Spectral Enhancement of Multispectral Imagery Using Partially Overlapped Hyperspectral Data and Sparse Signal Representation

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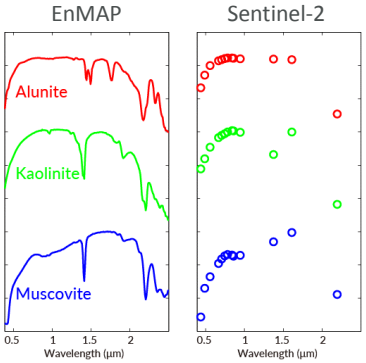
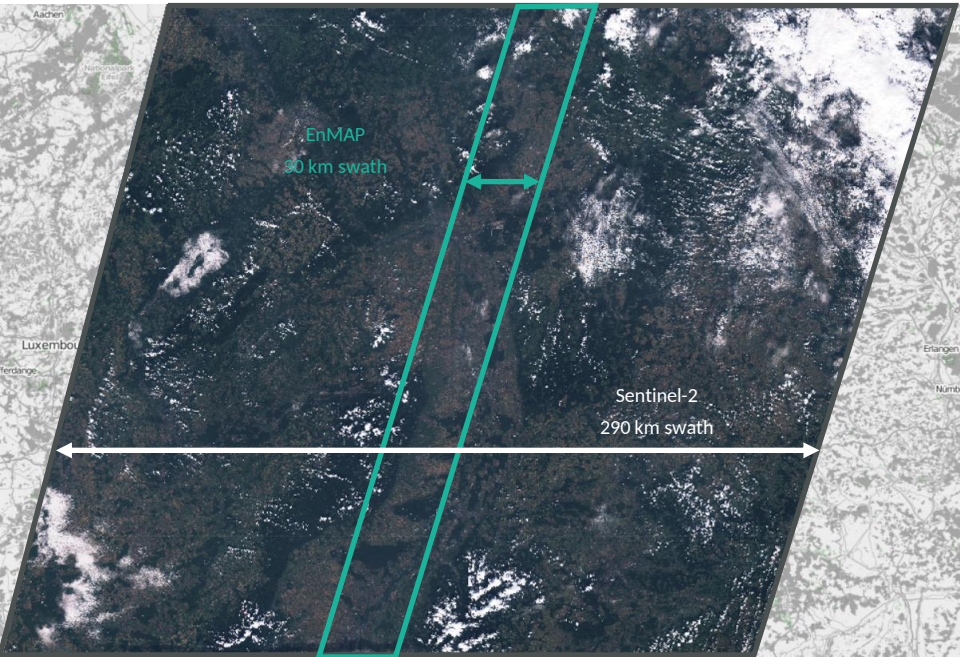
WHISPERS 2018 – September 24, 2018





DESIGN TRADEOFFS

EnMAP vs Sentinel-2

SPACEBORNE IMAGING SPECTROMETERS have tradeoffs between spectral resolution, spatial resolution, swath width (temporal resolution), and signal-to-noise ratio.

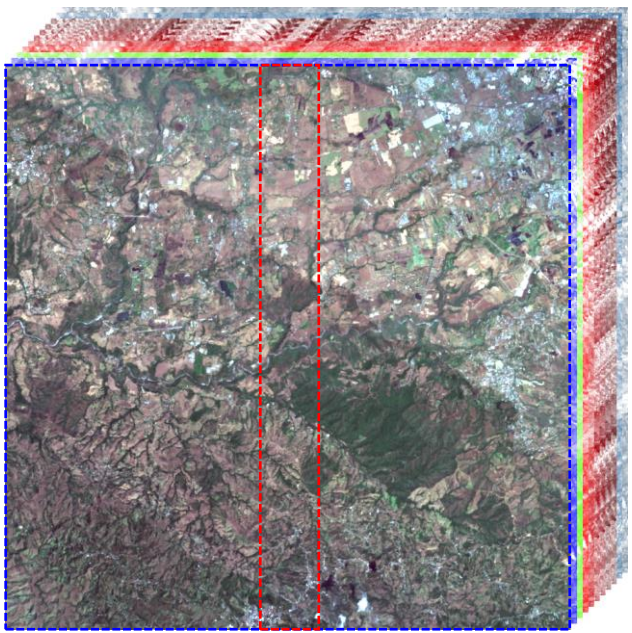
Spectral bands:
Sentinel-2: 13 bands
EnMAP: 244 bands

Temporal resolution:
Sentinel-2: 5 days
EnMAP: 27 days

Spatial resolution:
Sentinel-2: 10 - 20m
EnMAP: 30 m

SPECTRAL ENHANCEMENT OF SENTINEL-2 WITH ENMAP

Can we create EnMAP-like data for Sentinel-2 coverage?



