Empa
Materials Science and Technology

CoCO2
Prototype system for a Copernicus CO_2 service

Co-ordinated by ECMWF

ENHANCING AND DETECTING CO_2 PLUMES IN SATELLITE IMAGES USING COMPUTER VISION DENOISING, INPAINTING, AND RIDGE TRACING

Erik Koene, Gerrit Kuhlmann, Dominik Brunner

Empa, Dübendorf, Switzerland
24/11/2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958927.

Content

Background

Denoising

Inpainting

Ridge tracing

Simple examples followed by an application to satellite data

Discussion & summary

Background

Copernicus Carbon Dioxide Monitoring (CO2M) satellite constellation

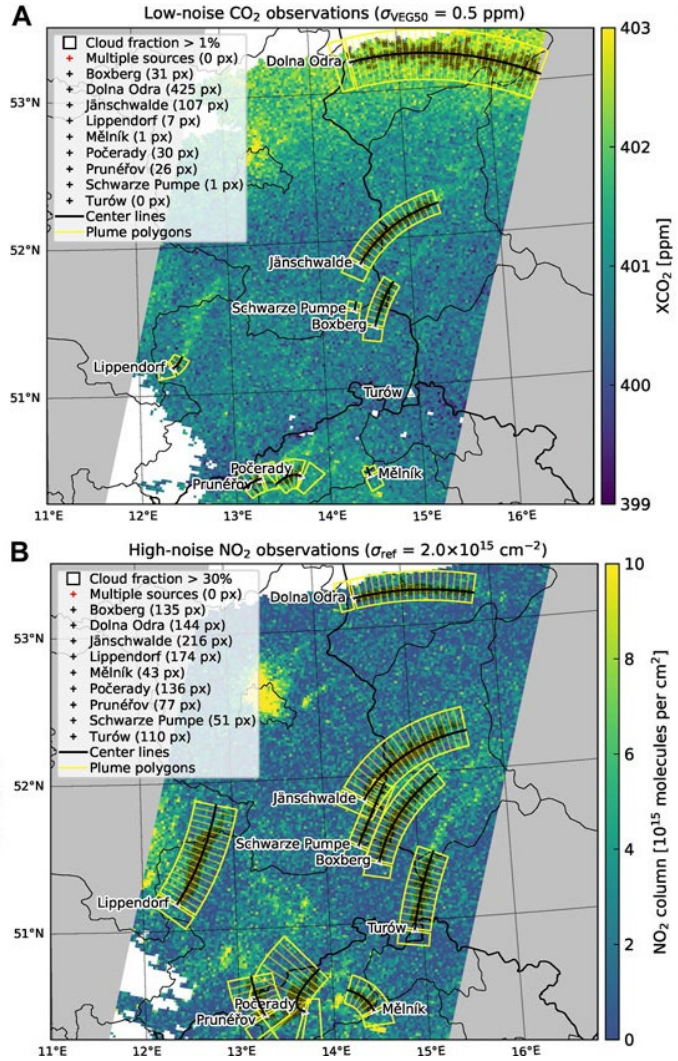
- To be launched in 2025
- 2×2 km^2 resolution
- Measures CO_2 [$\sigma_{VEG50} \approx 0.7$ ppm] and NO_2 [$\sigma_{ref} \approx 10^{15}$ molecules/cm^2] images

Purpose of this study

- **Evaluate potential of established computer-vision techniques** on satellite images
- Focus on **detecting plumes in future CO2M satellite images**

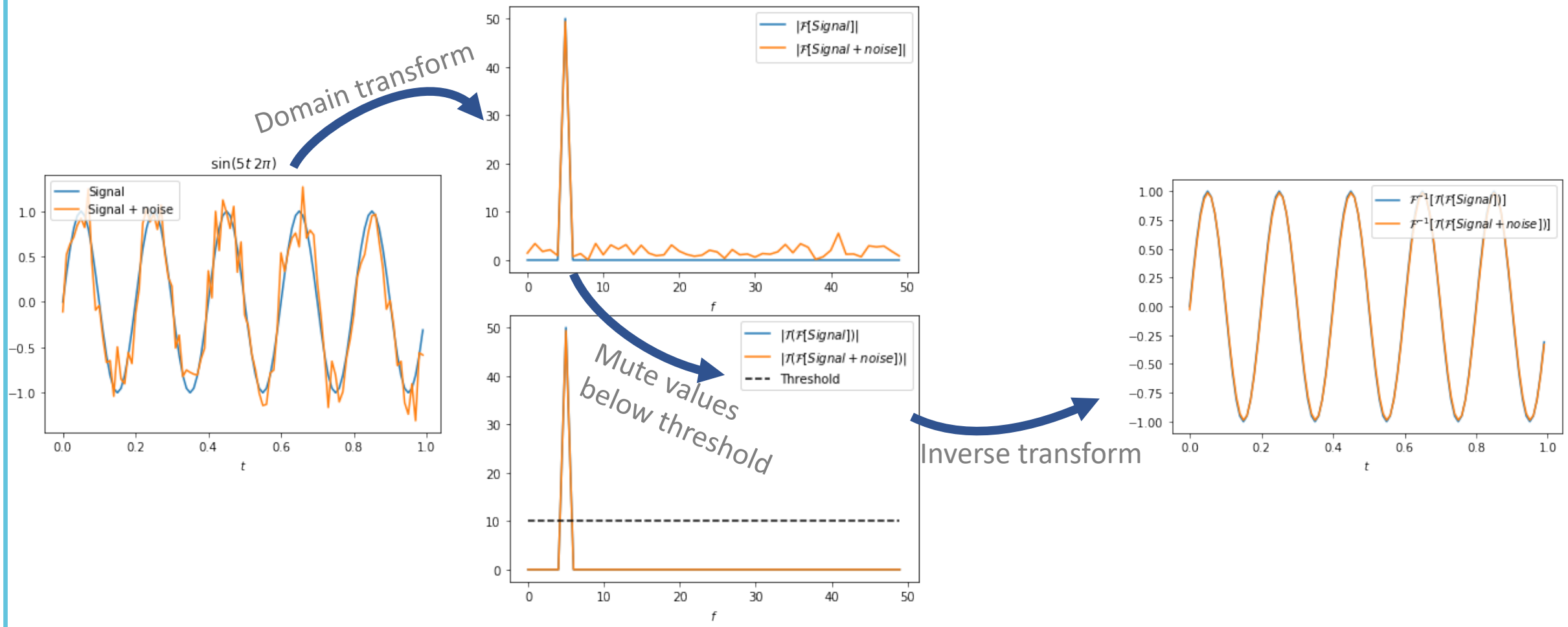
Used input data:

