# Towards a remote sensing solution to quantify $N_2O$ emissions by integrating shortwave and longwave infrared bands

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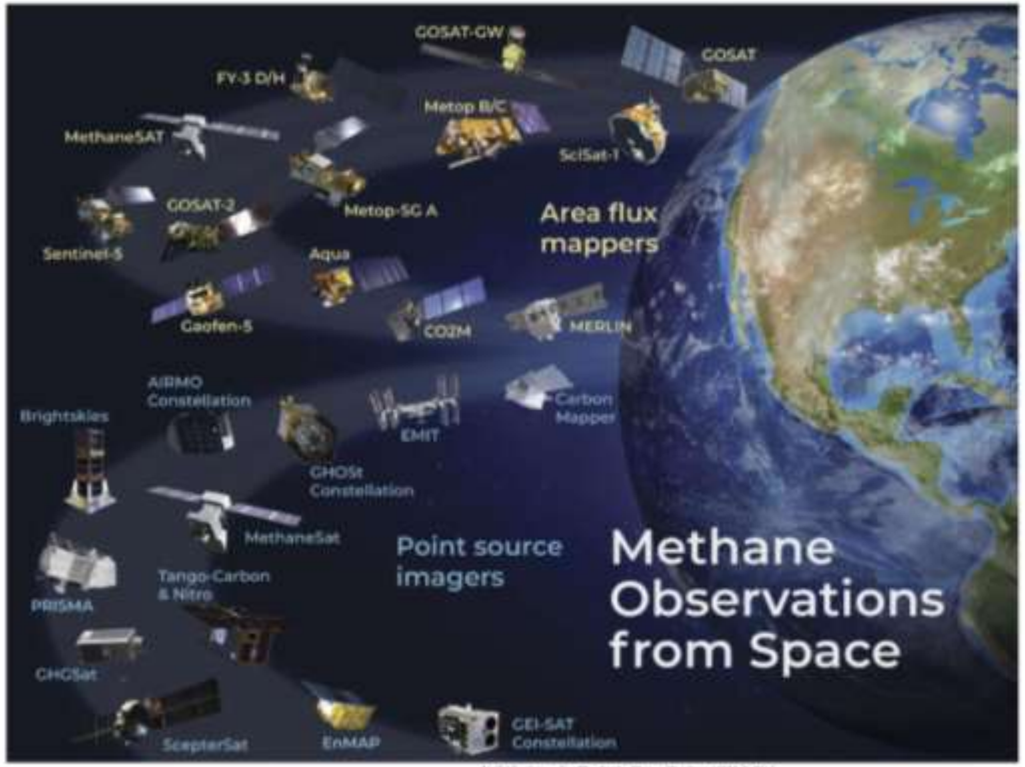
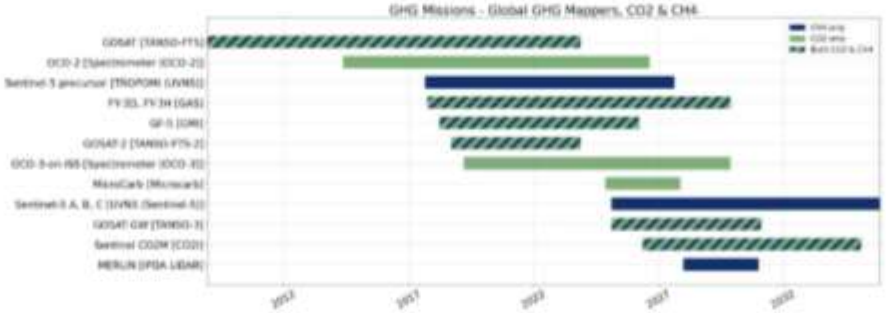
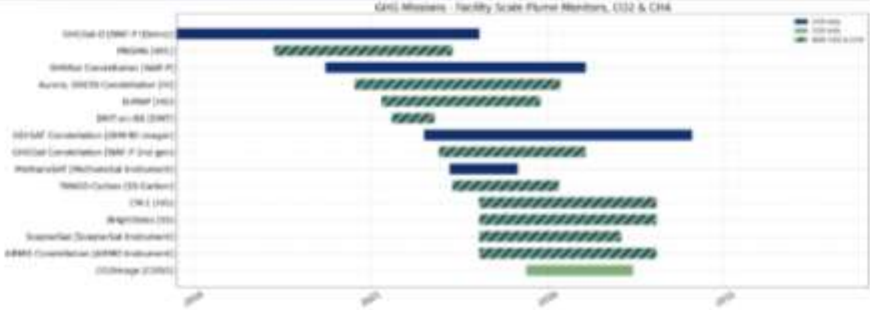
# $N_2O$: a key greenhouse gas overlooked from space

