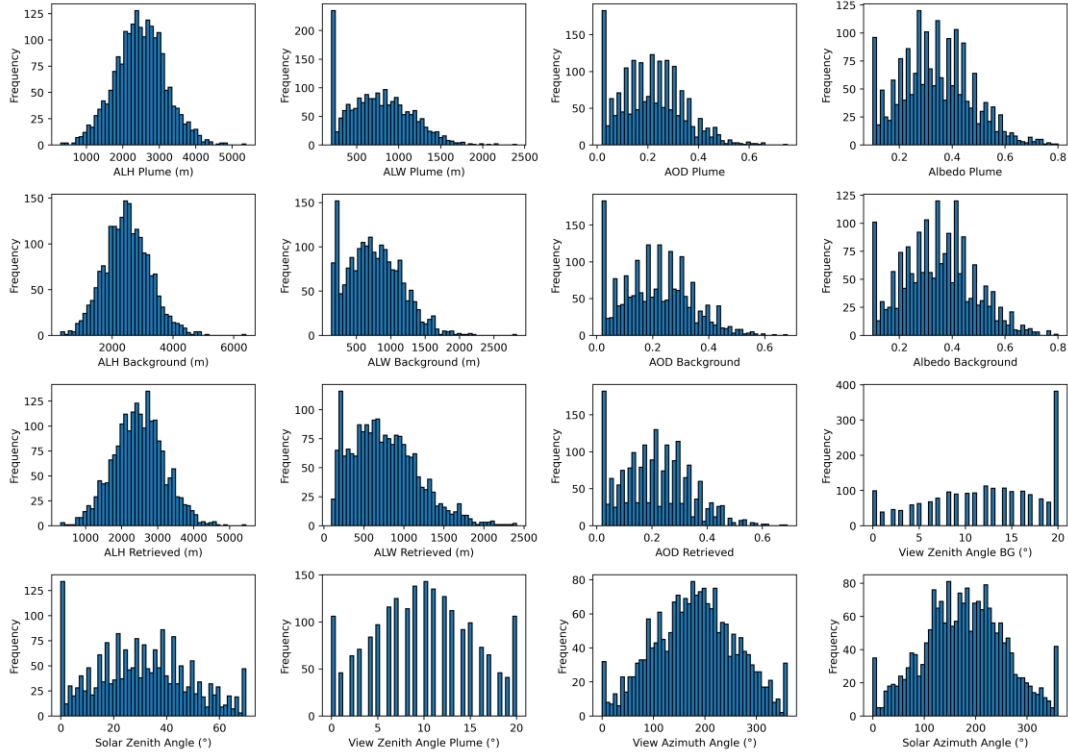


Figure 5. Example Monte Carlo distributions of aerosol, albedo and observation parameters used in the end-to-end simulations.

The mineral-dust optical model is represented by its scattering phase function and vertical extinction profile. An example profile with ALH = 2600 m and ALW = 750 m is discretized into the vertical model layers used by the radiative-transfer calculation.

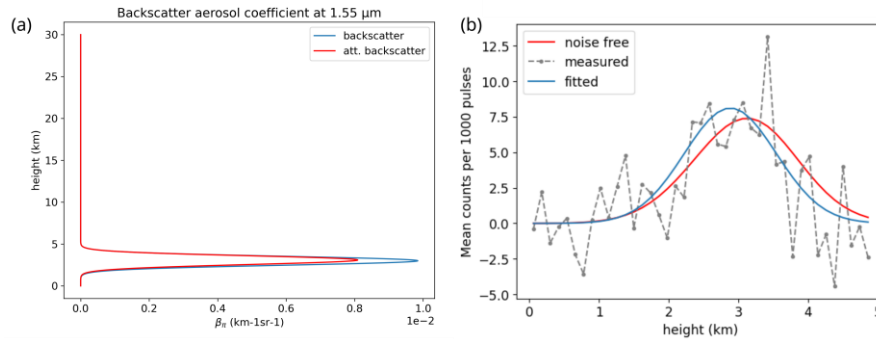


Figure 6. Lidar simulation input/output for the representative mineral-dust scenario.