- Synthetic data generated in SMARTCARB project [Kuhlmann et al., 2021]



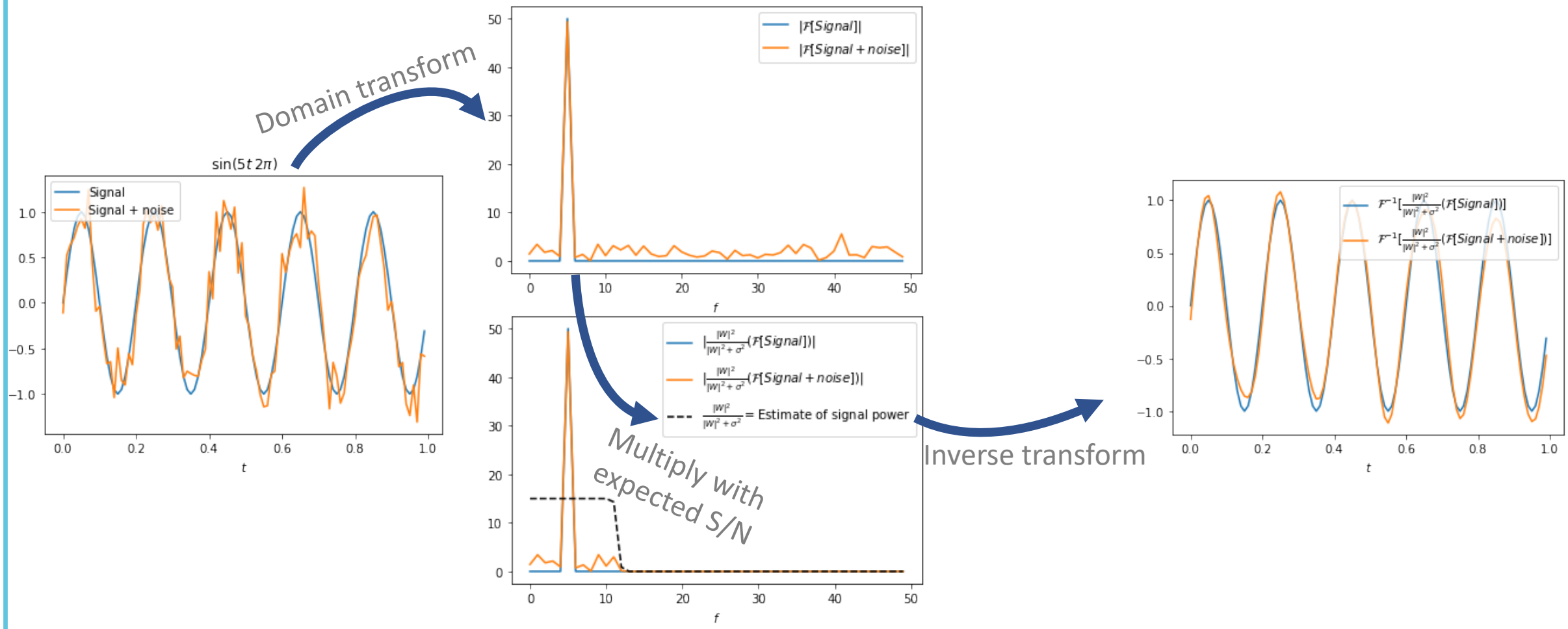
Denoising – example 1: hard thresholding

Denoising (suppress incoherent noise)

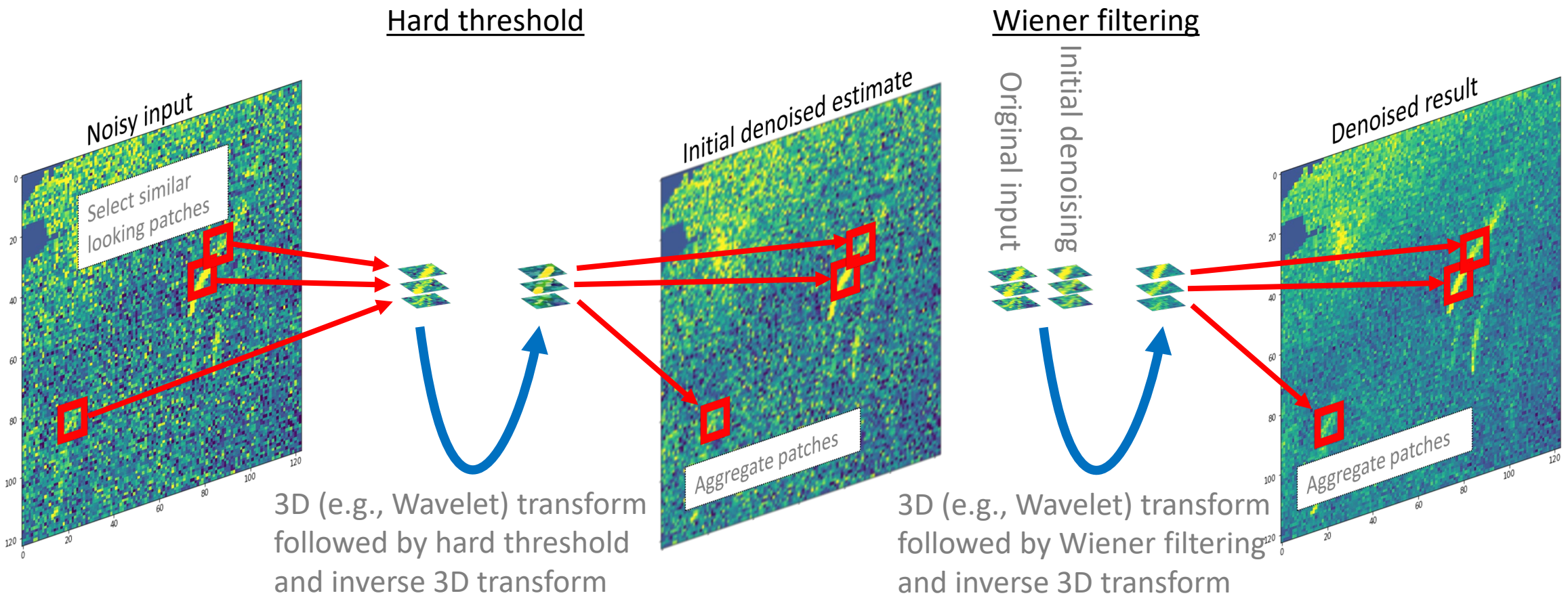


Denoising – example 2: Wiener filtering

Denoising (suppress incoherent noise)



