Quantifying methane emissions from individual coal mine vents with GHGSat-D satellite observations

Daniel J. Varon[1,2], Daniel J. Jacob[1], Dylan Jervis[2], Jason McKeever[2], Berke Durak[2]

[1] Harvard University, School of Engineering and Applied Sciences
[2] GHGSat, Inc.

Introduction

- GHGSat-D was launched in June 2016 as demonstration mission for a constellation of small satellites aiming to quantify individual methane point sources from space by observing them in the shortwave infrared (SWIR) at fine spatial resolution
- The design goal for column precision is 1%-5% on pixels of resolution <50 m over ~10 km domains; this can usefully quantify methane point sources down to 0.3 tons h^{-1} (75% of United States GHGRP sources) from a single observation[1]
- Actual GHGSat-D column precision is estimated at 13% of background, with strong correlated errors in the retrieved column density fields, but GHGSat-D can still detect some strong point sources from a single observation[2]
- Time-averaging of multiple satellite observations can improve signal-to-noise, allowing smaller point sources to be resolved than would normally be possible from a single observation[3]
- We use time-averaged GHGSat-D observations to quantify methane emissions from three coal mine vents in Australia, China, and the United States

Observations

- GHGSat-D has observed the Bulianta mine in China (Inner Mongolia), the Camden mine in Australia (New South Wales), and the San Juan mine in the United States (New Mexico) between 10 and 25 times each since launch in 2016

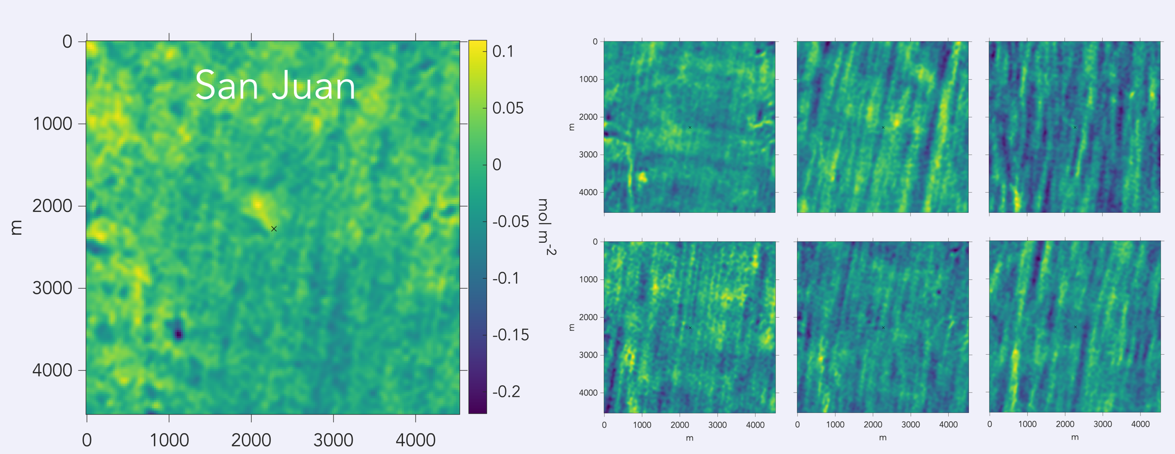


Figure 1: Example GHGSat-D observations of the San Juan mine. Some show strong instantaneous signals (left), others show no obvious signal (right).

- Coal mine emissions and local wind conditions are variable (see Figure 1)
- **Table 1:** GHGSat-D observation count by site

Bulianta	Camden	San Juan
13	12	22

Time averaging of GHGSat-D coal mine observations

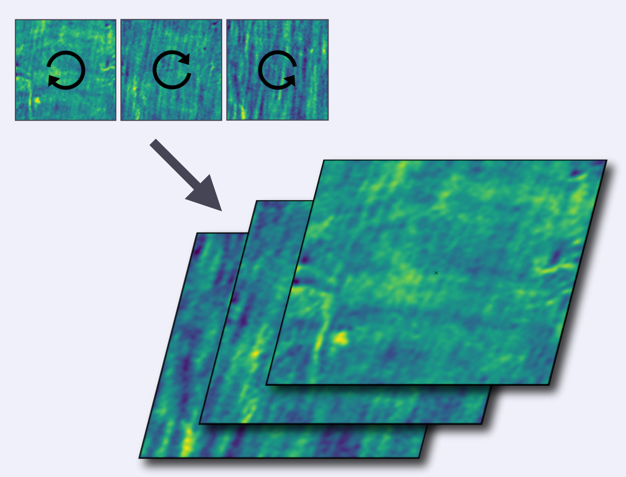


Figure 2: Rotate observations by reanalysis wind direction and stack them

- Time-averaged observations have lower background noise than instantaneous observations
- Assuming normally distributed errors and constant emissions and ventilation, averaging *N* observations reduces noise by 1/√N in the aggregate
- Actual improvements are smaller, because errors are systematic and emissions and ventilation are variable
- We rotate individual observations by an estimate of the local wind direction before averaging, to align the underlying plume signals; otherwise, the plume may be lost in the aggregation
- We use wind direction data from meteorological databases like the NASA GEOS-FP reanalysis[4] and Weather Underground[5]

