Detecting Methane Point Sources from Space Using Hyperspectral Surface Imagers

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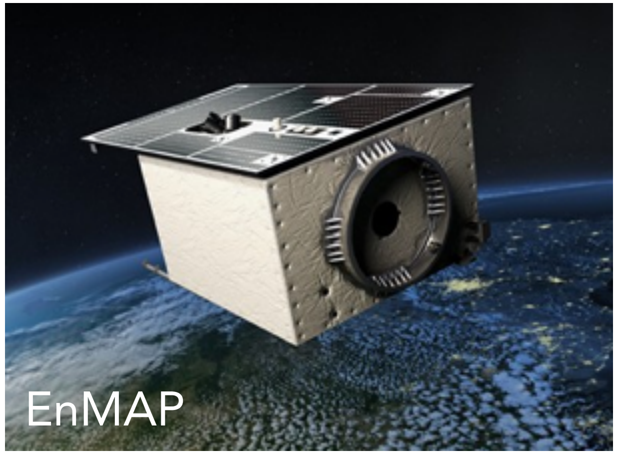

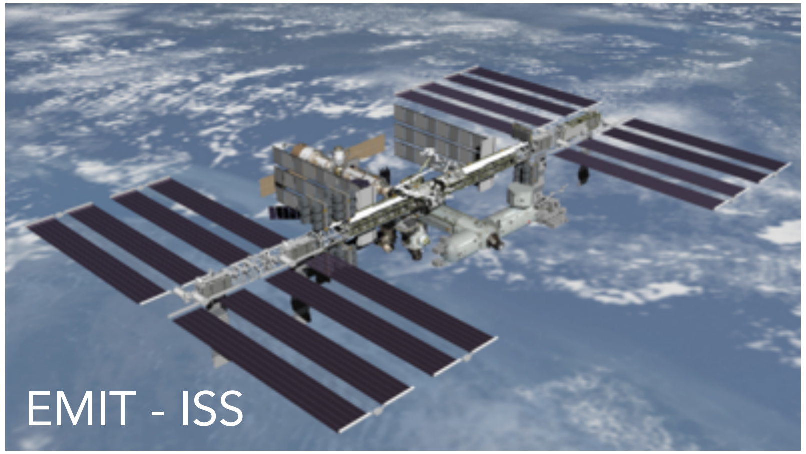

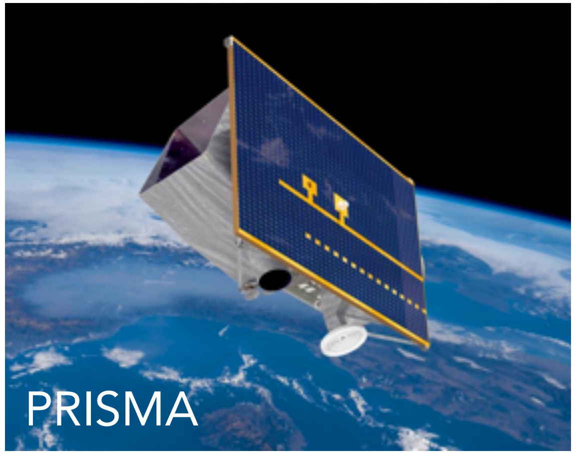

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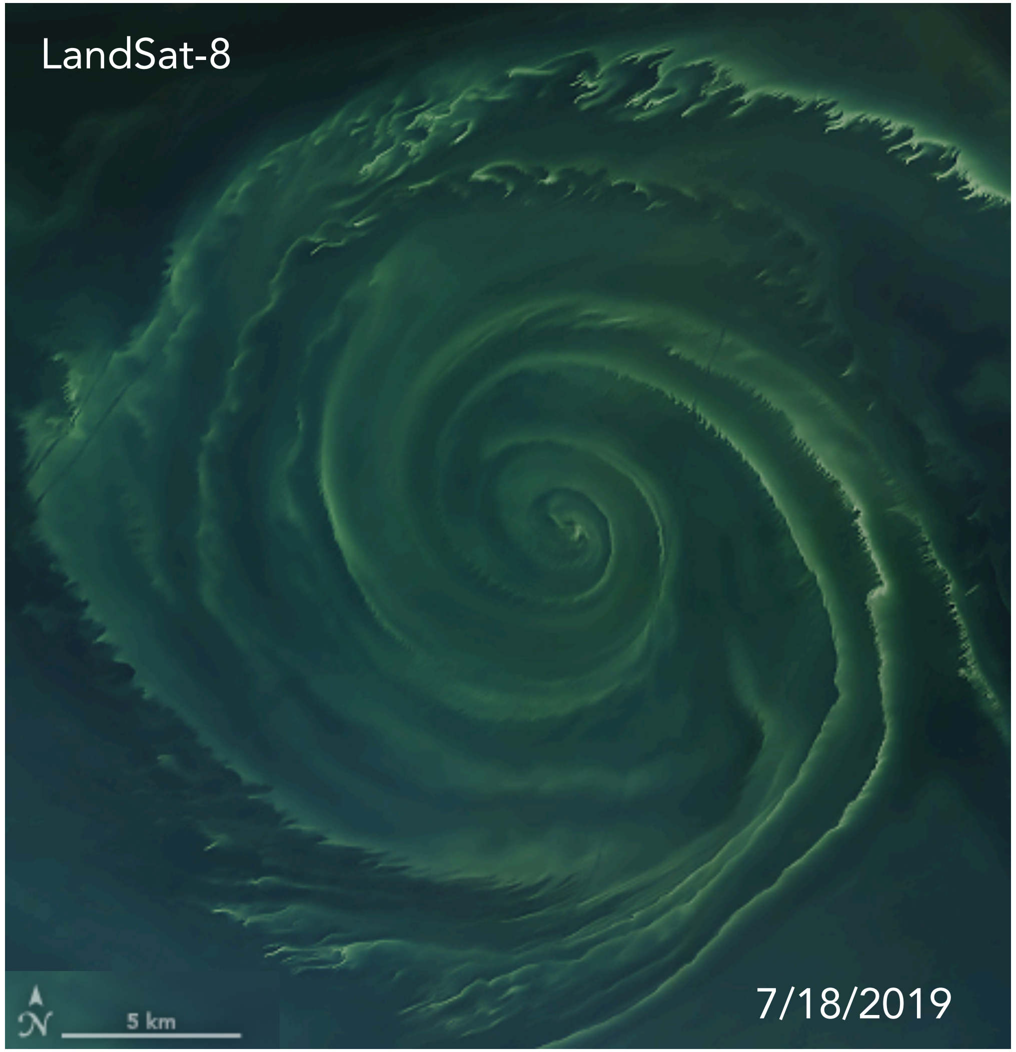