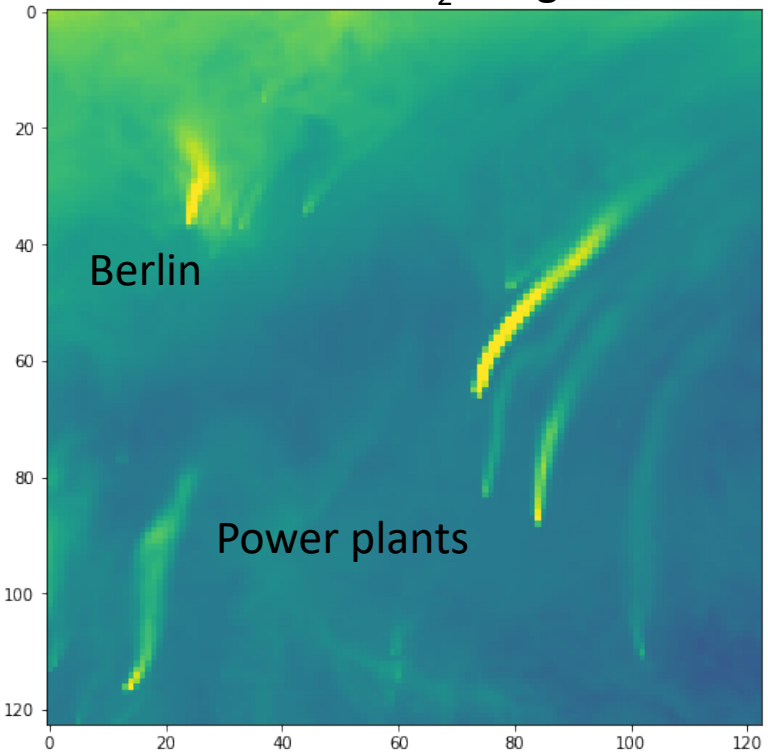
Denoising – BM3D



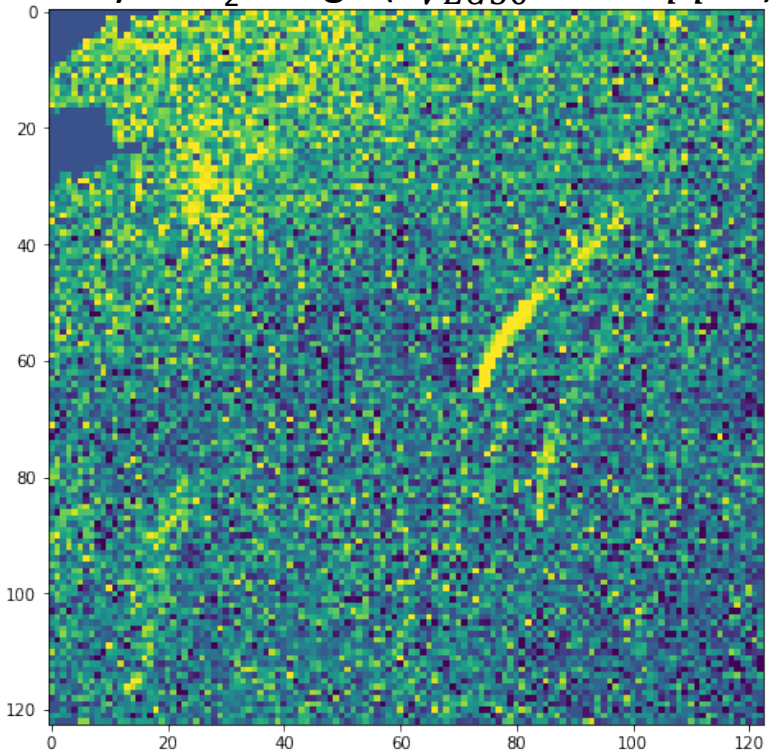
[Dabov et al. (2007)]

BM3D applied to satellite data

Noise free CO_2 image

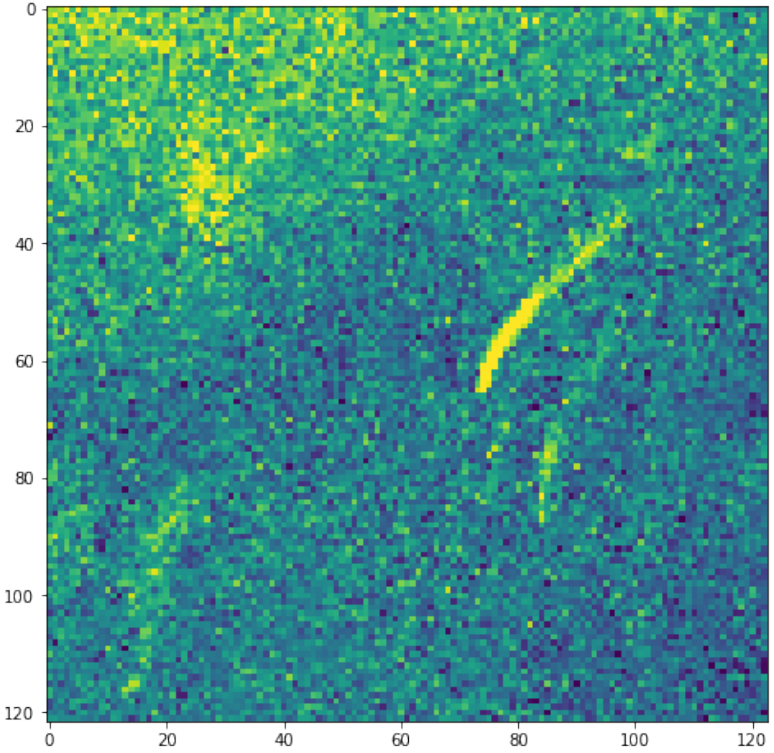


Noisy XCO_2 image ($\sigma_{VEG50} = 0.7\ ppm$)