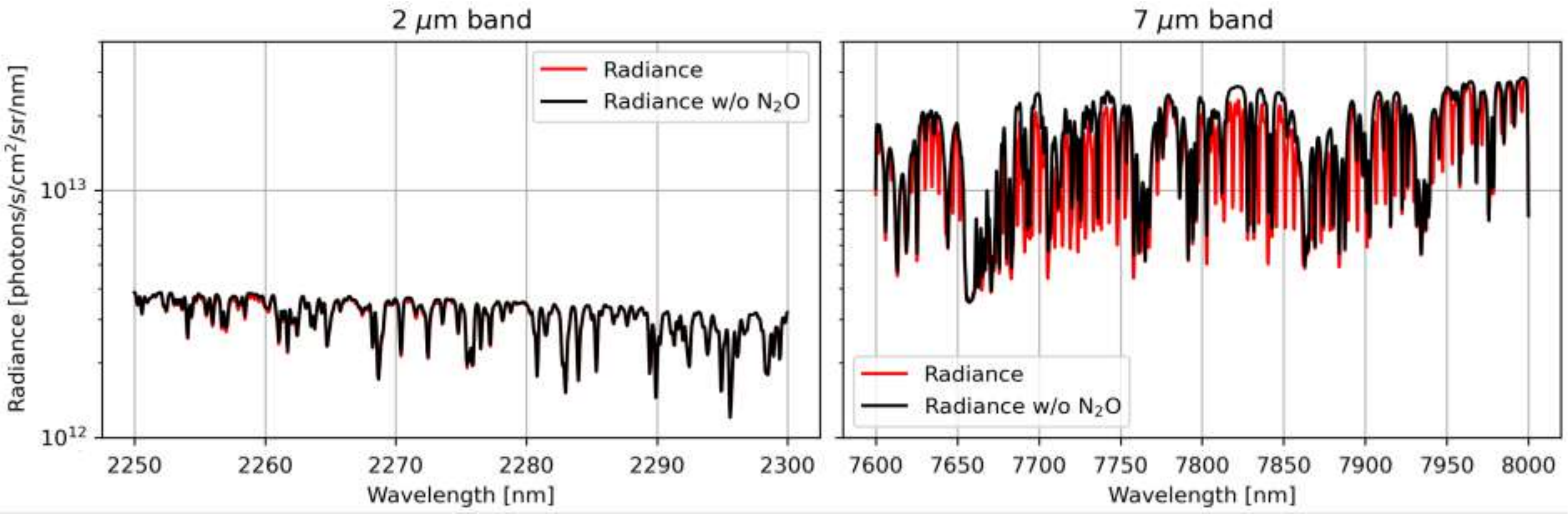




https://cpaess.ucar.edu/sites/default/files/2024-iwggms/Crisp-David.pdf

# The challenge of $N_2O$ remote sensing

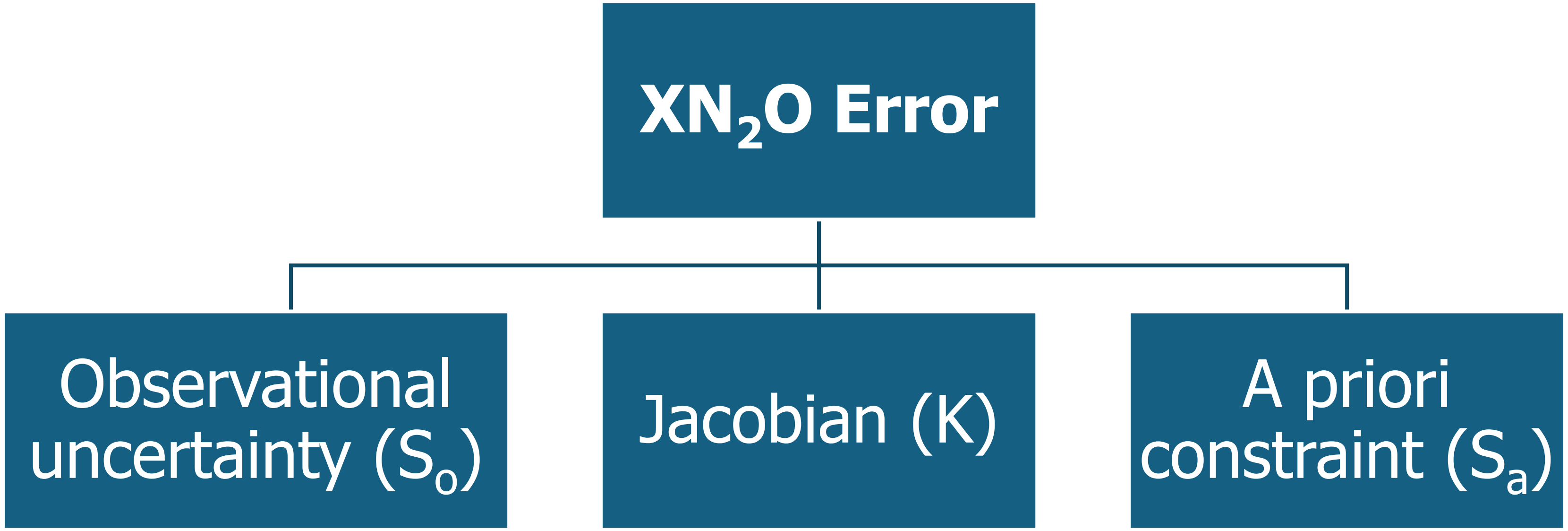
**Shortwave** **Longwave**




- 2 μm: consistent vertical sensitivity but very weak $N_2O$ absorption
- 7 μm: strong absorption and radiance level but weak near-surface sensitivity
- Integrate 2 μm and 7 μm to combine the strengths of short and longwave bands

# How precisely can we observe $XN_2O$?

- $XN_2O$: Column-integrated mixing ratio of $N_2O$ $\left(XN_2O = \frac{\Omega_{N2O}}{\Omega_A}\right)$