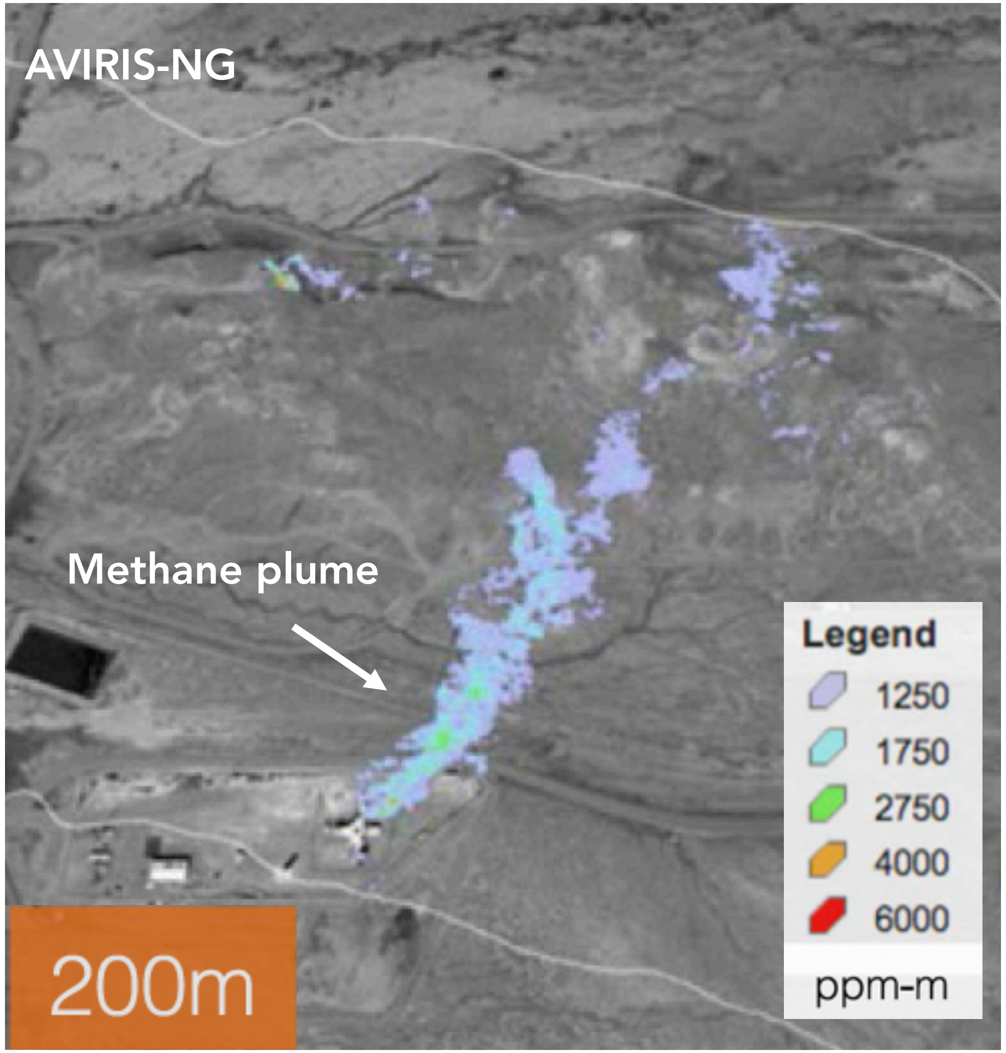
Imaging spectrometers are designed to provide high spatial resolution images of Earth's surface. Spectrometers with enough spectral resolution have been shown to detect methane plumes.

Phytoplankton bloom in the Baltic Sea



Uutiset (2018)