4% structural similarity

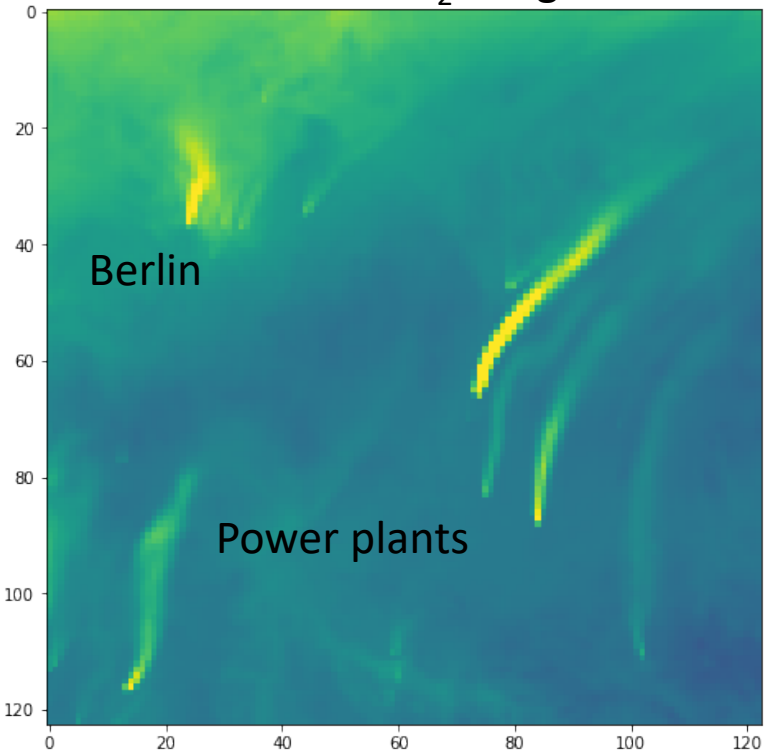
BM3D denoised



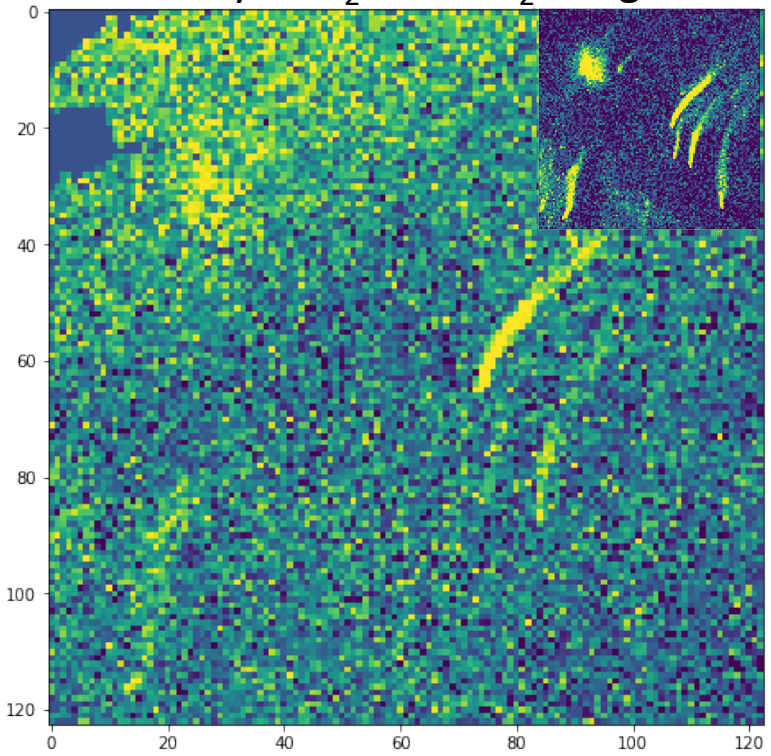
17% structural similarity; +6 dB PSNR

BM3D applied to satellite data

Noise free CO_2 image

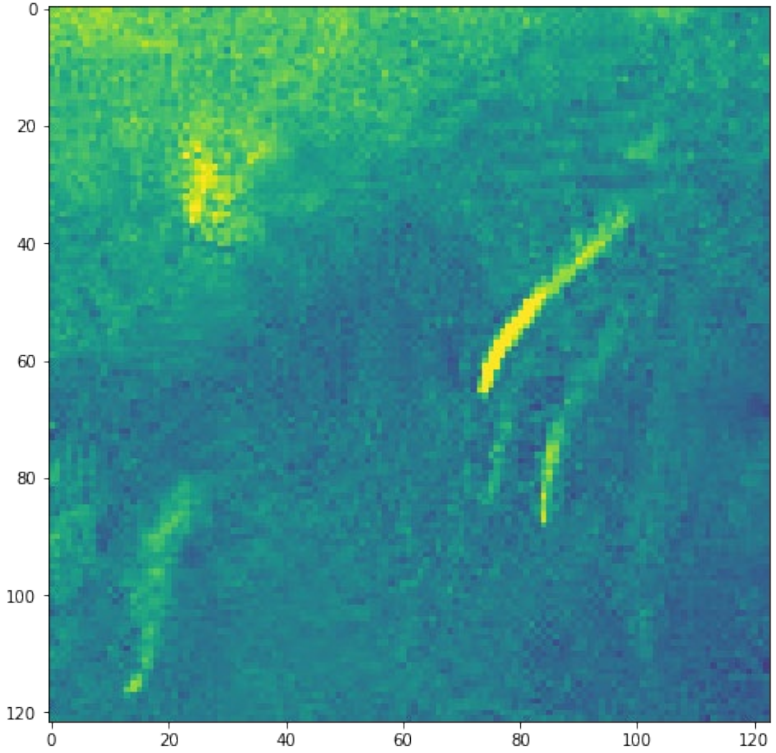


Noisy XCO_2 and NO_2 images