**$S_m$:** measurement error covariance matrix

$$S_m = GS_oG^T$$

$$G = S_aK^T\left(KS_aK^T + S_o\right)^{-1}$$

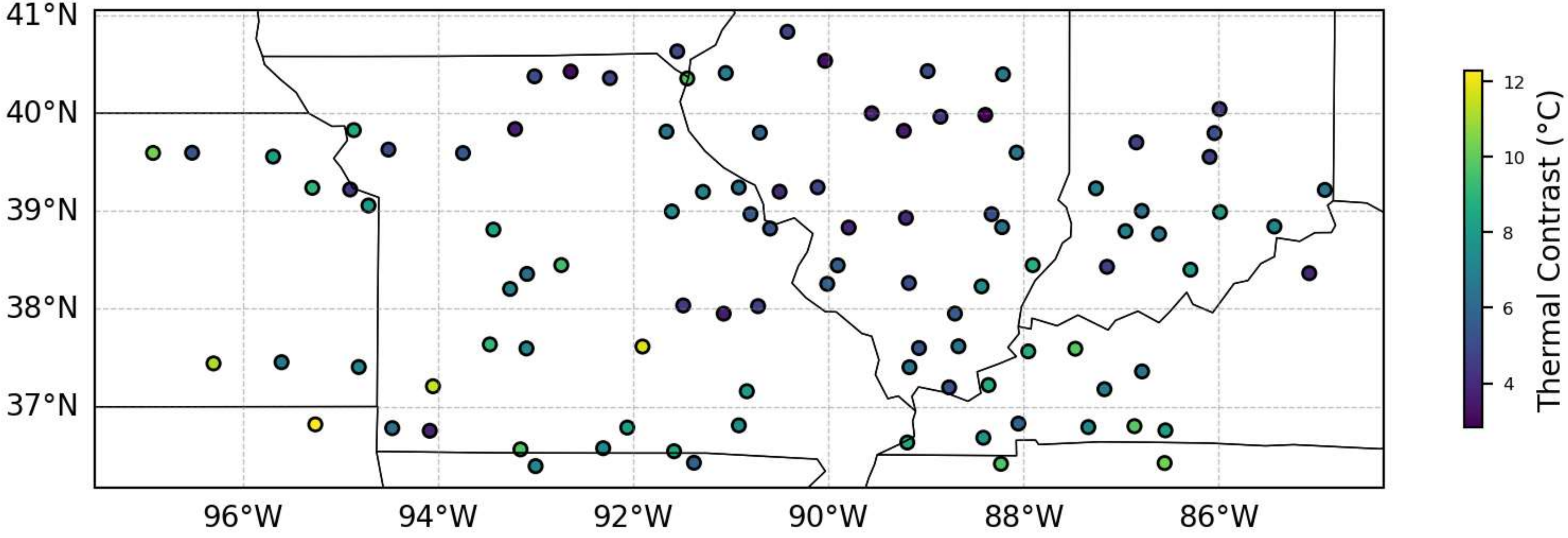
Measurement error of $XN_2O$

$$\sigma_{XN_2O(m)} = h^T S_m h$$

**h:** pressure weighing function

# Atmospheric and surface states

- CrIS Level 2 files for $N_2O$, $CH_4$, $H_2O$, and temperature from the JPL MUSES algorithm
- Atmospheric profiles and surface conditions extracted from 100 CrIS pixels
- Area: US Midwest (Part of corn belt)
- Observation date: 23 August 2023



# Observational uncertainty

| Parameter [unit] | 2 $\mu$m band | 7 $\mu$m band |
|---|---|---|
| Wavelength range [nm] | 2240–2300 | 7600–8000 |
| Spectral sampling [nm] | 0.0575 | 0.25 |
| Slit width [× spectral sampling][a] | 3 | 3 |
| Exposure time [s] | 0.1 | 0.1 |
| Detector pixel size [$\mu$m] | 18 | 18 |
| f-number | 2 | 2 |
| System efficiency | 0.5 | 0.5 |
| Readout noise [electrons] | 60 | 60 |
| Airborne observation altitude [km] | 10 | 10 |
| Spaceborne observation altitude [km] | 600 | 600 |
| Airborne along-track [m] | 20 | 20 |
| Spaceborne along-track [m] | 701 | 701 |
| Airborne across-track [m] | 2.95 | 2.95 |
| Spaceborne along track [m] | 155 | 155 |
| Airborne ground sampling distance [m] | 7.7 | 7.7 |
| Spaceborne ground sampling distance [m] | 330 | 330 |