Four Corners, New Mexico

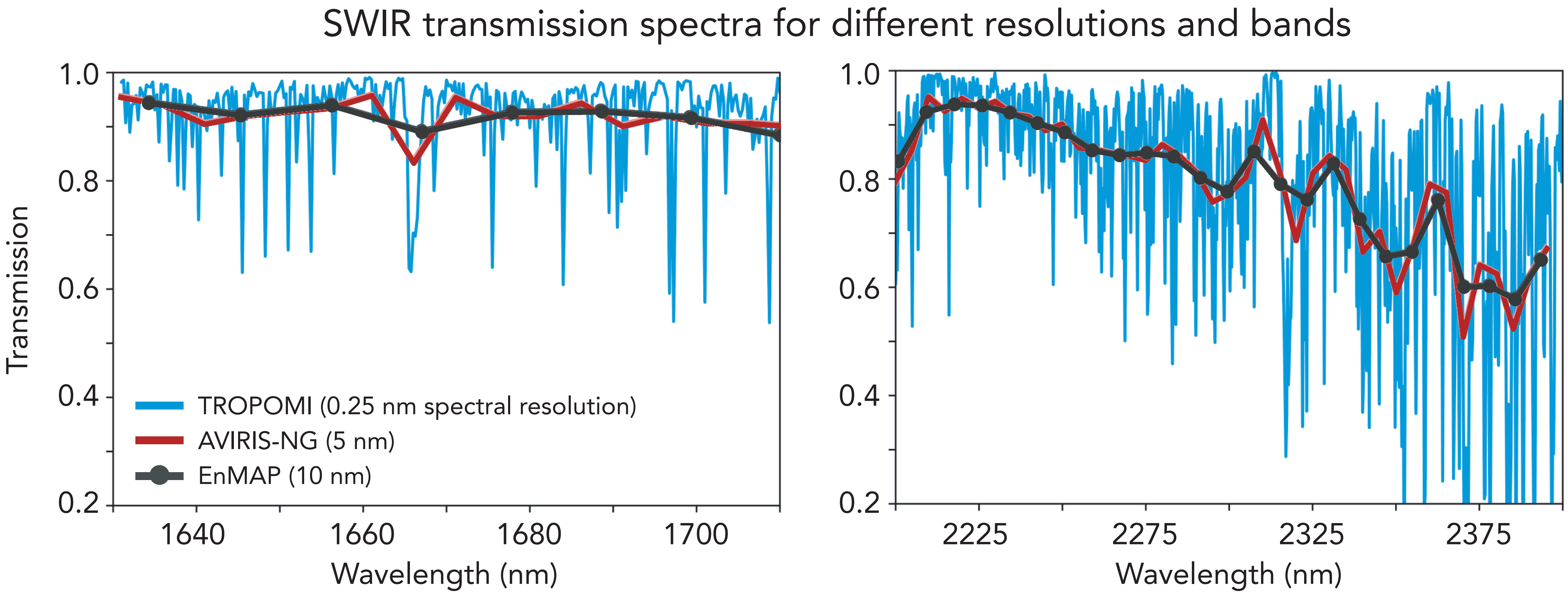


Frankenberg et al., 2016

Many satellite imaging spectrometers are slated to launch (or have already launched).

Instrument	Pixel size (km^2)	SWIR spectral range (nm)	Resolution (nm)	Signal-to-noise (SNR)	Observing epoch
Aircraft					
AVIRIS-NG	0.003 × 0.003	2200–2510	5.0	200-400	Campaigns
Satellite					
Atmospheric sensors					
SCIAMACHY	30 × 60	1630–1670	1.4	1500	2002-2012
GOSAT	10 × 10	1630–1700	0.06	300	2009-
GHGSat	0.03 × 0.03	1600-1700	0.1	TBD	2016-
TROPOMI	7 × 7	2305–2385	0.25	100	2017-
AMPS	0.03 × 0.03	1990–2420	1.0	200-400	Proposed
Imaging spectrometers					
PRISMA	0.03 × 0.03	2200–2500	10	180	2019-
EnMAP	0.03 × 0.03	2200–2450	10	180	2020-
EMIT	0.06 × 0.06	2200–2510	7-10	200-300	2022-
SBG	0.03 × 0.03	2200–2510	7-10	200-300	2025-

Imaging spectrometers trade spectral resolution for spatial resolution.