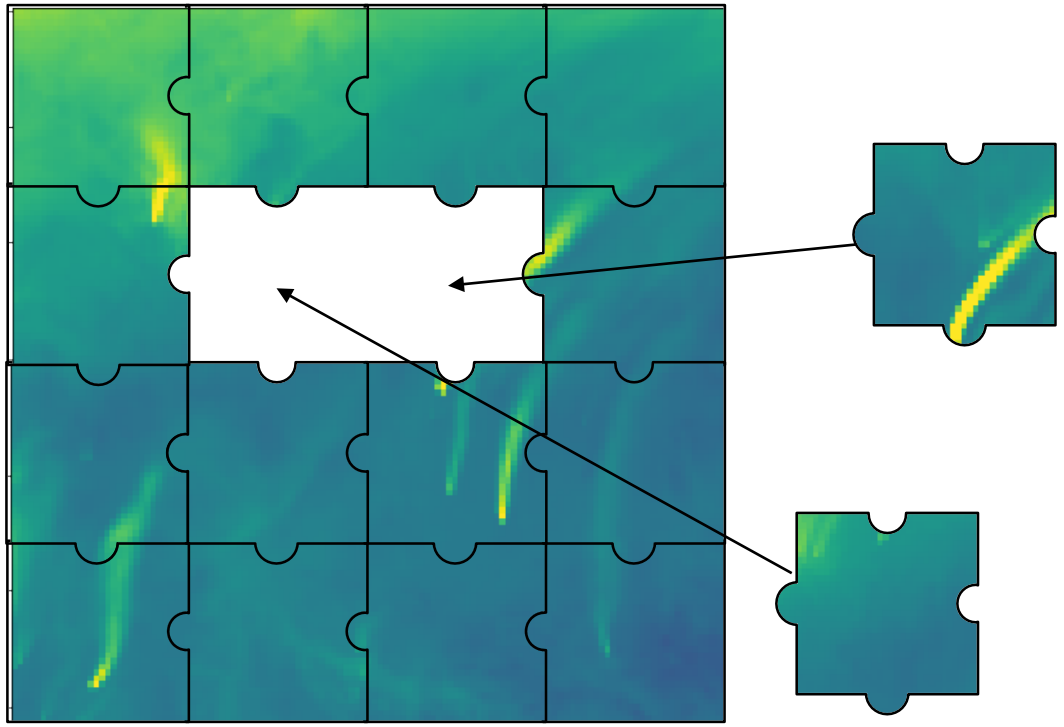
4% structural similarity

BM3D denoised using both inputs



53% structural similarity; +12 dB PSNR

Inpainting is like a jigsaw puzzle without pieces

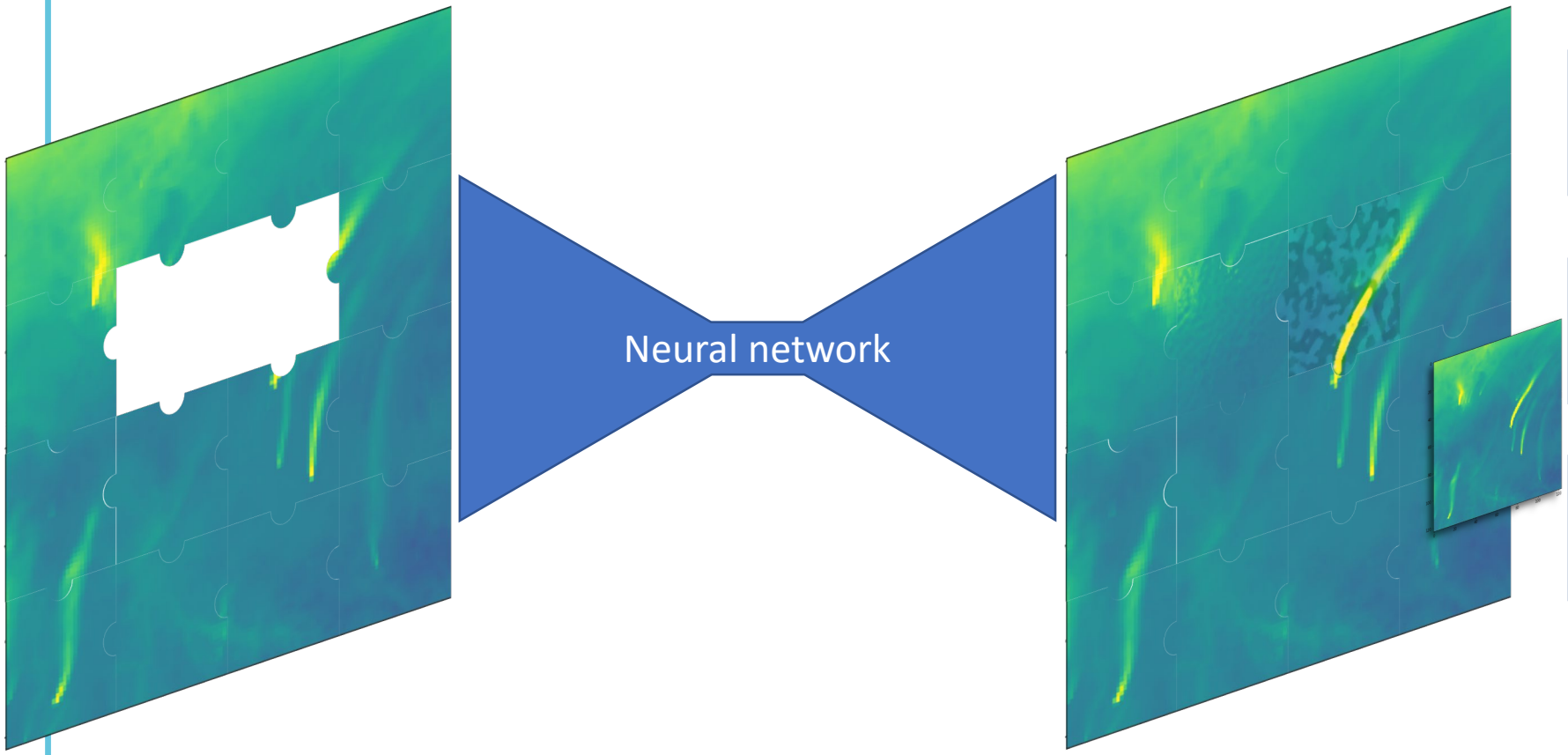


We complete jigsaw puzzles by trying to match patches that fit well with the surrounding data.