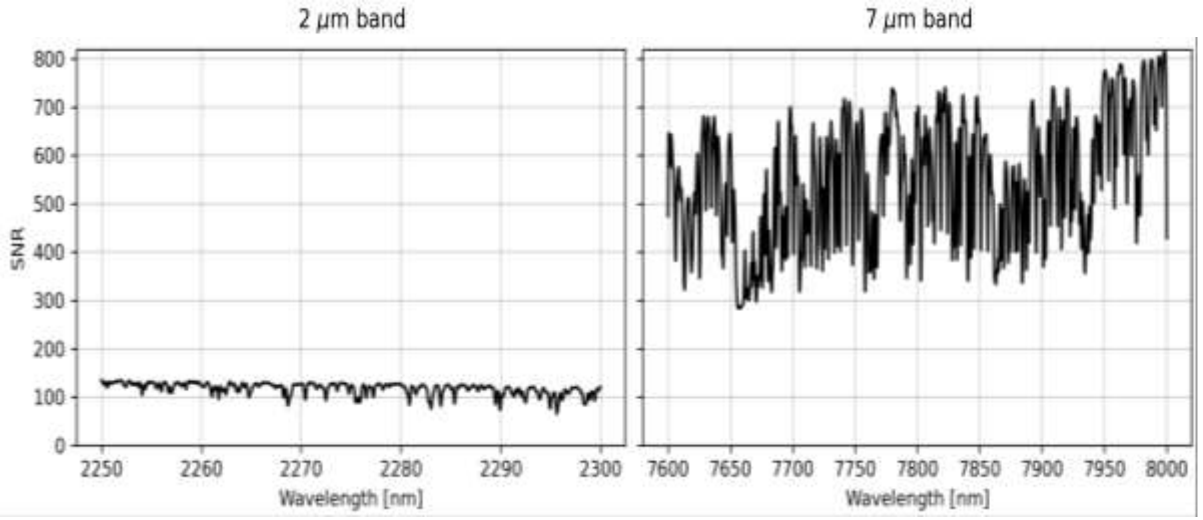
[a] Gaussian slit function (i.e., instrument spectral response function, ISRF) is assumed.

$$S = \frac{\pi}{4} \cdot \boxed{I} \cdot dp^2 \cdot \frac{1}{f^2} \cdot n_{\text{sample}} \cdot dt \cdot d\lambda \cdot \eta$$

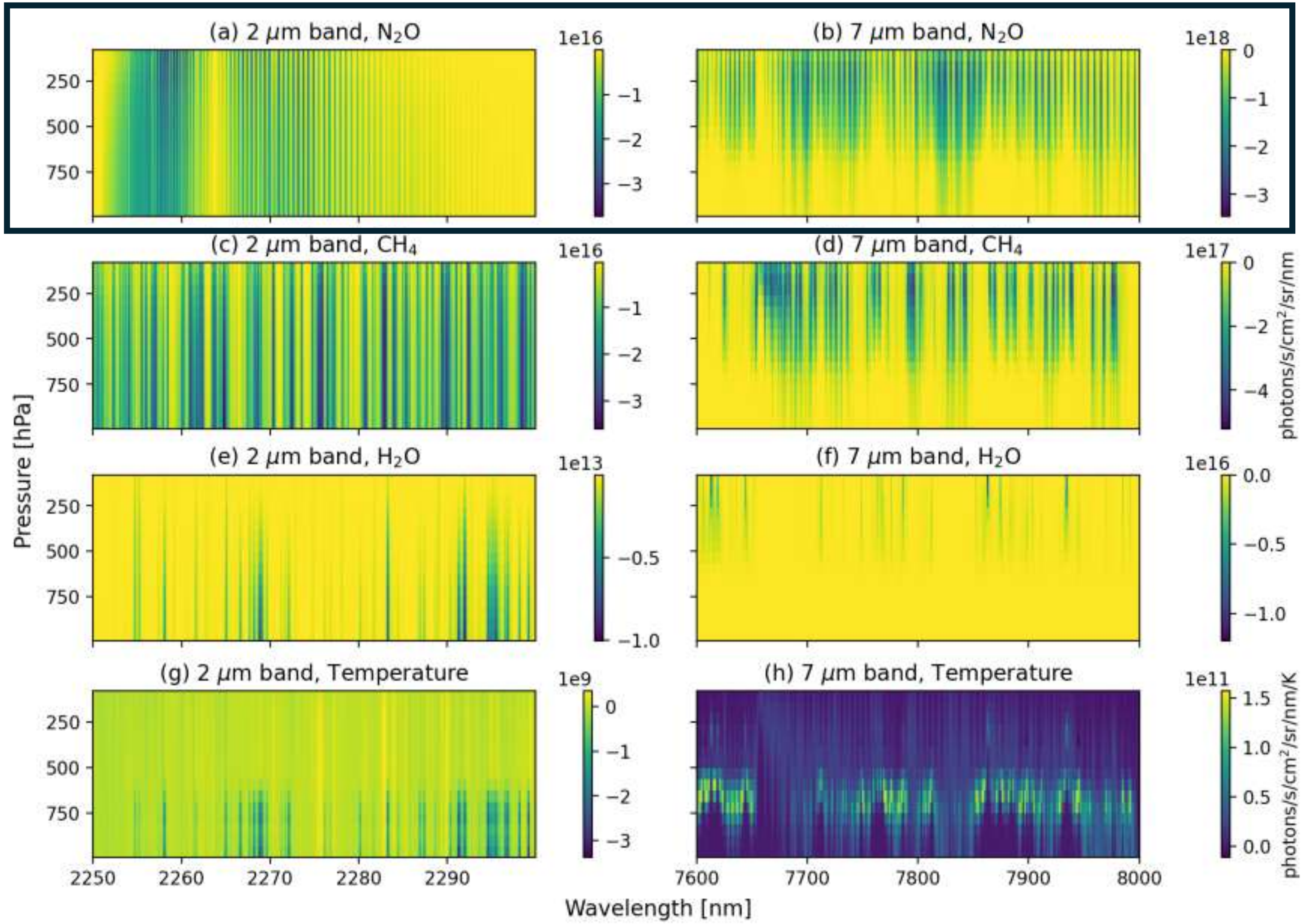
$$N = \sqrt{S + N_r^2}$$

$$\text{SNR} = \frac{S}{N}$$

SPLAT-VLIDORT radiative transfer model is used to simulate radiance (I)