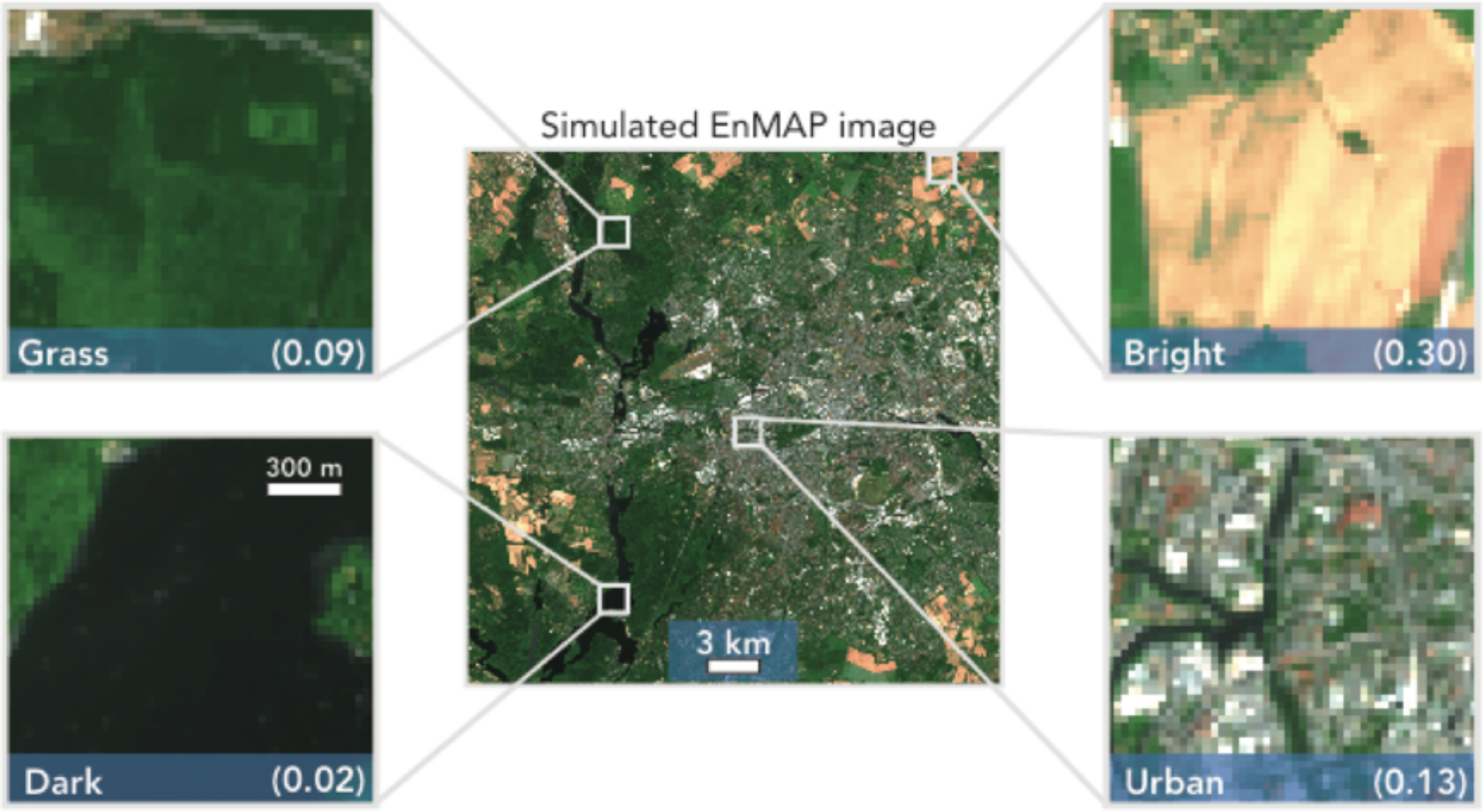


Questions for this study:

Will methane plumes be visible from space for new imaging spectrometers? With what precision?

What magnitude of plumes can we potentially constrain?

We simulate EnMAP scenes using the EnMAP End-to-End Simulation Tool (EeteS).

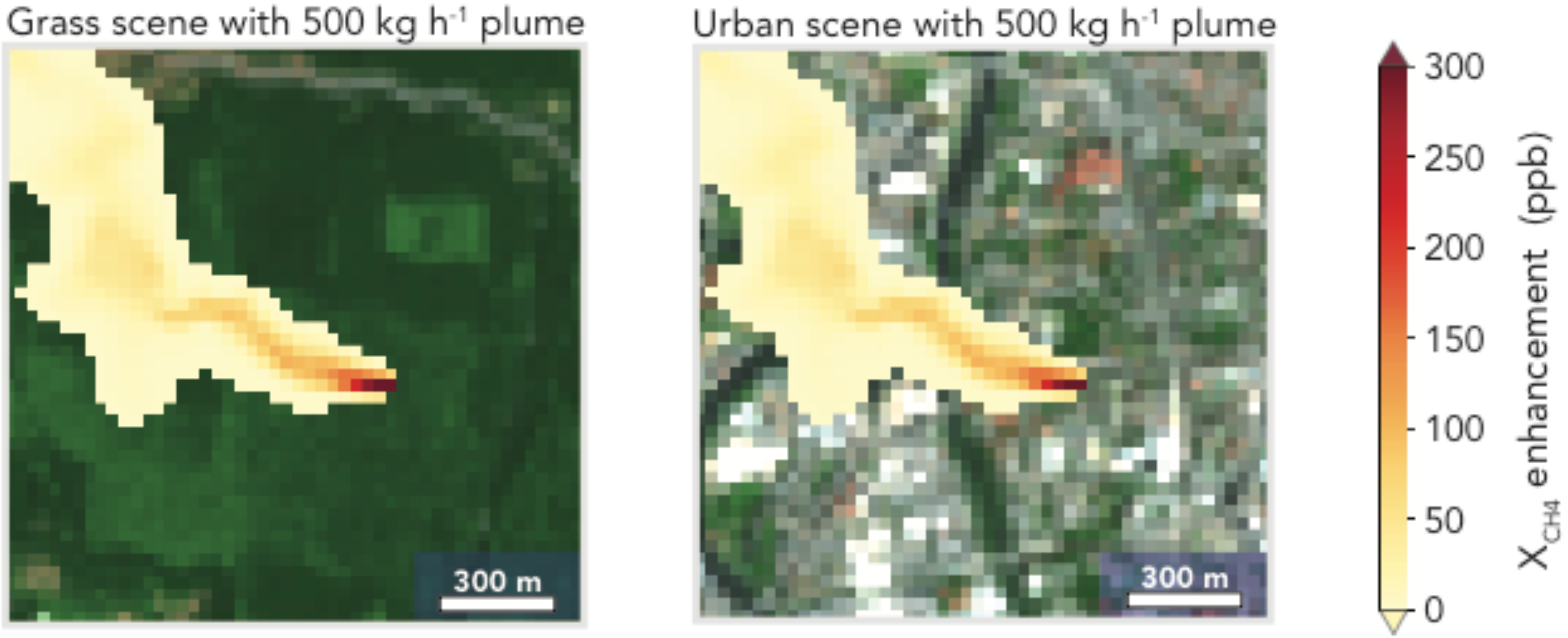


Default: horizontally invariant 1800 ppb column methane (XCH4)

EeteS flow

Example surface (e.g., SPOT-5)
↓
Atmospheric module
↓
Spatial module
↓
Spectral module
↓
Radiometric module
↓
EnMAP scene

We add WRF-LES plumes of different shapes and emission rates to each sub-scene.



For each EeteS pixel:

(1) Compute optical depth of plume ($\boldsymbol{\tau}$):

Density dry air

$$\tau(\lambda) = \sum_{i=1}^{72} \Delta VMR_i \, VCD_i \, \sigma_{H,i}(\lambda)$$

plume mixing ratio

HITRAN cross-section

(2) Apply plume transmission (T) to EeteS radiaince (L_0):

Airmass factor

$$T(\lambda) = \exp\{-A\tau(\lambda)\}$$

$$Y = T * L_0$$

Pseudo-observation

We employ the Iterative Maximum A Posteriori - Differential Optical Absorption Spectroscopy (IMAP-DOAS) algorithm to retrieve XCH4 from EeteS scenes.