Sentinel-2 (20 m GSD)

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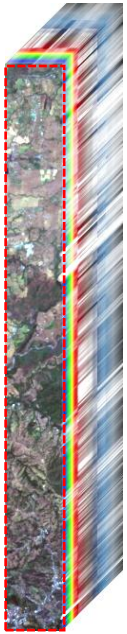
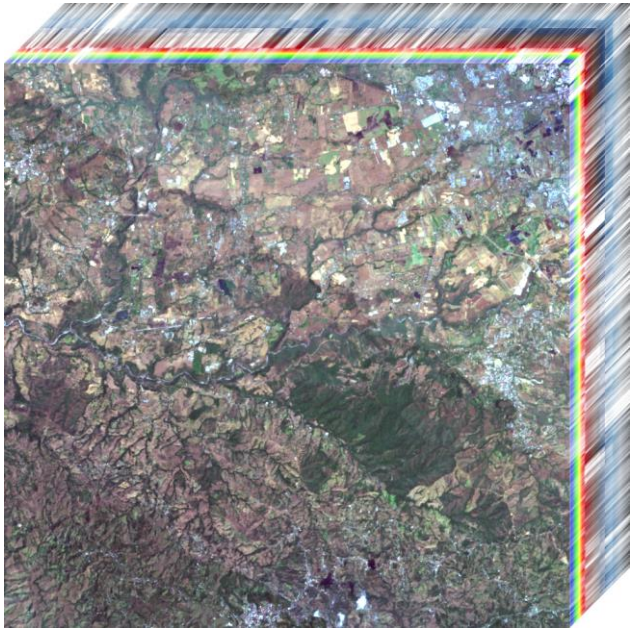
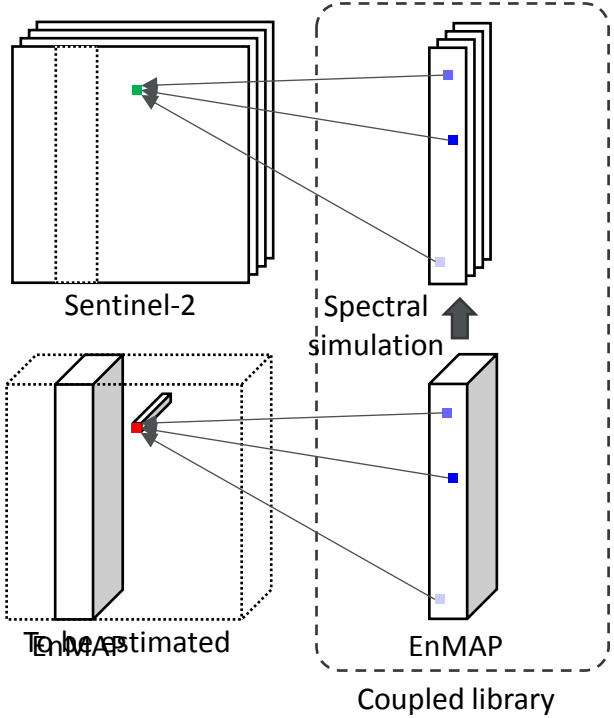


EnMAP (30 m GSD)



Reconstructed Hyperspectral Data (20 m GSD)

OUR ALGORITHM: CONCEPT



Prepare a coupled library by using spectral simulation based on spectral response function (or spatial correspondence)

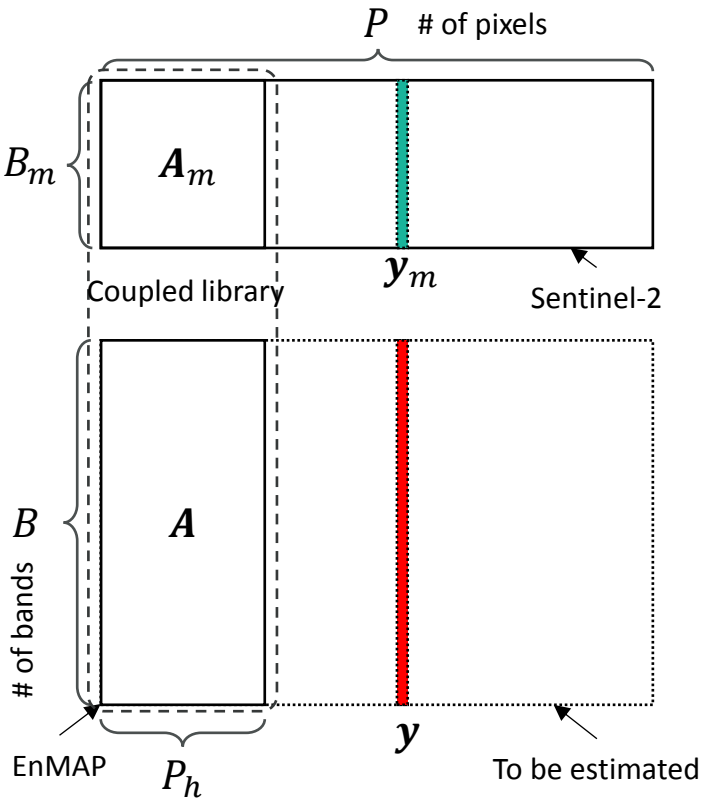
For a given target pixel

1) Find K nearest neighbors in Sentinel-2 (e.g., Euclidean distance, spectral angle distance)

2) Represent the Sentinel-2 spectrum at the target pixel by a linear combination of K nearest neighbors

3) Reconstruct the EnMAP-like spectrum at the target pixel using the coefficients learnt in Sentinel-2 and K nearest-neighbor pixel spectra from EnMAP

OUR ALGORITHM: FORMULATION



Assume that each missing spectrum can be approximated by a linear combination of the observed spectra:

$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{n}$$

S2 can be approximated by EnMAP with spectral degradation (Spectral Response Function: $\mathrm{R} \in \mathbb{R}^{B_m \times B}$)

$$\boldsymbol{y}_m = \boldsymbol{R}\boldsymbol{A}\boldsymbol{x} + \boldsymbol{n}_m$$
$$\boldsymbol{y}_m = \boldsymbol{A}_m\boldsymbol{x} + \boldsymbol{n}_m$$

Estimate coefficients

$$\min_{\boldsymbol{x}} \|\boldsymbol{y}_m - \boldsymbol{A}_m\boldsymbol{x}\|_2^2$$
$$\text{s.t.} \quad \boldsymbol{x} \geq 0, \|\boldsymbol{x}\|_0 < K + 1$$

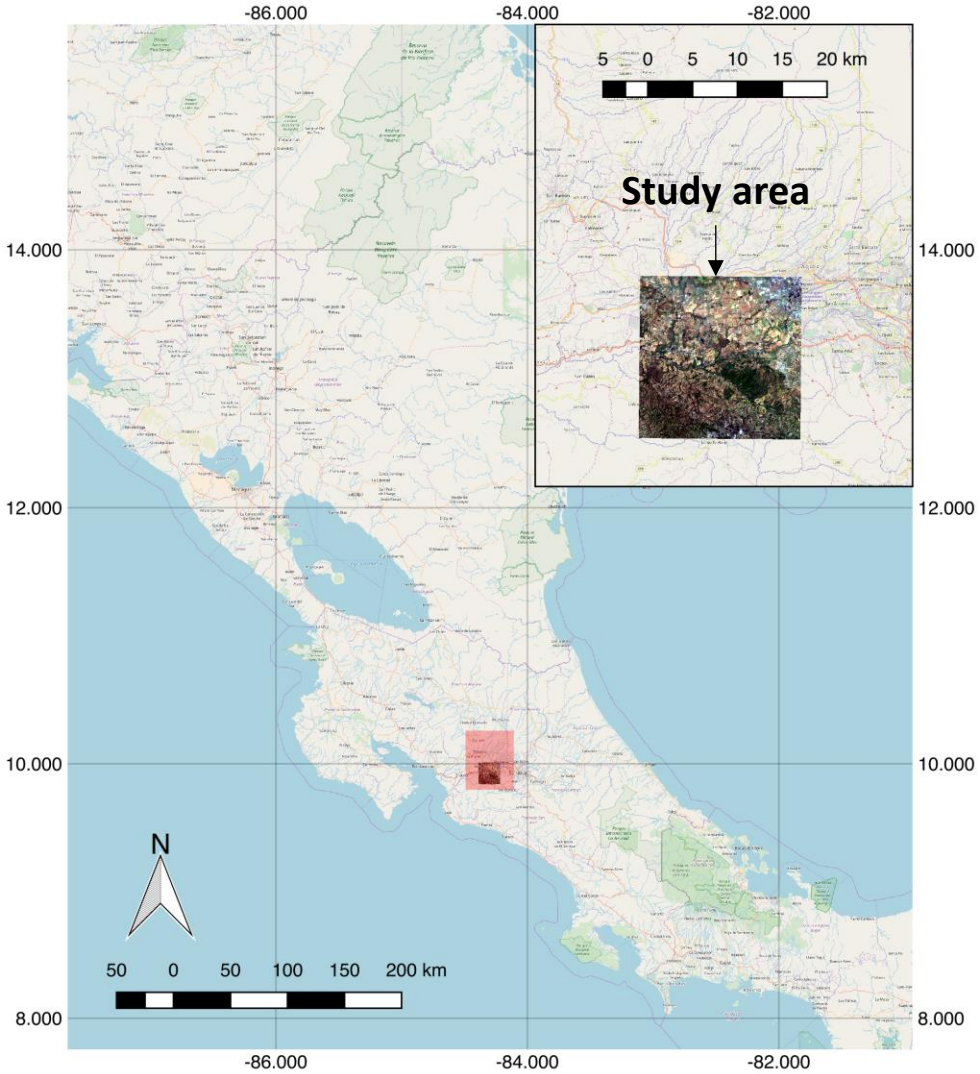
Reconstruct the EnMAP-like spectrum

$$\hat{\boldsymbol{y}} = \boldsymbol{A}\hat{\boldsymbol{x}}$$

STUDY AREA:
SAN JOSE, COSTA RICA

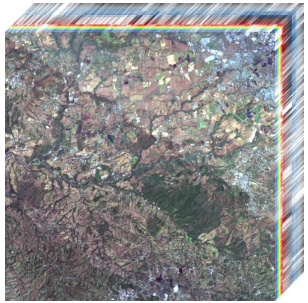
- HyMap imagery acquired over a west side of San Jose, Costa Rica, in 2005

- Main land covers include[1]
  - Photosynthetic vegetation
  - Non-photosynthetic vegetation
  - Bare soil

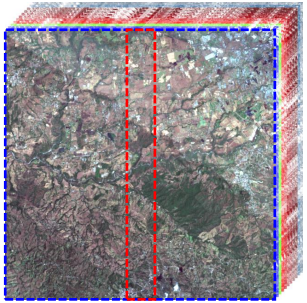


[1] S. Malec, D. Rogge, U. Heiden, A. Sanchez-Azofeifa, M. Bachmann, and M. Wegmann, "Capability of spaceborne hyperspectral EnMAP mission for mapping fractional cover for soil erosion modeling," *Remote Sensing*, vol. 7, no. 9, pp. 11776-11800, 2015.