3 Lidar Simulation

A representative lidar configuration was selected to quantify the uncertainty with which ALH and ALW can be supplied to the SRTM. The scenario uses AOD = 0.21, ALH = 3 km and ALW = 750 m. The lidar simulator calculates attenuated backscatter,

applies the aerosol lidar ratio, and models photon, solar-background and detector noise. The solar-background term is derived consistently from the E2E scene radiance.

For a representative SNR of 4, ALH and ALW were retrieved by fitting a Gaussian profile to the range-corrected lidar signal. Repeating the retrieval for 1000 independent noise realizations yielded $ALH = 3.09 \pm 0.126$ km and $ALW = 0.736 \pm 0.144$ km. These relative uncertainties were propagated to the 2000 E2E retrievals. The lidar observation conditions were fixed near the median of the Monte Carlo conditions; this provides a conservative estimate because solar-background noise is important.

4 Representative Results: Single Central Lidar with Noise

The representative lidar case assumes a single aerosol profile measured at the swath centre. Although this profile does not necessarily describe the complete plume/background scene, it provides ALH and ALW constraints for the SRTM. The key question is whether these partial constraints reduce differential Level-3 bias.

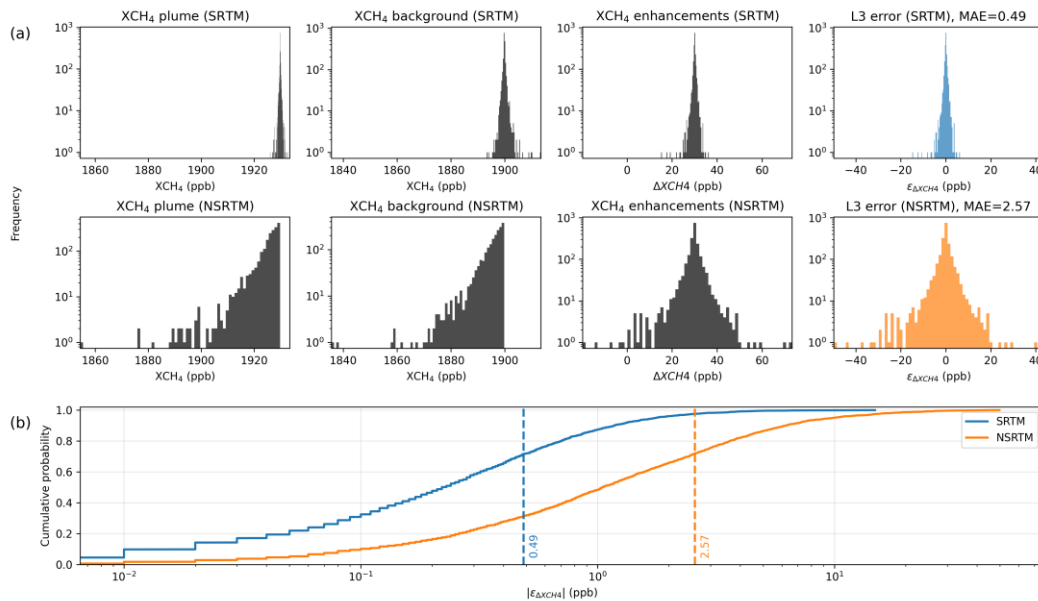


Figure 6. Lidar simulation for the representative mineral-dust scenario. (a) Backscatter and attenuated-backscatter profiles. (b) Simulated range-corrected signal with and without $SNR = 4$ noise and Gaussian fit used to retrieve ALH and ALW.

Across the 2000 Monte Carlo realizations, the NSRTM systematically underestimated XCH4. Individual Level-2 biases reached approximately -76 ppb for plume pixels and -64 ppb for background pixels. The corresponding mean absolute Level-3 bias was 2.56 ppb. Large Level-3 errors were associated particularly with low-albedo plume and/or background pixels, where aerosol-induced path and surface-coupling effects differ.

When the same realizations were processed with the lidar-constrained SRTM, the Level-3 error distribution shifted strongly toward zero and the MAE decreased to 0.49 ppb. The improvement results from two effects: the individual Level-2 biases are reduced, and the residual biases of plume and background become more similar. The latter is especially important for the differential Level-3 product.