Forward model:

Gas scaling factor

Surface represented as Legendre polynomial

$$F^h(\mathbf{x}, \lambda) = I_0(\lambda) \exp\left(-A \sum_{n=1}^{3} s_n \sum_{l=1}^{72} \tau_{n,l}\right) \sum_{k=0}^{K} a_k P_k(\lambda)$$

Solar spectrum

Airmass factor

Gas optical depth

State Vector (Total column scaling factors and Legendre coefficients):

$$\mathbf{x} = (s_{CH4}, s_{H2O}, s_{N2O}, a_0, \dots, a_K)$$

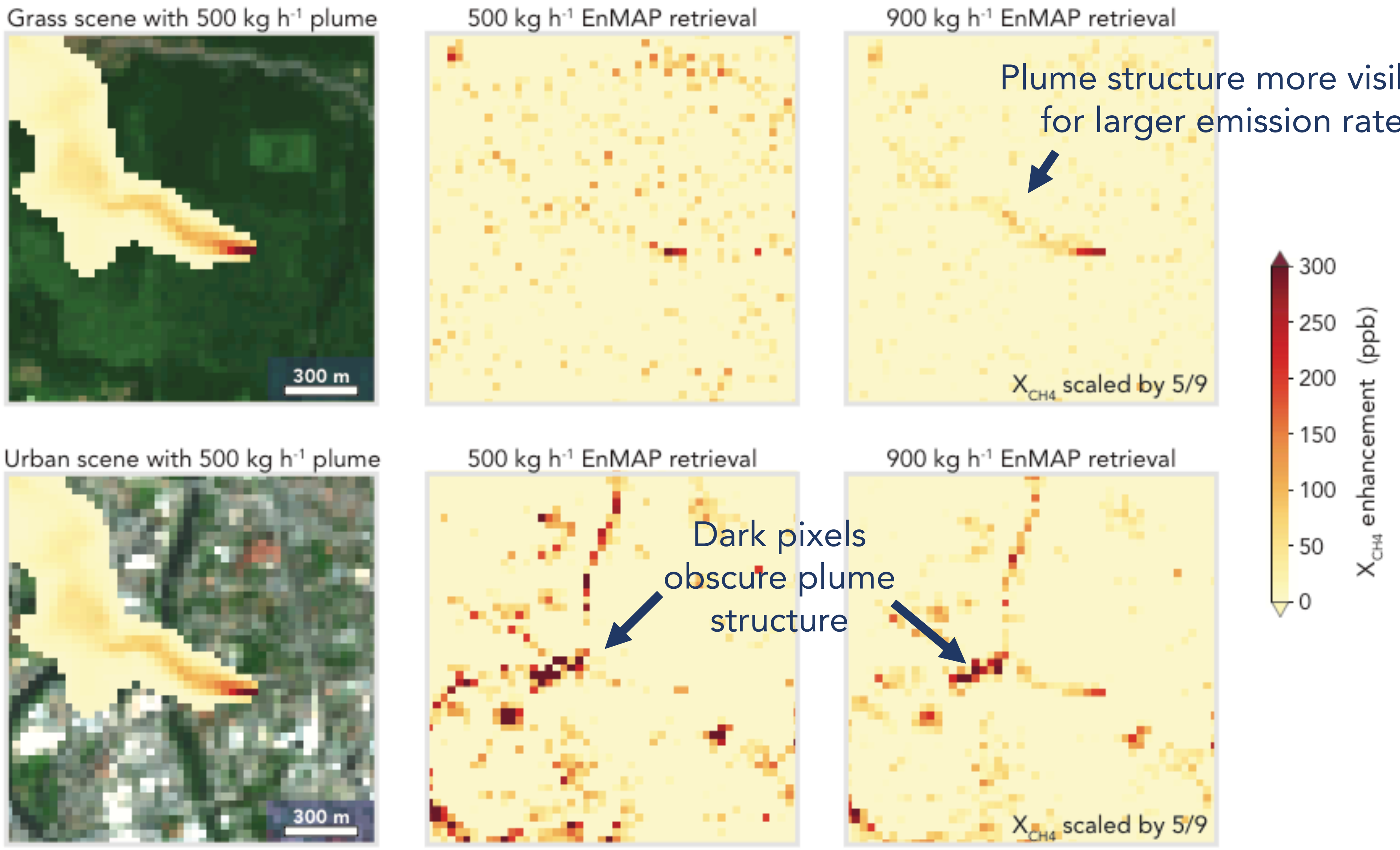
Optimal solution:

$$\mathbf{x}_{i+1} = \mathbf{x}_{\mathbf{A}} + \left(\mathbf{K}_i^T \mathbf{S}_{\mathbf{O}}^{-1} \mathbf{K}_i + \mathbf{S}_{\mathbf{A}}^{-1}\right)^{-1} \mathbf{K}_i^T \mathbf{S}_{\mathbf{O}}^{-1} [y - \mathbf{F}(\mathbf{x}_i) + \mathbf{K}_i(\mathbf{x}_i - \mathbf{x}_{\mathbf{A}})]$$