EVALUATION METHODOLOGY: RECONSTRUCTION



HyMap (16 m GSD)



Simulated [2] **Sentinel-2**
(20 m GSD)

$$\boldsymbol{Y} \in \mathbb{R}^{B\times P} = [\boldsymbol{y}_1, \dots, \boldsymbol{y}_i, \dots, \boldsymbol{y}_B]^T = [\boldsymbol{y}_1, \dots, \boldsymbol{y}_j, \dots \boldsymbol{y}_P]$$

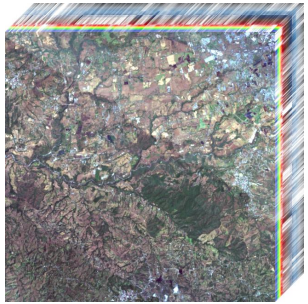
- Peak signal to noise ratio (PSNR)

$$\mathrm{PSNR} = \frac{1}{B}\sum_{i=1}^{B} 10\log_{10}\left(\frac{max(\boldsymbol{y}_i)^2}{\|\boldsymbol{y}_i - \hat{\boldsymbol{y}}_i\|_2^2/P}\right)$$

- Spectral angle mapper (SAM)

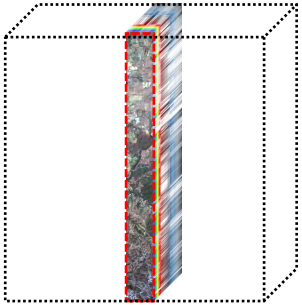
$$\mathrm{SAM} = \frac{1}{P}\sum_{j=1}^{P} \arccos\left(\frac{\boldsymbol{y}_j^T\hat{\boldsymbol{y}}_j}{\|\boldsymbol{y}_j\|_2\|\hat{\boldsymbol{y}}_j\|_2}\right)$$

Quality Measures

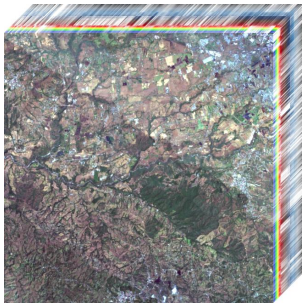


$\boldsymbol{Y}$

Simulated [2] **EnMAP Reference**
(20 m GSD)



Simulated [2] **EnMAP**
(20 m GSD, 10% swath)



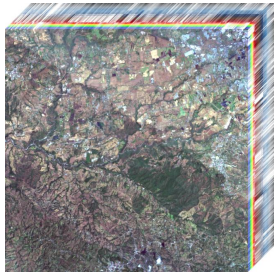
$\hat{\boldsymbol{Y}}$

Reconstructed EnMAP-like Data
(20 m GSD)

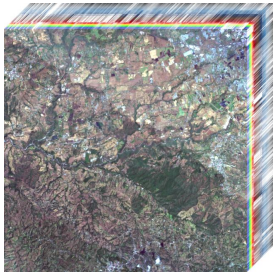
B: # of bands
P: # of pixels
$\boldsymbol{y}_i$: i-th band
$\boldsymbol{y}_j$: j-th pixel

[2] Segl, K., Guanter, L., Rogass, C., Kuester, T., Roessner, S., Kaufmann, H., Sang, B., Mogulsky, V., & Hofer, S. (2012). EeteS - THE ENMAP END-TO-END SIMULATION TOOL. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 5(2), 522–530.

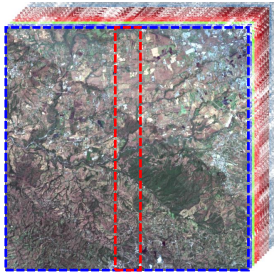
EVALUATION METHODOLOGY: UNMIXING



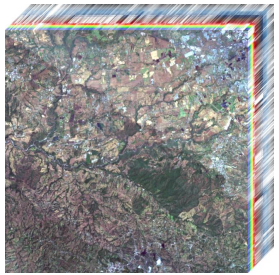
HyMap (4 m GSD)



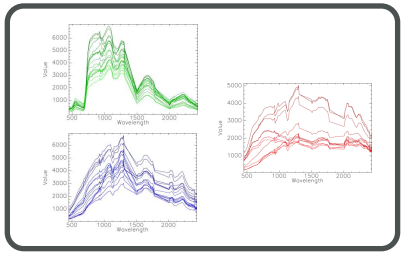
Reference EnMAP



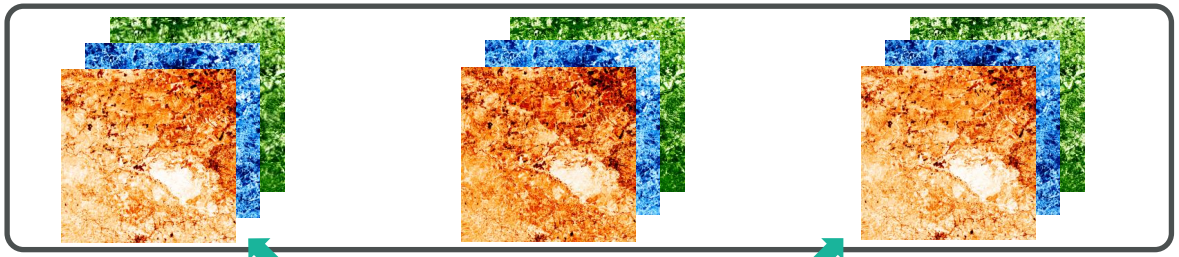
Sentinel-2



EnMAP-like Data



Endmembers
Photosynthetic vegetation
Non-photosynthetic vegetation
Bare soil
(Use endmembers in [1])