Figure 3: Time averaged methane plumes from the Bulianta, Camden, and San Juan coal mine vents

Optimizing wind direction to enhance signal

- We find substantial differences between GEOS-FP modeled wind directions and measured wind directions at 10 U.S. airports[6]
- In light of this and to enhance signal, we optimize the wind directions θ used in time averaging by minimizing the following cost function:

$$J(\theta) = \frac{|\mathrm{IME} - \mathrm{IME}_{\max}|}{\sigma} + (\theta - \theta_a)^T S_a^{-1} (\theta - \theta_a)$$

- This finds the set of wind directions θ that maximizes integrated mass enhancement (IME) in the time-averaged observation while minimizing the departure from prior wind directions obtained from meteorological databases

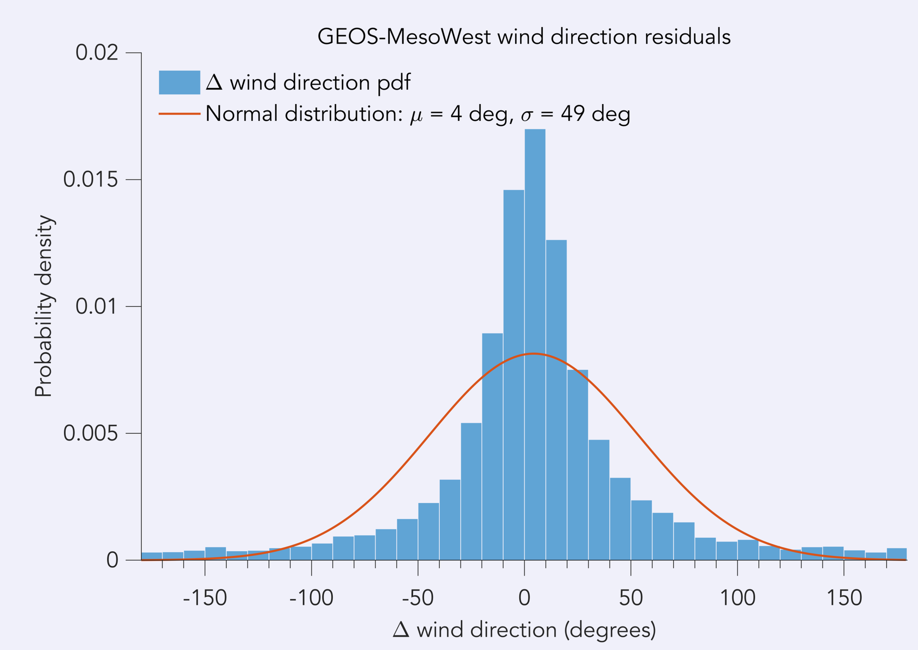


Figure 4: Residuals between modeled and measured wind directions

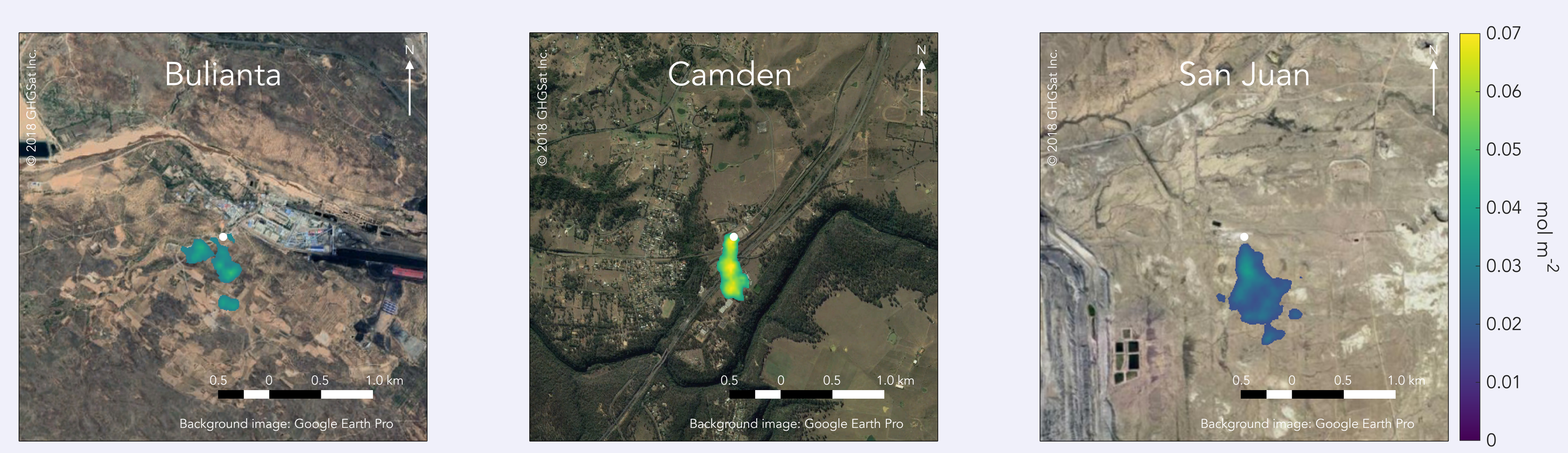
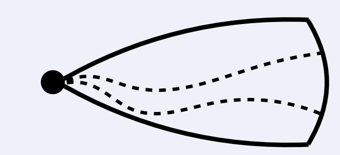