We perform inpainting in a similar way, but teach a computer to ***generate*** the missing jigsaw pieces, such that:

1. The filled patches look structurally similar to rest of image
2. The filled patches connect well to the rest of the image
3. The filled images looks ‘plausible’

Inpainting with a neural network



How (dis)similar are the generated patches to existing patches?

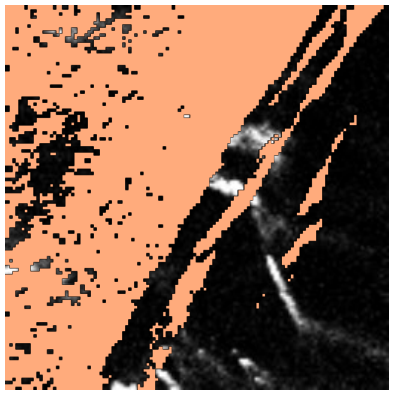
How similar to the groundtruth?

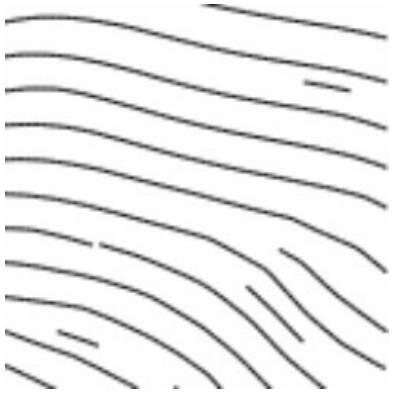
How fake does it look compared to the groundtruth?

[Zeng et al. (2021)]

Example application on satellite data

Image masked by cloud cover

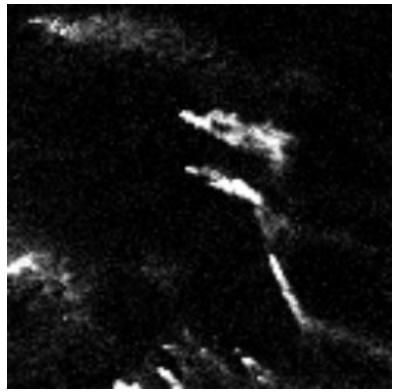




Wind field

Inpainted image

Ground truth



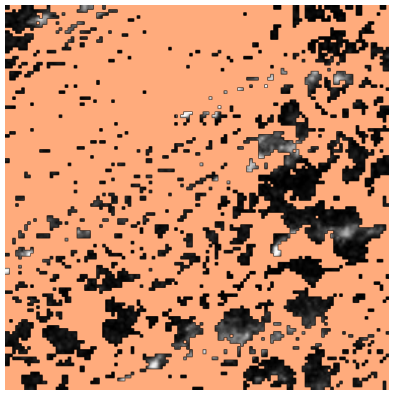
The inpainted images appear realistic, and correctly *connect* plumes that were disjoint by cloud cover

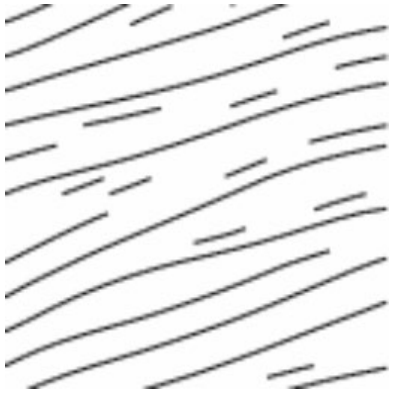
Note: at this stage, we do not recommend to use inpainted data for emissions estimations, just as a way to connect disjoint plume patches.

(addition of wind field reduces average L_1 error by 55%)

Example application on satellite data

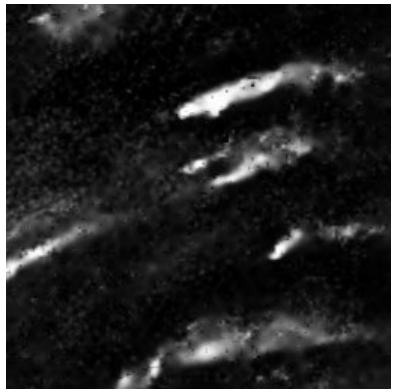
Image masked by cloud cover



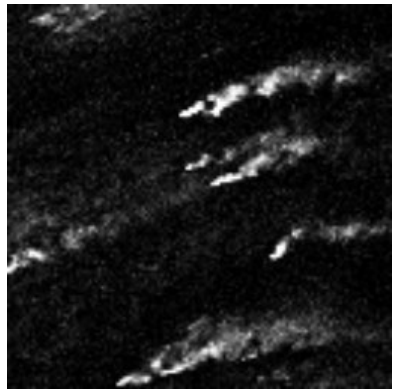


Wind field

Inpainted image



Ground truth

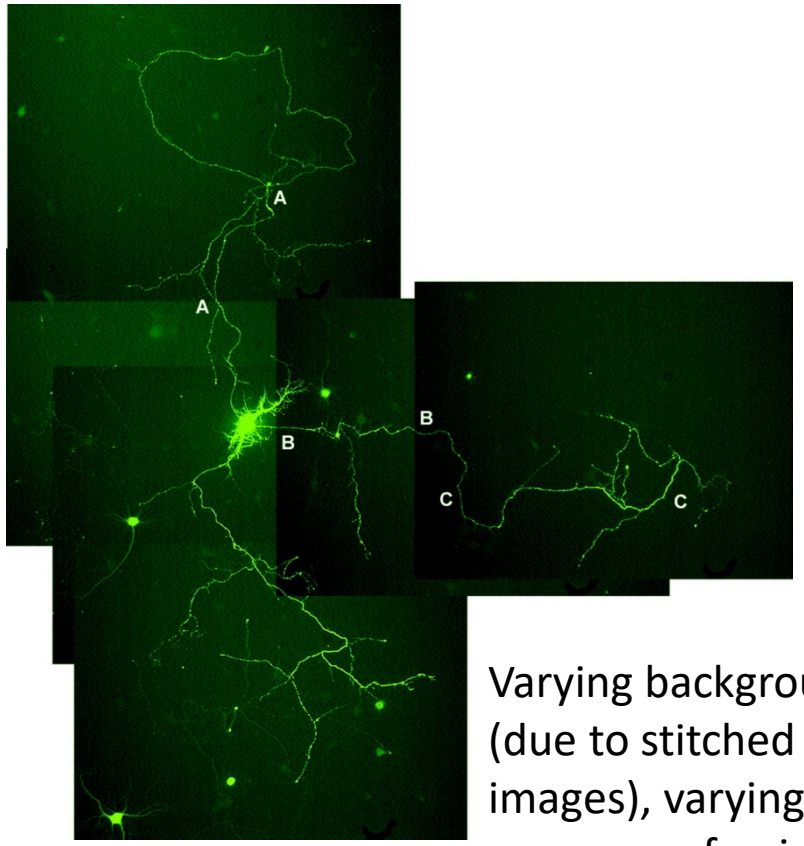


The inpainted images appear realistic, and correctly *connect* plumes that were disjoint by cloud cover