Abundance Maps

Quality measure

Root mean squared error (RMSE)

$$\mathrm{RMSE} = \sqrt{\frac{1}{MP}\left\|\boldsymbol{A} - \widehat{\boldsymbol{A}}\right\|_F^2}$$

Abundance matrix:
$\boldsymbol{A} \in \mathbb{R}^{M \times P}$ (M: # of endmembers)

[1] S. Malec, D. Rogge, U. Heiden, A. Sanchez-Azofeifa, M. Bachmann, and M. Wegmann, "Capability of spaceborne hyperspectral EnMAP mission for mapping fractional cover for soil erosion modeling," *Remote Sensing*, vol. 7, no. 9, pp. 11776-11800, 2015.

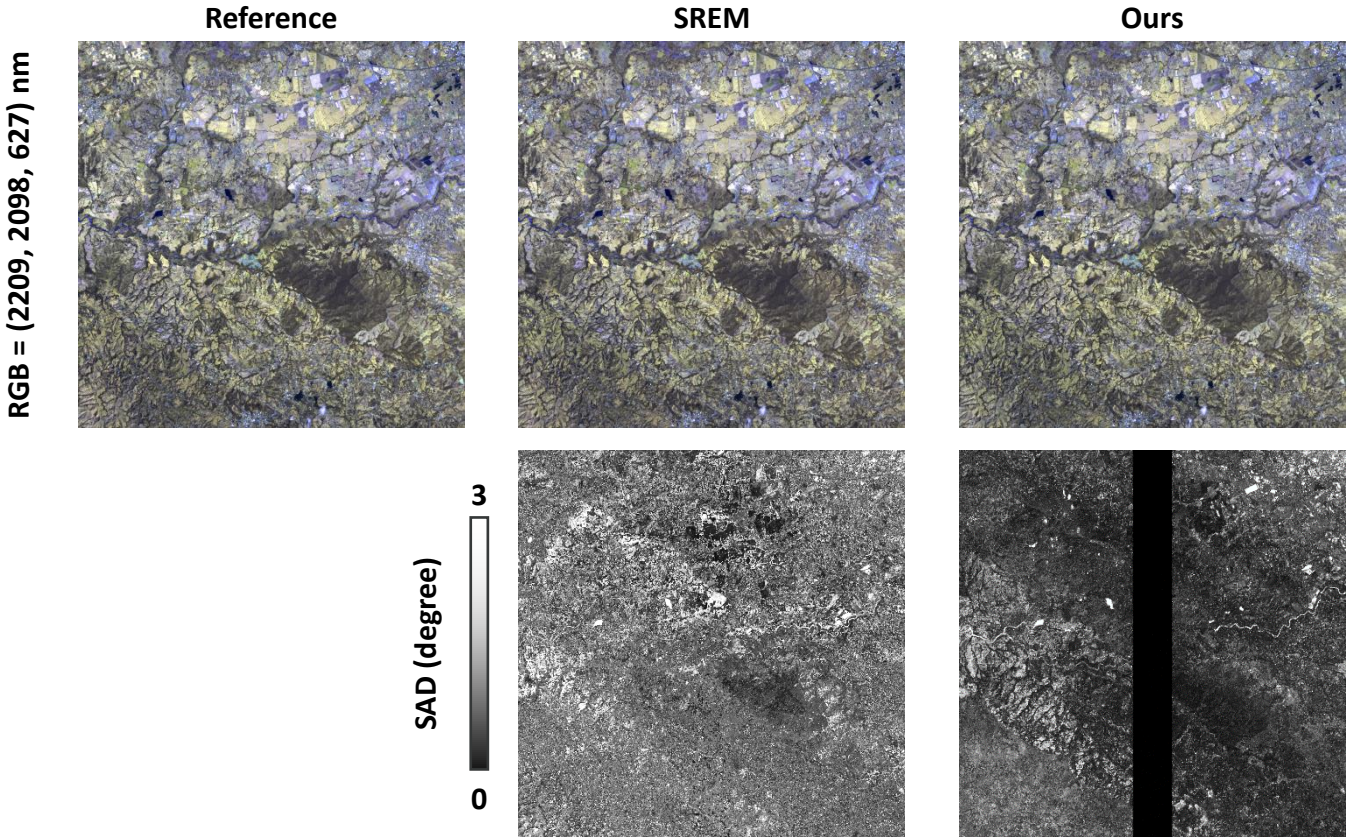
EVALUATION METHODOLOGY: BENCHMARKS

- Use a spectral resolution enhancement method (**SREM**) proposed in [3] as the benchmark method for both reconstruction-based and unmixing-based evaluation
  - SREM estimates linear transformation matrices for different endmembers that convert multispectral signatures to hyperspectral ones

- Use Sentinel-2 (S2) data as another benchmark for unmixing-based evaluation to investigate whether reconstructed data have added values in application