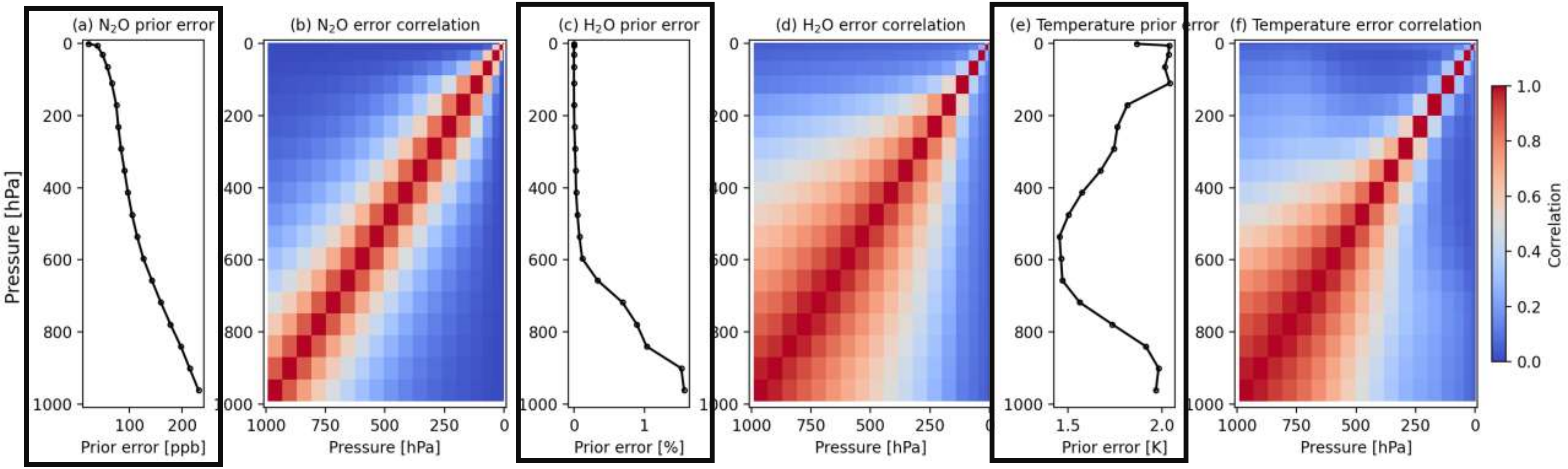


# Radiance sensitivity to state vector (Jacobians)



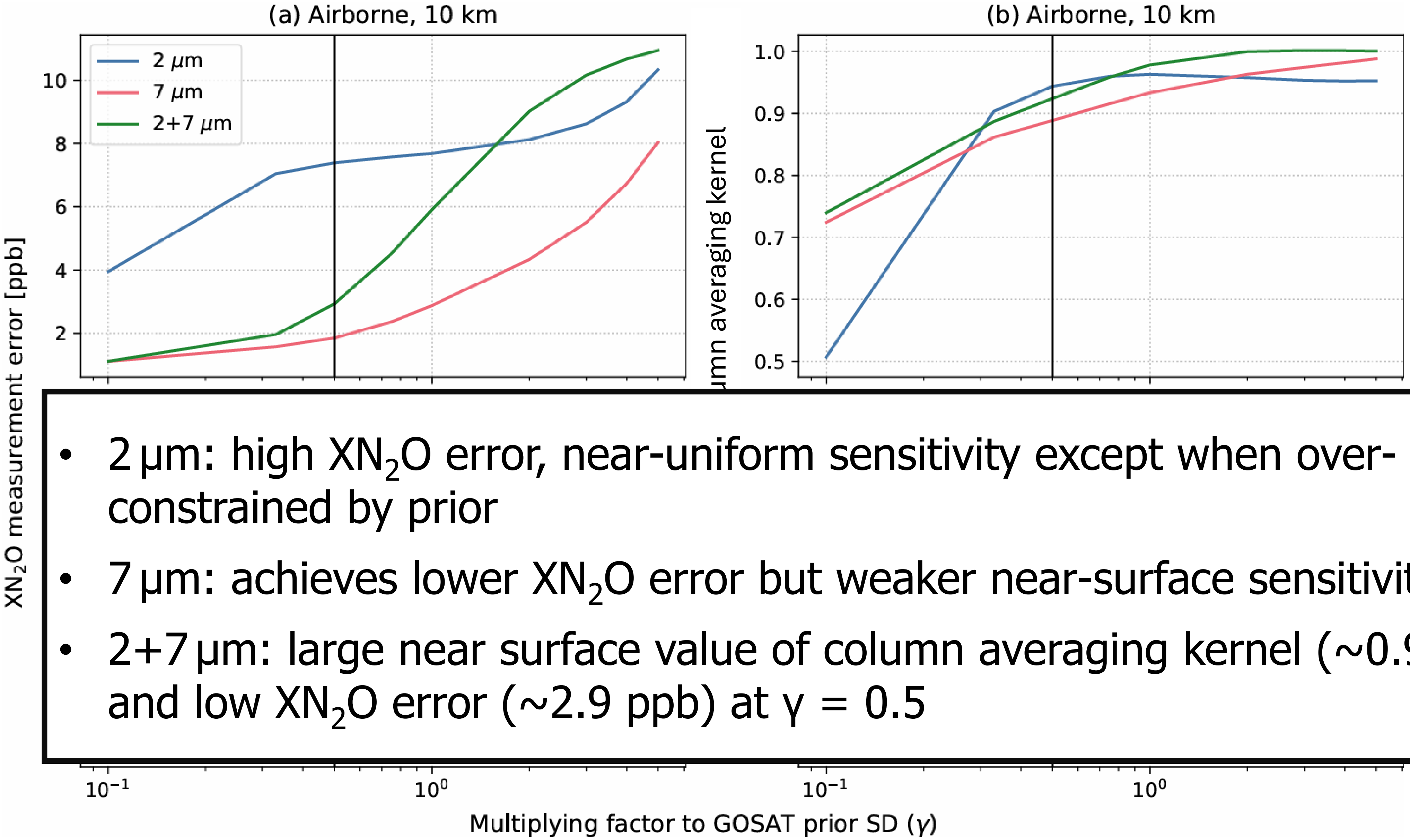

- State vector includes $N_2O$, $CH_4$, water vapor, temperature profiles, and surface temperature
- 2 µm: sensitivity to the whole column including near-surface
- 7 µm: stronger sensitivity to $N_2O$ as compared to the 2 µm band, but less sensitive to near-surface layers

# A priori constraint




- $N_2O$ prior error is derived from University of Leicester GOSAT $CH_4$ retrieval, scaled by their background concentration ratio (330 ppb / 1900 ppb)