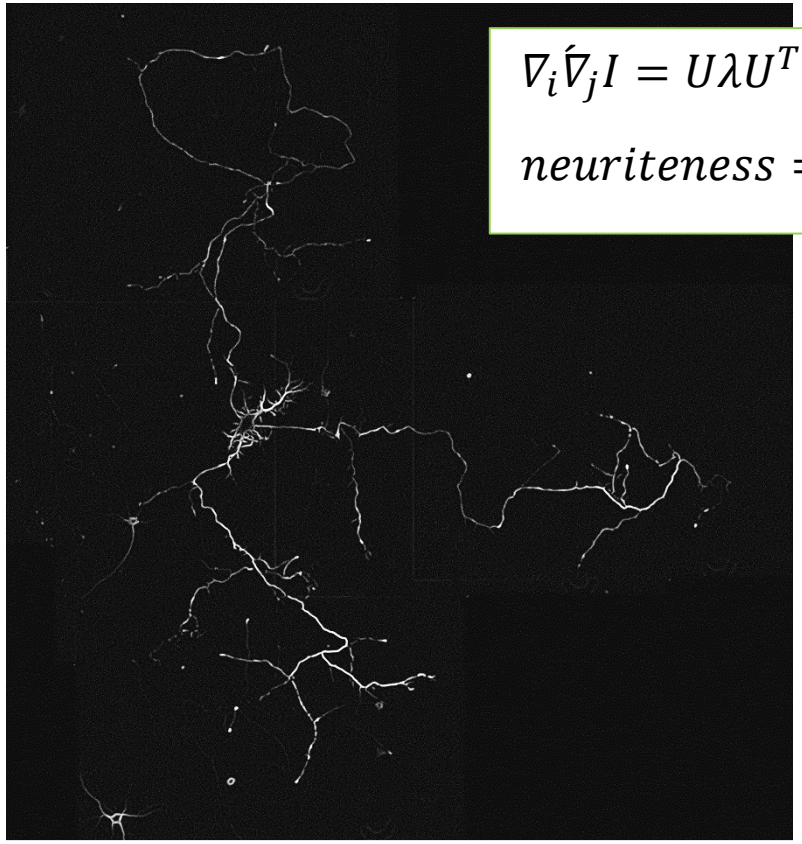
Note: at this stage, we do not recommend to use inpainted data for emissions estimations, just as a way to connect disjoint plume patches.

(addition of wind field reduces average L_1 error by 55%)

Neurite detection



Varying background strengths (due to stitched microscope images), varying contrast, in presence of noise

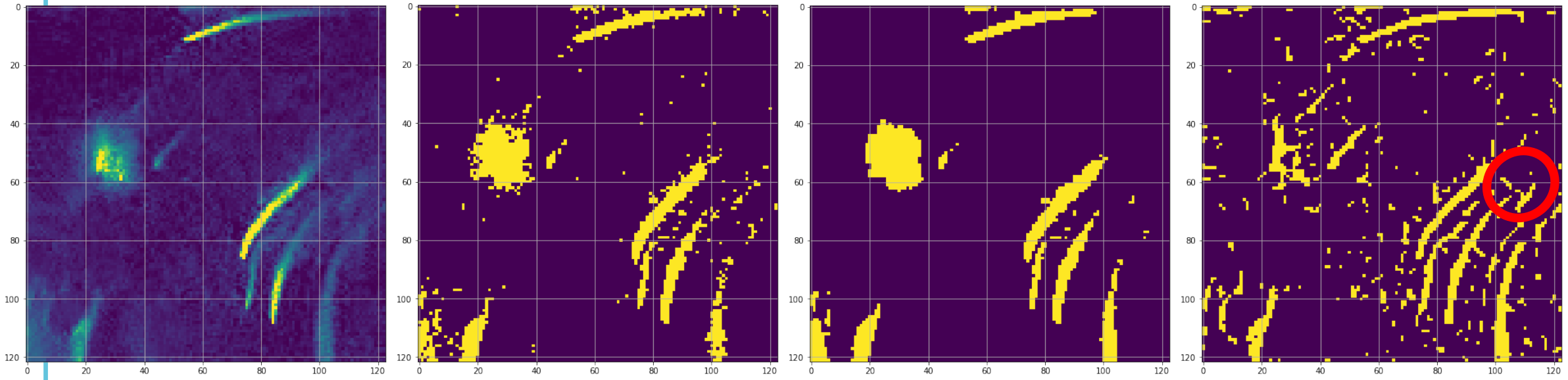


$$\nabla_i \bar{\nabla}_j I = U \lambda U^T$$

$$neuriteness = \frac{\lambda_{max}}{\lambda_{min}}$$

[Meijering et al. (2004)]

Plume detection



Too sensitive...