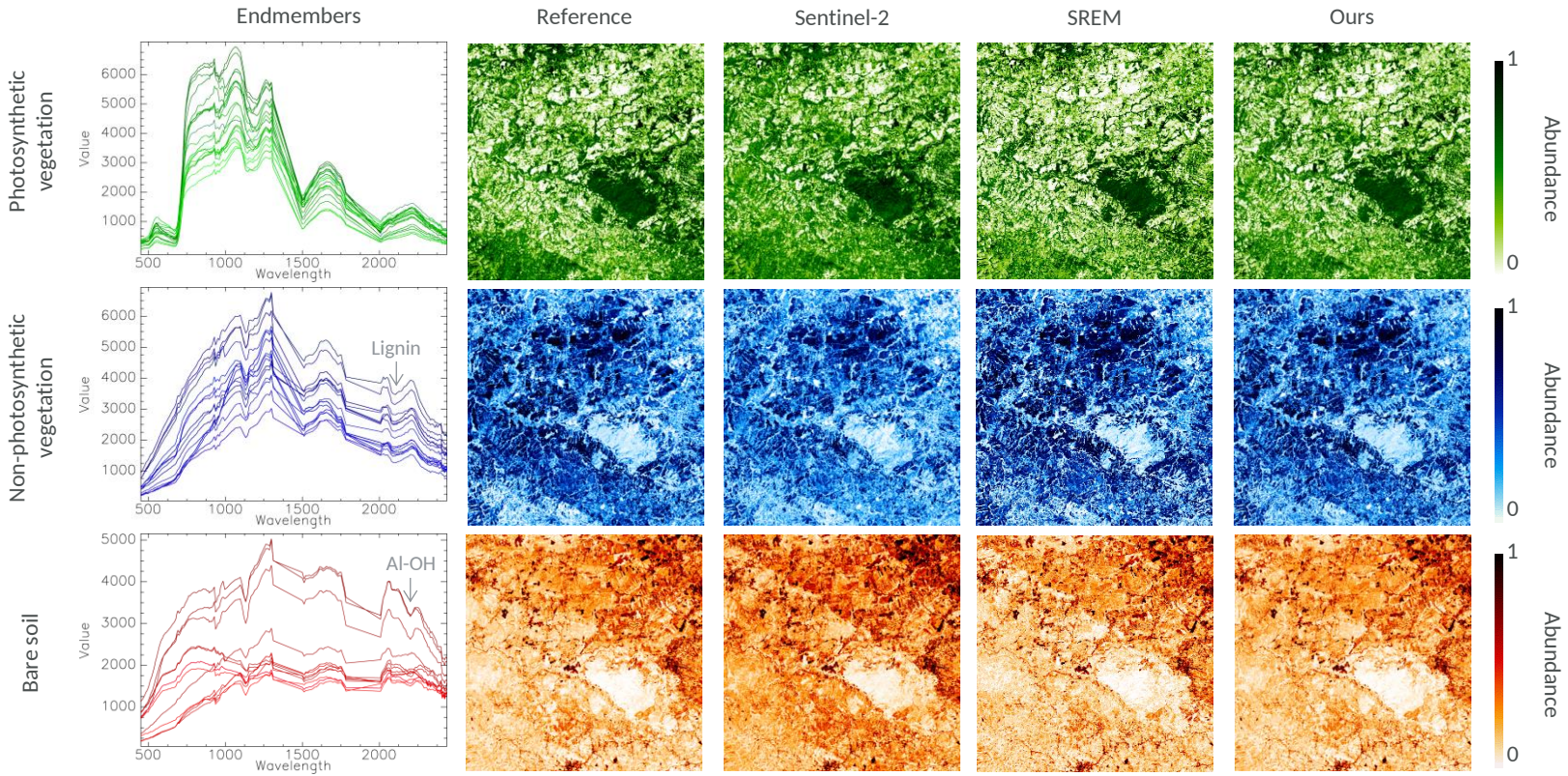
[3] X. Sun, L. Zhang, H. Yang, T. Wu, Y. Cen, and Y. Guo, "Enhancement of Spectral Resolution for Remotely Sensed Multispectral Image," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 5, pp. 2198-2211, 2015.