- $H_2O$ and temperature priors are adopted from CrIS algorithm
- Scaling factor gamma (γ) is applied to $N_2O$ prior standard deviation to tune prior constraint strength

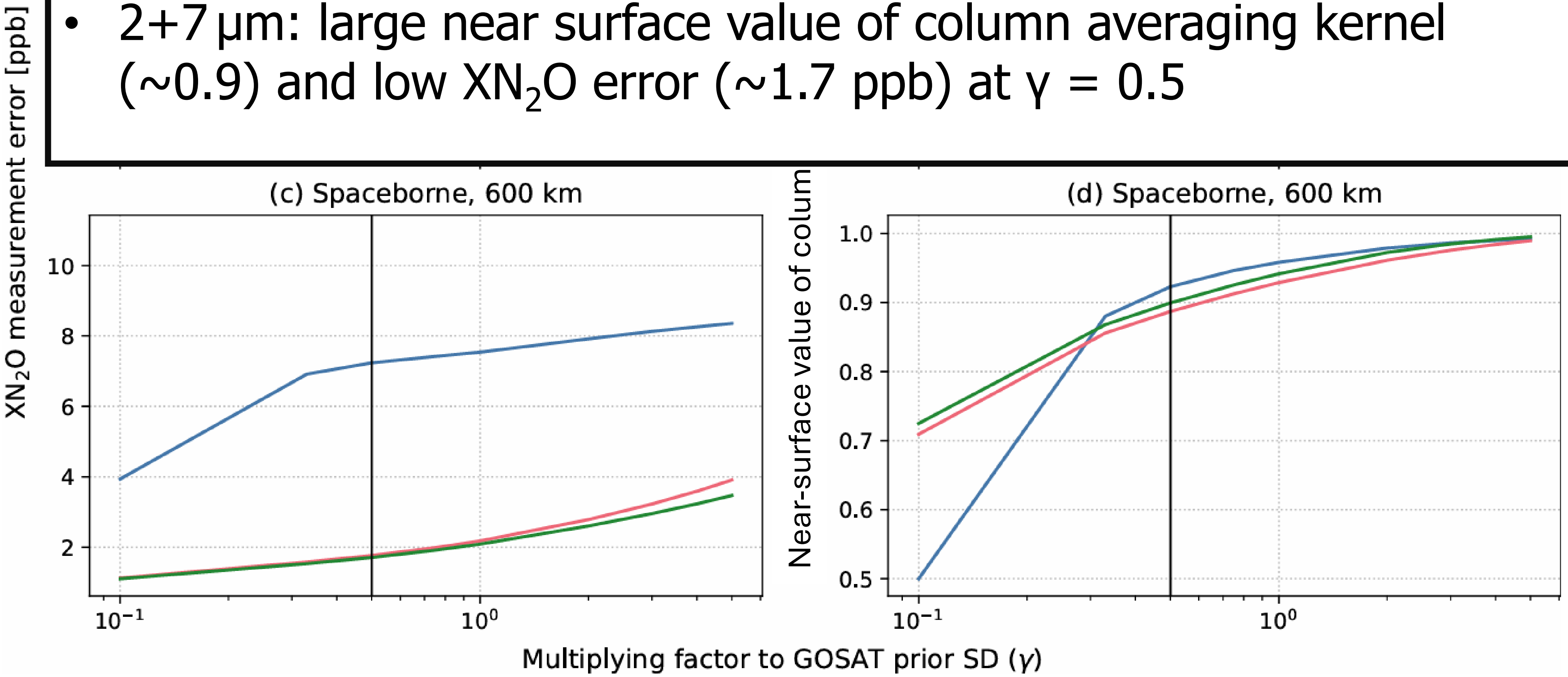
# $XN_2O$ precision




- 2 μm: high $XN_2O$ error, near-uniform sensitivity except when over-constrained by prior
- 7 μm: achieves lower $XN_2O$ error but weaker near-surface sensitivity
- 2+7 μm: large near surface value of column averaging kernel (~0.91) and low $XN_2O$ error (~2.9 ppb) at $\gamma = 0.5$