NO_2 (BM3D denoised)

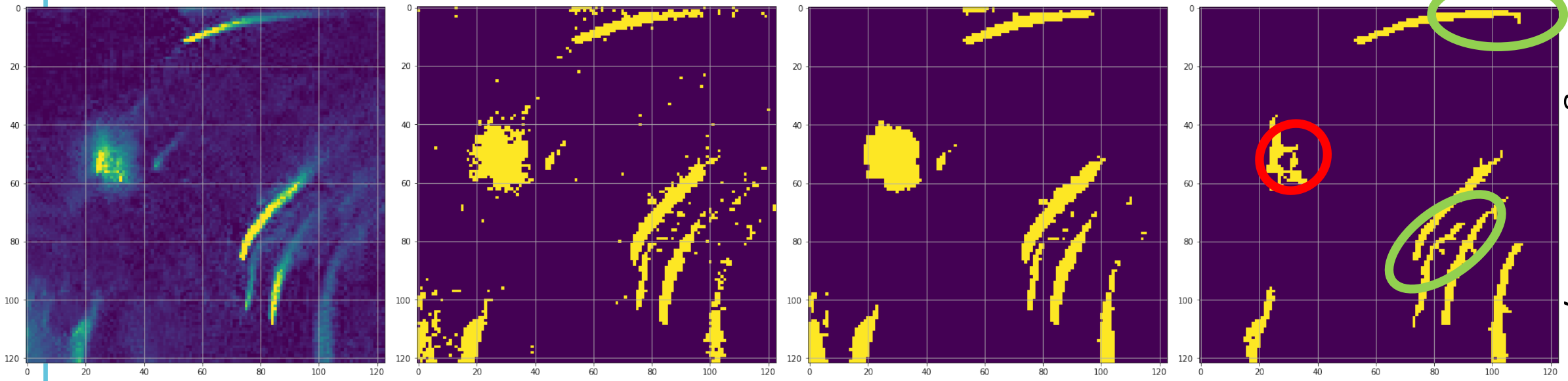
$$\frac{NO_2 - \mu}{\sigma^2} > P_z(0.99)$$

$$\frac{BM3D[NO_2] - \mu}{\sigma^2} > P_z(0.99)$$

Meijering

[Kuhlmann et al., 2019, 2021]

Plume detection



NO_2 (BM3D denoised)

$$\frac{NO_2 - \mu}{\sigma^2} > P_z(0.99)$$

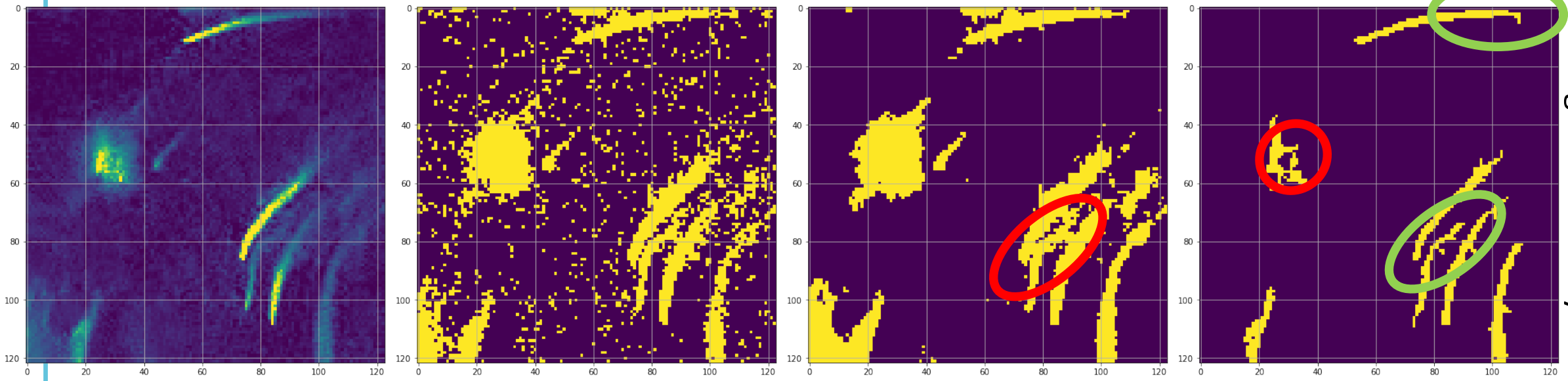
$$\frac{BM3D[NO_2] - \mu}{\sigma^2} > P_z(0.99)$$

Meijering

Selecting plume bodies fixed to large sources only

[Kuhlmann et al., 2019, 2021]

Plume detection



NO_2 (BM3D denoised)

$$\frac{NO_2 - \mu}{\sigma^2} > P_z(\mathbf{0.85})$$

$$\frac{BM3D[NO_2] - \mu}{\sigma^2} > P_z(\mathbf{0.85})$$

Meijering

Selecting plume bodies fixed to large sources only

[Kuhlmann et al., 2019, 2021]

Plumes are detected about 10% longer without connecting to close-by plumes

Discussion & Conclusion

- The methods thus far were only applied or trained on SMARTCARB data, but as of yet untested on real satellite images
- Meijering method not well-suited for broad point-sources (such as city of Berlin), and detection of the late tail of plumes is only of limited value as emissions are more dispersed at that stage
- Many further uncertainties remain to not just detect but also **quantify** plume emissions

- BM3D shows a great potential for improving image quality by considering joint XCO_2 and NO_2 images
- Image inpainting can connect disjoint plume pixels due to cloud cover remarkably well. *NB: we recommend to use this for small cloud clover fractions only, as the data quality will be bad for large cloud cover fractions.*
- Meijering method can detect narrow plume features for long distances

References

- Dabov, K., Foi, A., Katkovnik, V., & Egiazarian, K. (2007). Image denoising by sparse 3-D transform-domain collaborative filtering. *IEEE Transactions on image processing*, *16*(8), 2080-2095.
- Kuhlmann, G., Broquet, G., Marshall, J., Clément, V., Löscher, A., Meijer, Y., & Brunner, D. (2019). Detectability of CO_2 emission plumes of cities and power plants with the Copernicus Anthropogenic CO_2 Monitoring (CO2M) missions. *Atmospheric Measurement Techniques*, 6695-6719.
- Kuhlmann, G., Henne, S., Meijer, Y. & Brunner, D. (2021) Quantifying CO_2 Emissions of Power Plants With CO_2 and NO_2 Imaging Satellites. Front. Remote Sens. 2:689838. doi: 10.3389/frsen.2021.689838
- Meijering, E., Jacob, M., Sarria, J. C., Steiner, P., Hirling, H., & Unser, M. (2004). Design and validation of a tool for neurite tracing and analysis in fluorescence microscopy images. *Cytometry Part A: the journal of the International Society for Analytical Cytology*, *58*(2), 167-176.
- Zeng, Y., Lin, Z., Lu, H., & Patel, V. M. (2021). CR-Fill: Generative Image Inpainting With Auxiliary Contextual Reconstruction. In *Proceedings of the IEEE/CVF International Conference on Computer Vision* (pp. 14164-14173).