VISUAL COMPARISON: COLOR COMPOSITE & SAM



Setting of our method
Distance metric: SAD
K: 7

IMPACT OF SPECTRAL ENHANCEMENT ON UNMIXING



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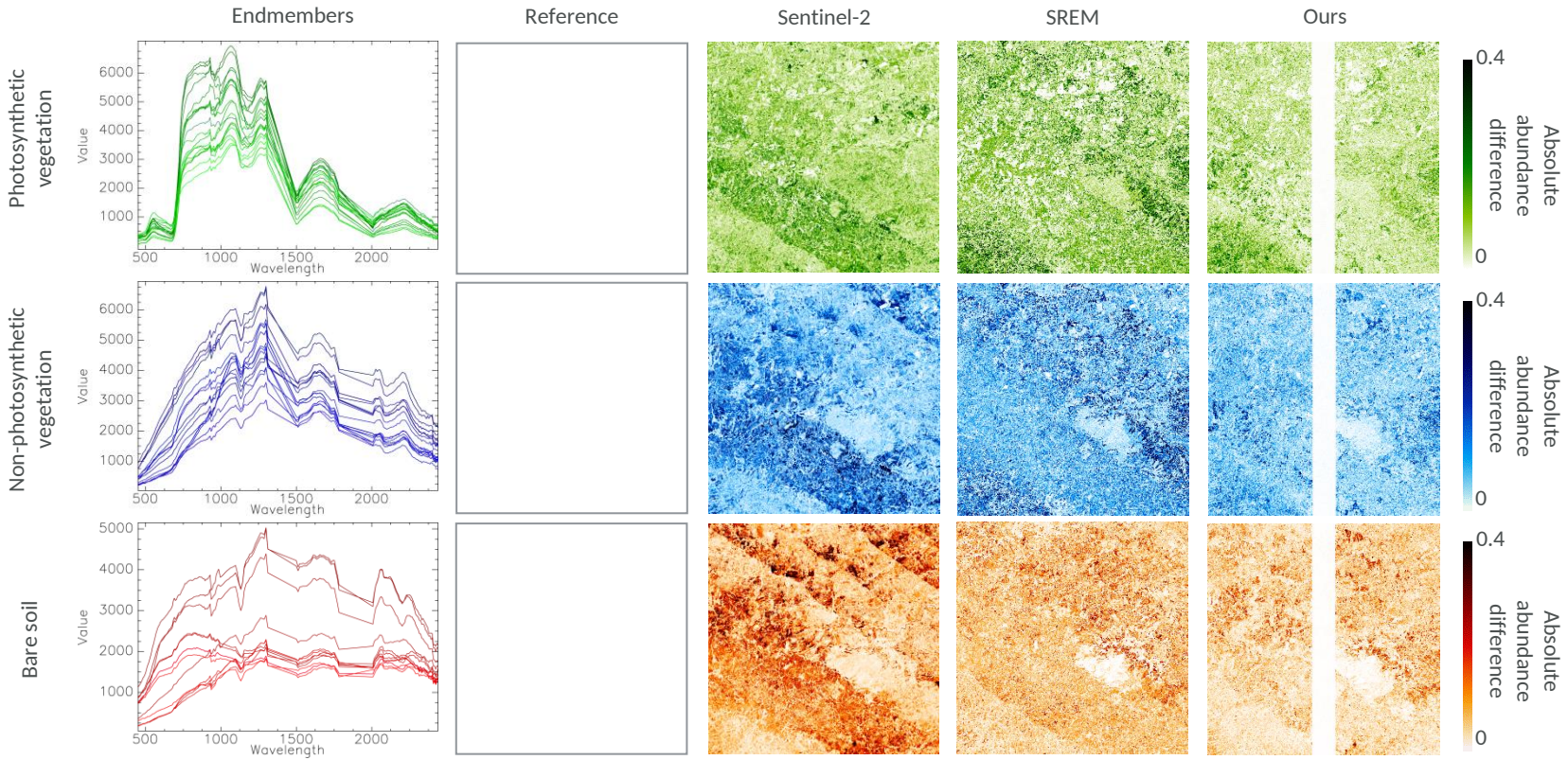

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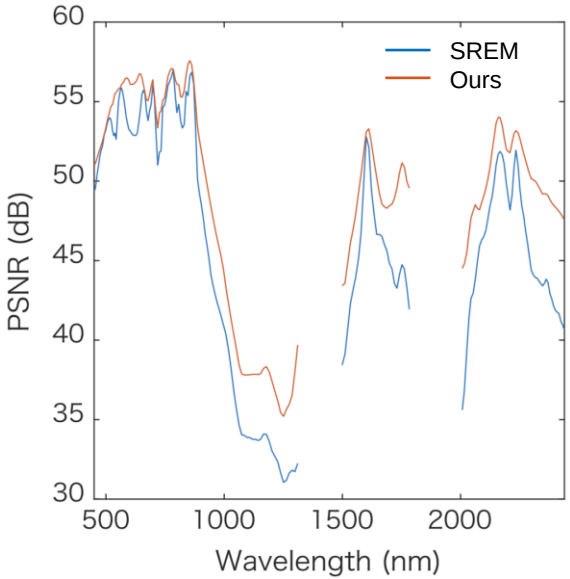
NUMERICAL EVALUATION

Accuracy of reconstruction and unmixing

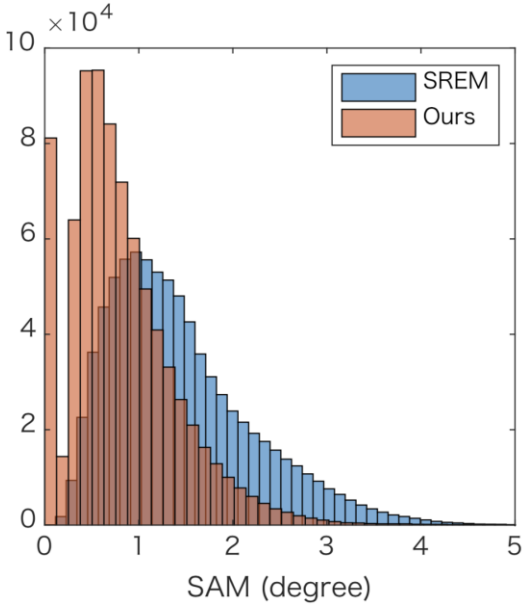
	Reconstruction		Unmixing
	PSNR (dB)	SAM (deg)	RMSE
Ideal	∞	0	0
S2	---	---	0.108
SREM	46.86	1.454	0.101
Ours	**50.01**	**0.830**	**0.064**