# $XN_2O$ precision

- 2 μm: highest $XN_2O$ error across all prior strengths
- 7 μm: comparable $XN_2O$ error with dual-band approach but weaker near-surface sensitivity
- 2+7 μm: large near surface value of column averaging kernel (~0.9) and low $XN_2O$ error (~1.7 ppb) at γ = 0.5



# How precisely can we observe $XN_2O$?

Using 2 µm and 7 µm integration and at a moderate prior strength ($\gamma = 0.5$), we achieve:

- 2.9 ppb $XN_2O$ error for airborne
- 1.7 ppb $XN_2O$ error for spaceborne
- ~0.9 near surface value of column averaging kernel for both

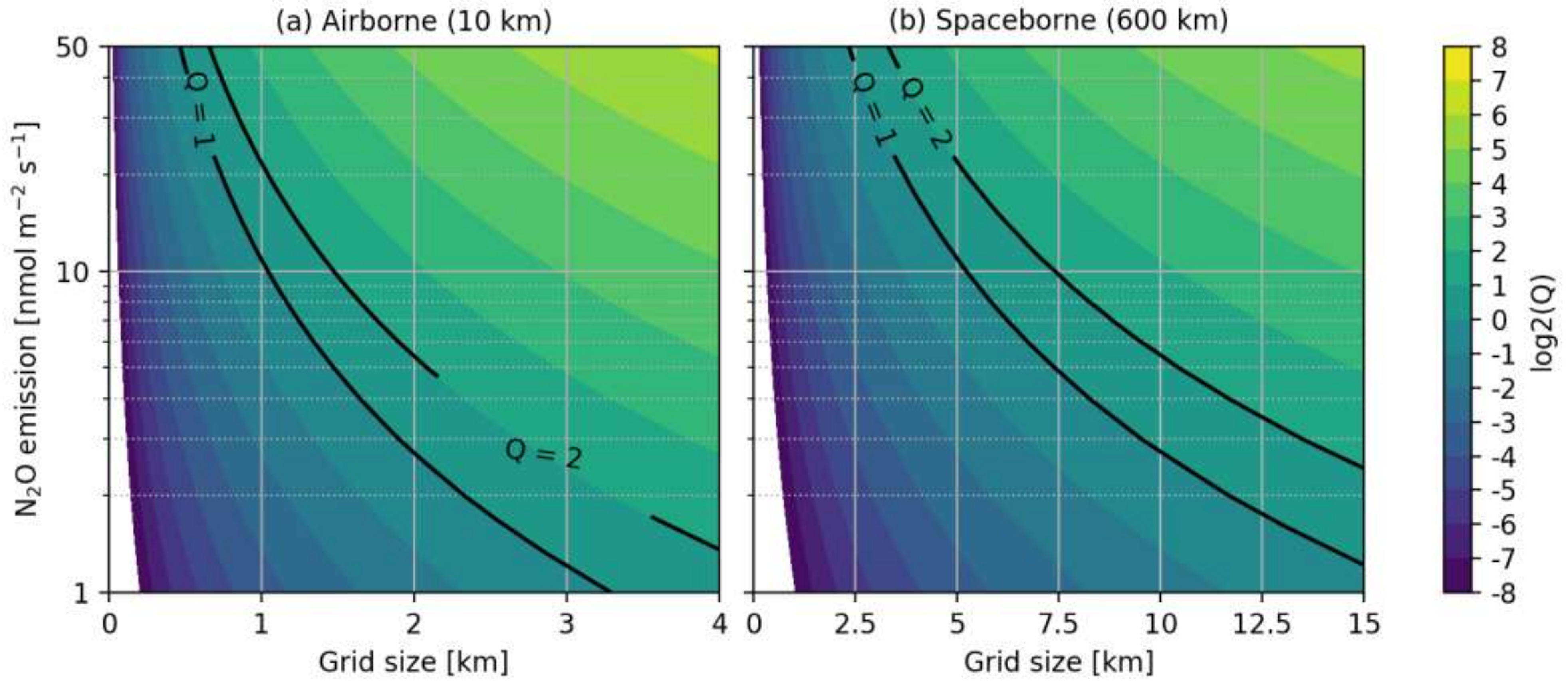
**With those precisions, can we detect actual surface emissions, and at what spatial scale?**

# Estimating $N_2O$ emissions using errors

$$Q = \frac{Emission\ induced\ enhancement\ (\Delta\Omega)}{Column\ error\ (\sigma_\Omega)} = \frac{E\Delta x^2 M_{air} g}{|u|\sigma_{XN2O} x_0 P_{air}}$$

| Parameter | Value [unit] |
|---|---|
| Emissions (E) | 1-50 [nmol $m^{-2}$ $s^{-1}$] |
| Airborne ground sampling distance ($x_{0\_air}$) | 7.7 [m] |
| Spaceborne ground sampling distance ($x_{0\_space}$) | 330 [m] |
| Airborne aggregation scale ($\Delta$x) | $X_{0\_air}$ to 4 [km] |
| Spaceborne aggregation scale ($\Delta$x) | $X_{0\_space}$ to 15 [km] |
| Molar mass of dry air ($M_{air}$) | 0.029 [kg $mol^{-1}$] |
| Acceleration due to gravity (g) | 9.8 [m $s^{-2}$] |
| Wind speed ($|u|$) | 1.389 [m $s^{-1}$] |
| Airborne $\sigma_{XN2O}$ | 2.9 [ppb] |
| Spaceborne $\sigma_{XN2O}$ | 1.7 [ppb] |
| Pressure ($P_{air}$) | 1e5 [Pa] |