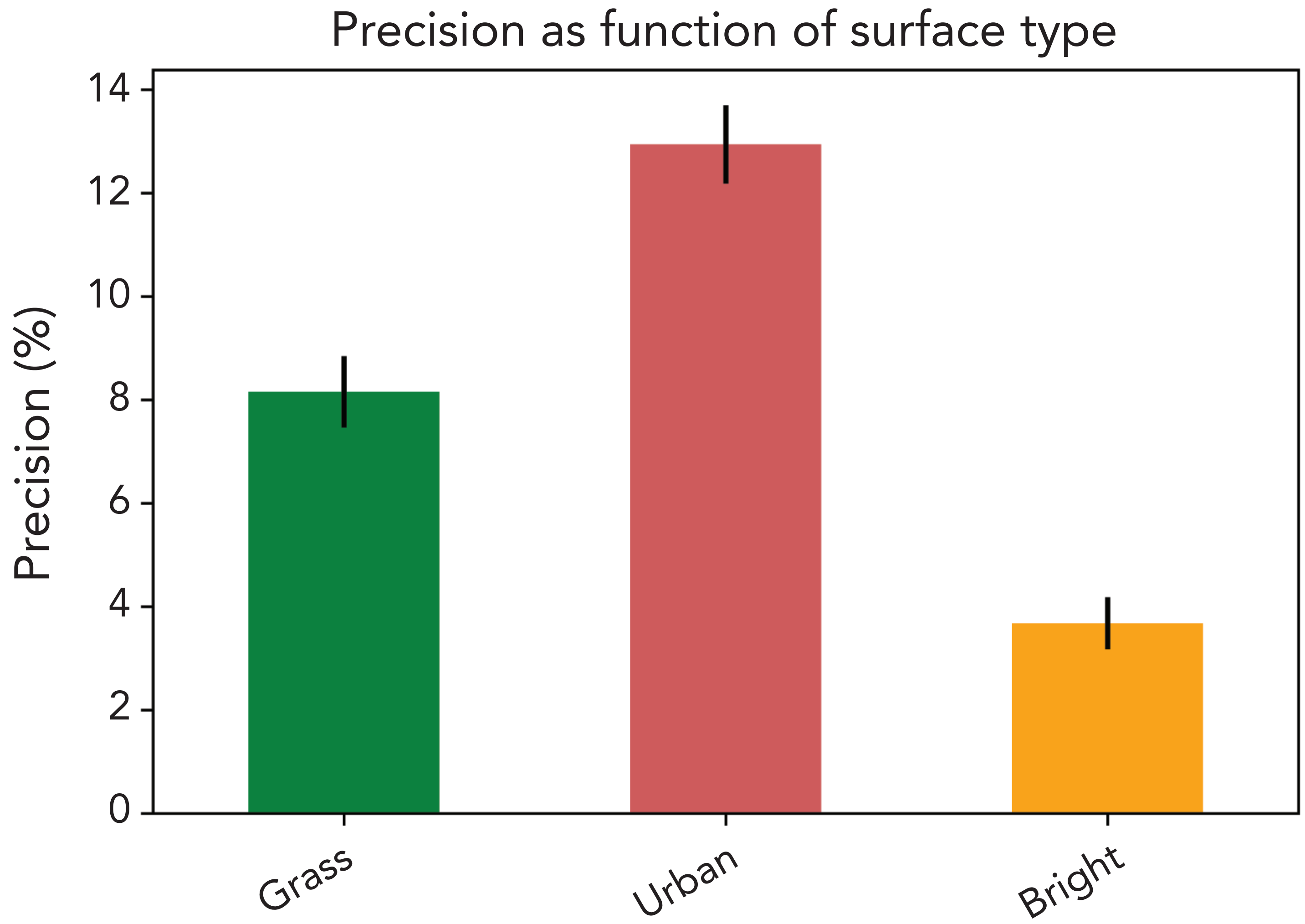
$$\hat{\mathbf{S}} = \left(\mathbf{K}_i{}^{\mathrm{T}} \mathbf{S}_{\mathbf{O}}^{-1} \mathbf{K}_i + \mathbf{S}_{\mathbf{A}}^{-1}\right)^{-1}$$

Where **K** = Jacobian Matrix

Homogeneous surfaces are larger emission rates produce better retrievals, as expected.



We compute the relative root-mean squared-error (RRMSE) over Grass, Urban, and Bright scenes for 5 plume shapes and 100, 500, and 900 kg/h emission rates (15 plumes total).