* S2: Sentinel-2

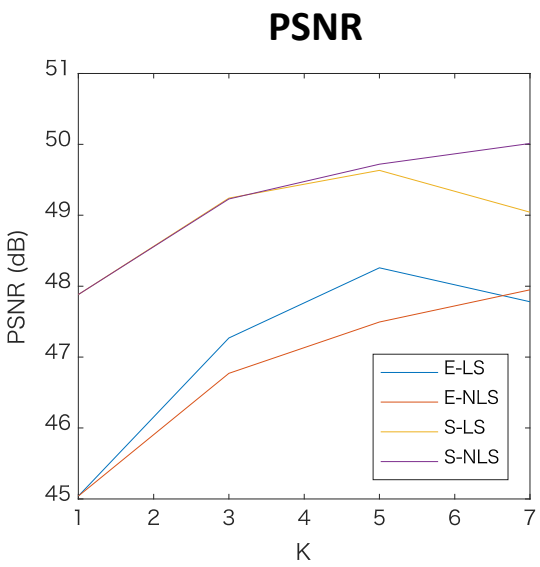
PSNR plot

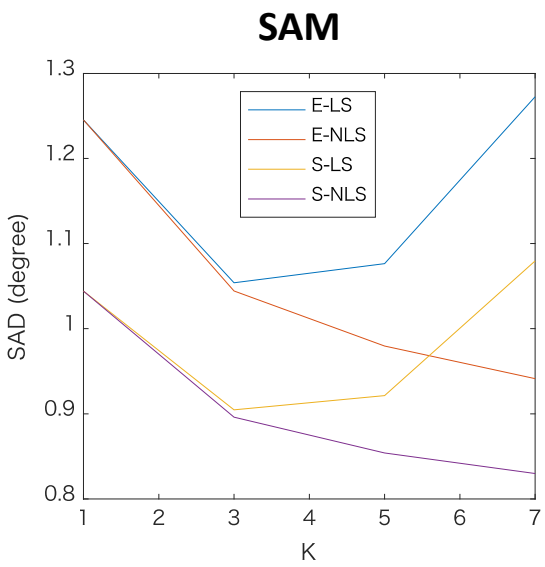


SAM histogram



IMPACT OF K, SIMILARITY METRIC, & NONNEGATIVITY





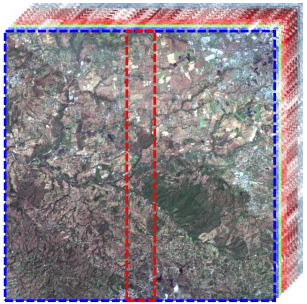
Similarity metric & nonnegativity =

- E-LS: Euclidean distance and least squares (without nonnegativity)
- E-NLS: Euclidean distance and nonnegative least squares (with nonnegativity)
- S-LS: SAD and least squares (without nonnegativity)
- **S-NLS: SAD and nonnegative least squares (with nonnegativity)**

IMPACT OF OVERLAPPING SCENARIOS

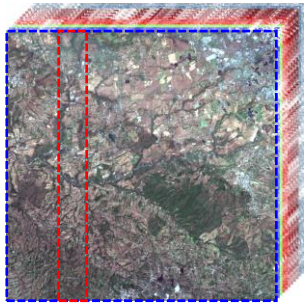
- - - EnMAP - - - Sentinel-2

Scenario 1



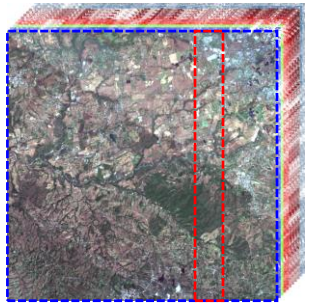
PSNR: 50.01
SAM: 0.830

Scenario 2



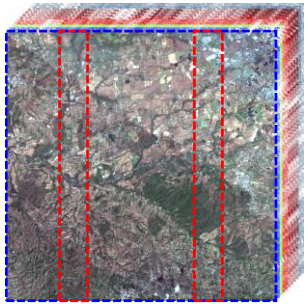
PSNR: 50.09
SAM: 0.861

Scenario 3



PSNR: 50.53
SAM: 0.854

Scenario 4



PSNR: 52.62
SAM: 0.644

- Our method assumes that spectral signatures of all materials in the S2 coverage are included in the EnMAP coverage (If not, reconstruction performance decreases)
- More overlaps lead to better reconstruction accuracy

CONCLUSION

- ✓ Proposed a sparse representation based method for spectral enhancement of multispectral imagery using partially overlapped hyperspectral data
- ✓ Demonstrated the advantage of the proposed method in terms of reconstruction accuracy compared to the benchmark method using simulated EnMAP and Sentinel-2 data
- ✓ Demonstrated the effectiveness of the proposed method for discriminating non-photosynthetic vegetation and bare soil via spectral unmixing
- ☐ Different spatial resolutions will be handled by combining the proposed method with data-fusion-based spatial-resolution enhancement techniques
- ☐ Will be tested on DESIS and Sentinel-2