The result demonstrates why a single central lidar can be useful even if aerosol properties are not homogeneous. The lidar does not need to reconstruct every local aerosol variation; it needs to constrain the dominant aerosol structure sufficiently to reduce the unequal radiative-transfer bias between plume and background.

4.1 Interpretation of Bias Cancellation

For equal observation conditions, especially equal albedo, and a constant aerosol profile, plume and background Level-2 biases are approximately equal and therefore largely cancel in $\Delta XCH4$. This explains why an aerosol correction can appear unnecessary in idealized homogeneous cases. Once albedo or geometry differs, however, the same aerosol layer can produce substantially different Level-2 biases. An NSRTM can then generate significant Level-3 errors even without strong aerosol gradients.

4.2 Monte Carlo Results and Table 1

Table 1 illustrates representative Monte Carlo realizations. The SRTM errors are generally small, whereas the NSRTM can produce substantially larger errors when plume and background albedo differ. Cases with low albedo are particularly sensitive to aerosol-induced radiance changes.

alh _pl (m)	alw _pl (m)	aod _pl	alh _bg (m)	alw _bg (m)	alh _ret (m)	alw _ret (m)	aod _bg	albedo _pl	albedo _bg	XCH4 _pl SRT M (ppb)	XCH4 _bg SRTM (ppb)	XCH4 _pl NSRT M (ppb)	XCH4 _bg NSRT M (ppb)	SRT M	NSRT M
220	116	0.2	195	103	221	1018	0.21	0.33	0.26	1929.	1900.0	1927.	1897.0	-	0.46

8	6		0	0	1					85	9	47	1	0.24	
246	134	0.29	263	144	255	1351	0.3	0.14	0.44	1930.	1899.6	1918.	1895.7	0.7	-7.23
1	2		0	0	9					36	6	51	4		
100	832	0.18	780	640	956	1122	0.19	0.49	0.5	1929.	1900.1	1928.	1899.0	-	-0.26
5										9	2	8	6	0.22	
364	875	0.42	432	104	371	819	0.39	0.31	0.17	1929.	1897.7	1918.	1879.5	2.03	8.97
8			0	0	1					75	2	54	6		
124	112	0.35	118	107	124	846	0.31	0.27	0.1	1929.	1900.0	1926.	1893.4	-0.6	3.01
5	6		0	0	2					46	7	47	6		
191	820	0.27	165	710	204	1116	0.29	0.2	0.38	1930.	1900.4	1924.	1897.0	-	-2.31
1			0		4					36	2	69	1	0.06	
285	993	0.3	263	910	285	972	0.29	0.47	0.32	1929.	1900.2	1925.	1894.5	-	1.24
2			0		1					75	9	74		0.53	
162	832	0.32	196	100	166	857	0.35	0.19	0.21	1930.	1898.1	1921.	1890.3	2.11	1.05
8			0	0	4					3	9	43	9		
175	758	0.02	213	920	173	898	0.02	0.43	0.54	1929.	1899.7	1929.	1899.6	0.02	-0.01
9			0		1					8	7	63	4		
186	494	0.02	184	490	197	481	0.02	0.26	0.41	1929.	1899.8	1929.	1899.7	0.00	-0.06
4			0		0					82	2	65	1		

Table 1. Excerpt of Monte Carlo results for the single central-lidar scenario. “pl” and “bg” denote plume and background; “ret” denotes retrieved aerosol parameters. Values are reproduced from the original analysis.