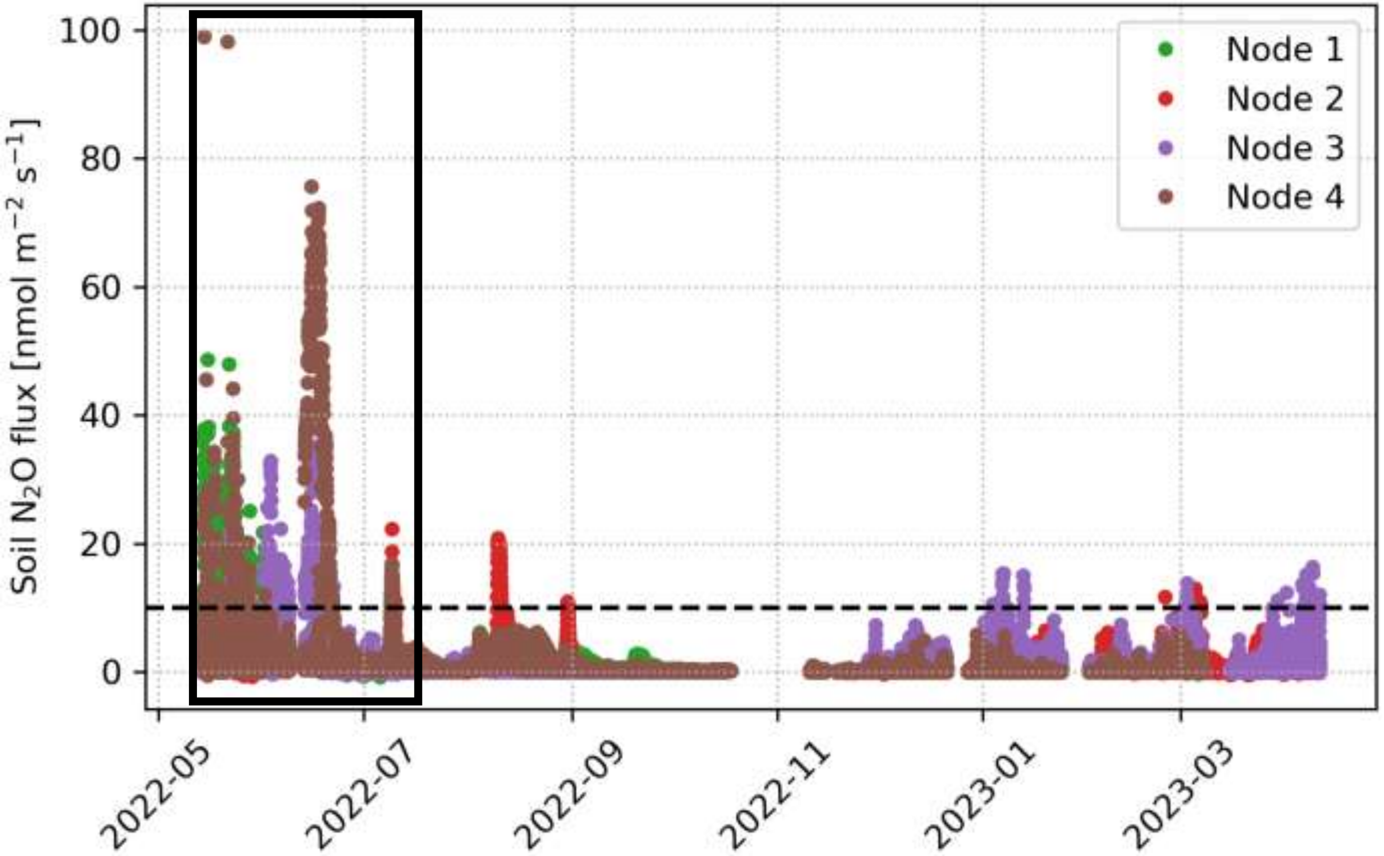
# Estimating $N_2O$ emissions using errors




- Airborne: 10 nmol $m^{-2}$ $s^{-1}$ emission flux is observable at unit signal-to-noise ratio (Q) at ~1 km
- Spaceborne: 10 nmol $m^{-2}$ $s^{-1}$ emission flux is observable at unit signal-to-noise ratio (Q) at ~5 km

# $N_2O$ chamber data from University of Illinois

**Auto-chambers on conventionally tilled maize field in central Illinois, USA**




- 4 Nodes, 5 chambers per node
- $5 \times 10^4$ $m^2$ area of the field, with nodes 50–100 m distance apart
- 10 nmol $m^{-2}$ $s^{-1}$ or higher $N_2O$ emission does occur in the real field especially during growing season
- $N_2O$ flux correlated for nodes that are 100 m apart

# Conclusion

- Evaluated remote sensing solutions for high-resolution mapping of $N_2O$ flux variability in agricultural landscapes

- Integrating the shortwave and longwave bands deliver strong near-surface sensitivity (AVK ≈ 0.9) and low $XN_2O$ error (≈ 2.9 ppb airborne; 1.7 ppb spaceborne)

- Emission flux of 10 nmol $m^{-2}$ $s^{-1}$ is observable at Q = 1 down to ~1 km for airborne and ~5 km for spaceborne