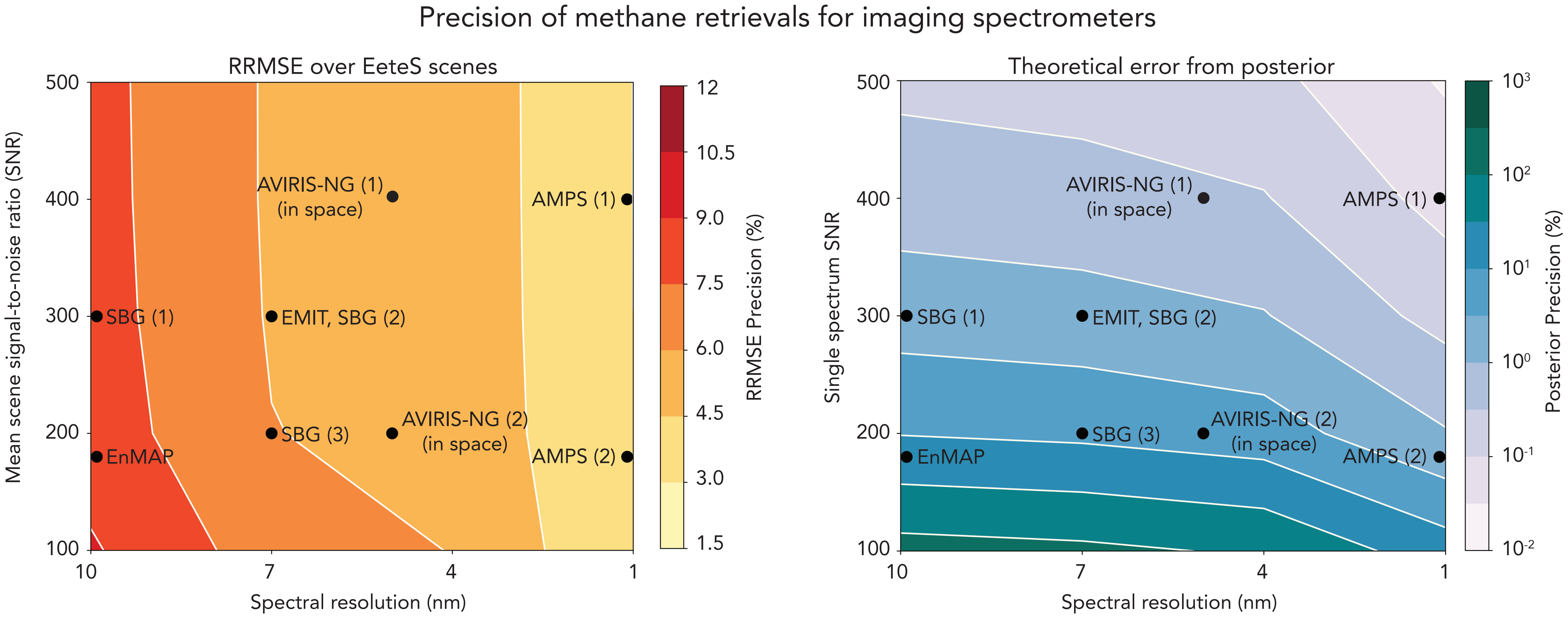


Though the Urban scene is on average brighter ($\overline{\alpha}$= 0.13) than the Grass scene ($\overline{\alpha}$= 0.09), the heterogeneities make the RRMSE worse.

The Bright scene ($\overline{\alpha}$= 0.30) has better than 4% precision on average.

RMSE is relative to the mean XCH4 within the scene

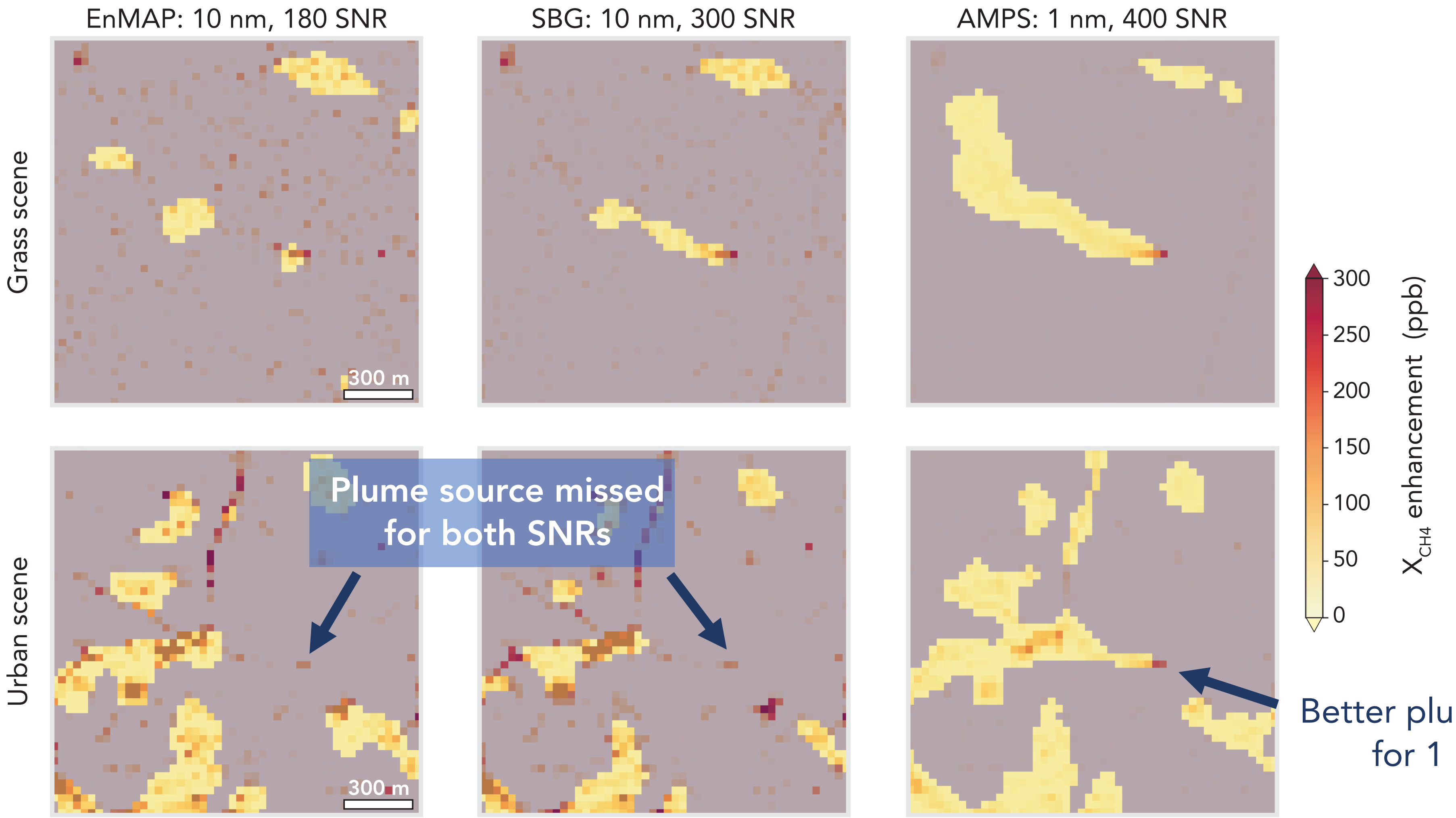
We vary SNR and spectral resolution and compare error for different theoretical instruments.



Depending on how error is quantified (RRMSE vs. $\hat{\mathbf{S}}$), either improving SNR or spectral resolution can be considered more effective at improving retrievals.