Figure 5: Time averaged methane plumes from the three coal mine vents after optimizing wind directions. Source location marked by white dot.

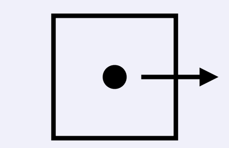
Retrieving source rates

- Four methods for retrieving source rates:



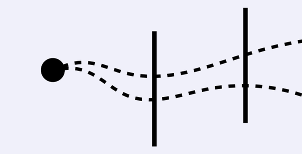
$$Q = U\Delta\Omega(x,y)\left(\sqrt{2\pi}\sigma_y(x)e^{\frac{y^2}{2\sigma_y(x)^2}}\right)$$

Gaussian plume inversion method



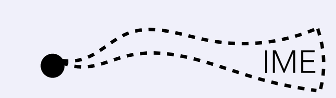
$$Q = \frac{UWp}{g\Omega_a}\Delta\Omega$$

Source pixel mass balance method



$$Q = \int_{-\infty}^{\infty} U(x,y)\Delta\Omega(x,y)dy = CU_{\mathrm{eff}}$$

Cross-sectional flux method



$$Q = \frac{1}{\tau}\mathrm{IME} = \frac{U_{eff}}{L}\mathrm{IME} = \frac{U_{eff}}{L}\sum_{j=1}^{N}\Delta\Omega_j A_j$$

Integrated mass enhancement method (IME)

- Gaussian plume inversion method fails because the plumes are not Gaussian
- Source pixel method fails due to large uncertainty in transport and turbulent diffusion at the pixel scale
- Time-averaged wind speed is computed as the mean database 10 m wind speed across all observations, and converted to effective wind speed U_{eff} using[1]:

IME: $U_{\mathrm{eff}} = 1.1\log(U_{10}) + 0.6\ \ \mathrm{m\ s^{-1}}$

Cross-sectional flux: $U_{\mathrm{eff}} = 1.3U_{10}\ \ \mathrm{m\ s^{-1}}$

- **Table 2:** Source rates (kg h^{-1}) by site and retrieval method

	Bulianta	Camden	San Juan
IME	1650	2650	1500
Cross-sectional flux	2300	3900	2100
Previous estimates	None	1000-10,800 [7]	360-2800 [8]

Conclusions

- Aggregating observations from multiple overpasses improves GHGSat-D's ability to quantify coal mine methane emissions
- Source rates retrieved with the IME and cross-sectional flux methods are consistent with previous estimates
- Rotating observations with optimized wind directions helps preserve plume signal in the time-averaged observation

References

1. Varon, D. J., Jacob, D. J., McKeever, J., Durak, B., Jervis, D., Xia, Y., Huang, Y. *Atmos. Meas. Tech.* **2018**, 11, 5673-5686, https://doi.org/10.5194/amt-11-5673-2018.
2. Jervis, D., McKeever, J., Gains, D., Varon, D. J., Germain, S., Sloan, J., Durak, B. Abstract (A54G-07) presented at 2018 AGU Fall Meeting, Washington DC, 10-14 December **2018**.
3. Pommier, M., McLinden, C. A., Deeter, M. *Geo. Res. Let.* **2013**, 40, 3766-3771, https://doi.org/10.1002/grl.50704.
4. Global Modeling and Assimilation Office (GMAO): GEOS-FP, available at: https://portal.nccs.nasa.gov/cgi-lats4d/opendap.cgi? &path=
5. *Weather Underground*, The Weather Company, https://www.wunderground.com/
6. University of Utah: MesoWest database, available at: http:// mesowest.utah.edu/
7. Ong, C., Day, S., Halliburton, B.,Marvig, P., White, S. (**2017**). Regional methane emissions in NSW CSG basins. CSIRO, Australia.
8. Frankenberg, C. et al. *Proc. Nat. Aca. Sci.* **2016**, 113 (35), 9734-9739, https://doi.org/10.1073/pnas.1605617113