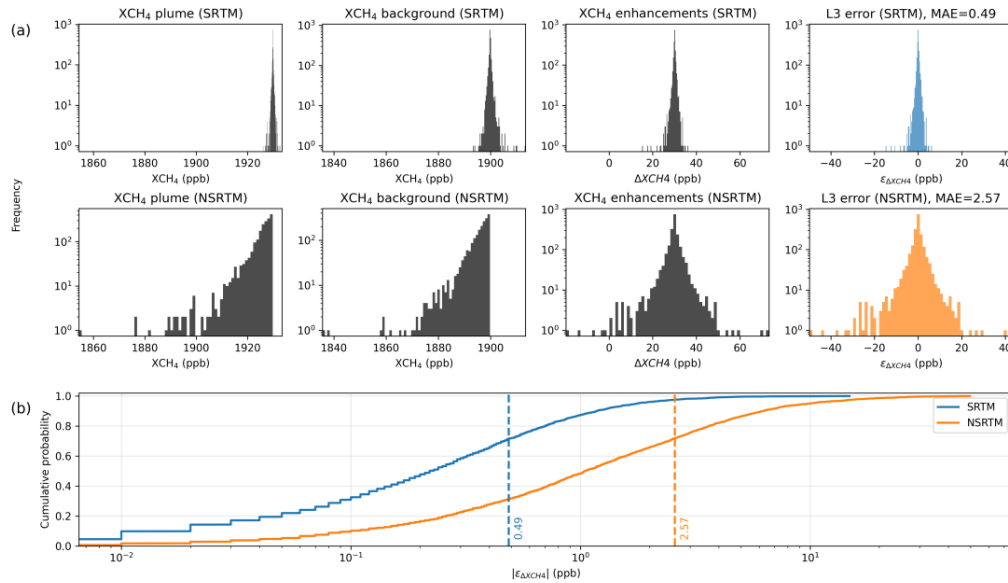


Figure 7. Results for the single central-lidar scenario: (a) plume/background Level-2 and Level-3 distributions and errors for SRTM and NSRTM; (b) cumulative distribution of absolute Level-3 errors.

The cumulative distribution confirms the reduction in error. The SRTM Level-3 MAE is approximately 0.49 ppb compared with 2.56 ppb for NSRTM. The improvement is particularly important where the plume/background albedo contrast is large. It also persists for homogeneous albedo when albedo is low and aerosol loading and vertical extent are high.

5 Key Performance Requirements

The simulations indicate that ALH should be known to within a few hundred metres to keep Level-3 bias below about 10 ppb (roughly 30% of the example enhancement). AOD should be known better than approximately 50% for the lidar-constrained SRTM to remain effective. In the simulated 2000 cases, using an AOD uncertainty below 10% reduced the Level-3 MAE to ~0.5 ppb, with a minimum/maximum bias of -14.9/+6.3 ppb. The fraction of cases with $|\text{bias}| \geq 5$ ppb fell from 13.5% to 0.4%.

6 Conclusions

This study assessed whether a single co-aligned aerosol-lidar sounding can improve physics-based methane retrievals when the lidar probes only the swath centre. The hypothesis that such a sounding would be ineffective because it does not capture the background aerosol profile is rejected by the E2E Monte Carlo results.

The main conclusions are: (1) for equal observation conditions and constant aerosol properties, plume/background Level-2 biases can largely cancel, producing small Level-3 bias even without correction; (2) different observation conditions, notably surface

albedo, break this cancellation and can produce Level-3 errors of several to tens of ppb with an NSRTM or poorly constrained SRTM; (3) a lidar-constrained SRTM reduces both Level-2 bias and plume/background bias inequality; and (4) the improvement is strongest for high albedo contrast, but is also relevant for low albedo combined with high AOD/ALH and aerosol variability. In the 2000-case Monte Carlo experiment, the lidar-constrained SRTM achieved an L3 MAE of ~ 0.5 ppb and reduced the occurrence of errors ≥ 5 ppb from 13.5% to 0.4%. Since Level-4 flux bias scales approximately with Level-3 bias, the correction is potentially most valuable for weak or diluted plumes, particularly sources below $100 \text{ kgCH}_4 \text{ h}^{-1}$. This could increase the number of sources that can be detected and quantified.

External aerosol information may complement lidar retrievals when a sounding fails or when additional spatial/temporal coverage is required. AERONET and EarthCARE products are possible sources, although their availability and uncertainty must be assessed for operational use. The same aerosol-correction principle is relevant to CO₂ retrievals and potentially to volcanic degassing, where aerosol and trace-gas signals can be strongly coupled.

The next step is validation with high-altitude airborne measurements and a more complete assessment of spatio-temporal aerosol variability. Overall, the results support retaining a co-aligned micro-lidar in the AIRMO mission concept: even a single central profile can materially improve methane plume quantification over extended mineral-dust scenes.

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