Improving spectral resolution reduces the error correlation between XCH4 and the Legendre polynomial, which allows for reduced retrieval artifacts.

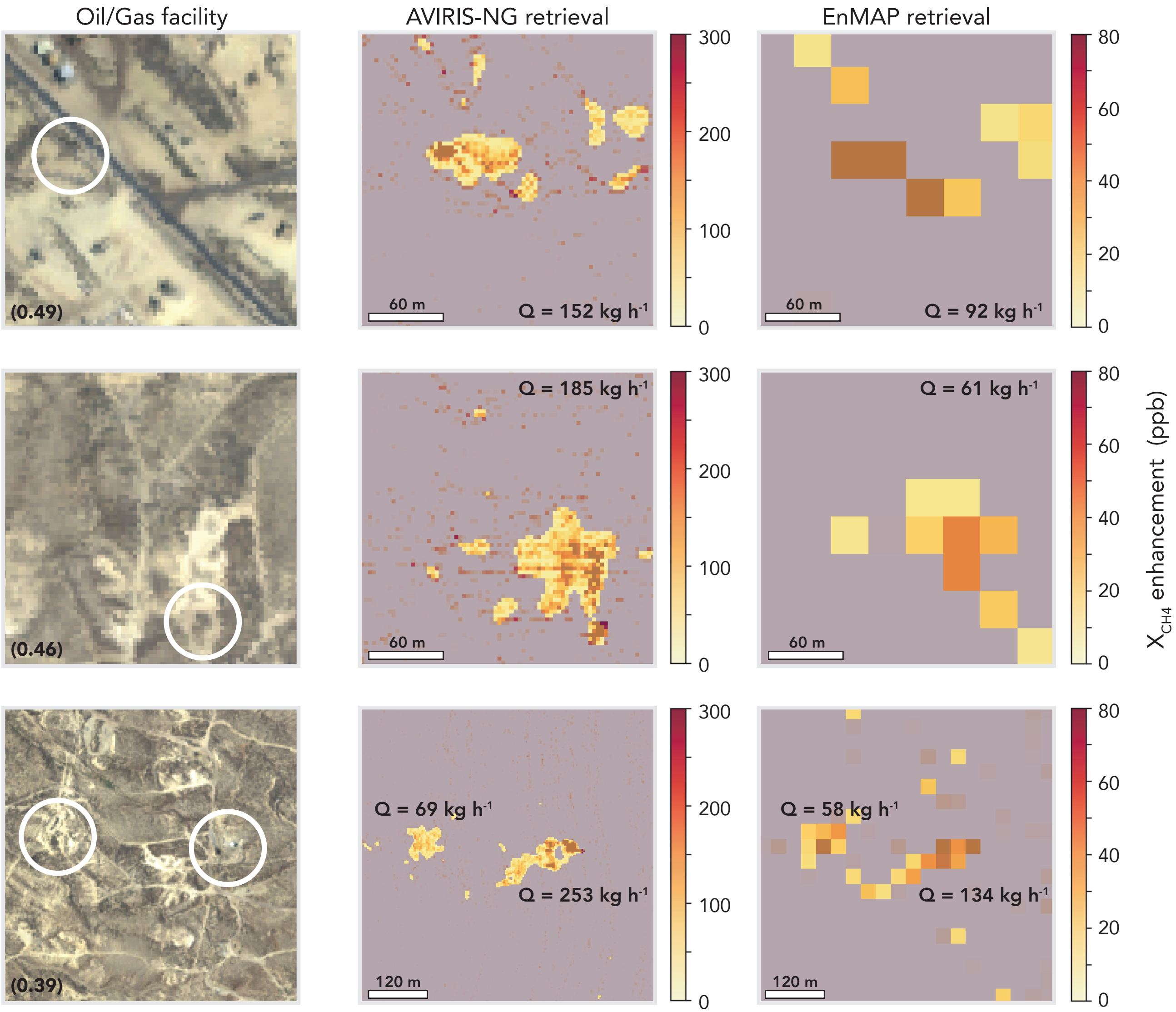
Plume pattern recognition for different instrument specifications



Plume masks determined by applying median and gaussian filters to pixels above the 85th percentile XCH4.

Better plume representation for 1 nm resolution

We convert AVIRIS-NG images to EnMAP-like images by spatially and spectrally downsampling, and by computing additional transmission through the atmosphere.



We infer emission rates (Q) using the Integrated Mass Enhancement (IME), plume mask, and estimated wind speed:

$$IME = \sum_{i=1}^{N} \Delta\Omega_i \, \Lambda_i$$

XCH4 enhancement ($\Delta\Omega_i$)

Pixel area (Λ_i)

$$Q = \frac{U_{eff}}{L} IME$$

Effective wind speed (U_{eff})

Plume length $L = \sqrt{\sum_{i=1}^{N} \Lambda_i}$

AVIRIS-NG and EnMAP-like inferred emission rates agree within a factor of 1-3.

Conclusions

- Retrievals of EeteS scenes show that EnMAP should be able to constrain emitters of at least 500 kg/h over a variety of surfaces.
- EeteS and downsampled AVIRIS-NG images show that over bright, homogeneous surfaces, EnMAP should constrain emitters of at least ~100 kg/h.
- A spaceborne AVIRIS-NG instrument with multiple along-track sampling can be expected to have a precision of 1-5.5%.
- Depending on how error is quantified (RRMSE vs $\hat{\mathbf{S}}$), SNR or spectral resolution can be seen as the most effective lever in improving retrievals.
- Improving spectral resolution reduces error correlation between XCH4 and the surface representation in the retrieval. This allows for better representation of the plume structure (i.e., plume mask), which produces better emission rate estimates.