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

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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?
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:

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

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

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

$$\mathbf{y}_m = \mathbf{A}_m\mathbf{x} + \mathbf{n}_m$$

Estimate coefficients

$$\min_{\mathbf{x}} \| \mathbf{y}_m - \mathbf{A}_m\mathbf{x} \|_2^2$$

s.t. $\mathbf{x} \geq 0$, $\|\mathbf{x}\|_0 < K + 1$

Reconstruct the EnMAP-like spectrum

$$\hat{\mathbf{y}} = \mathbf{A}\hat{\mathbf{x}}$$
STUDY AREA: SAN JOSE, COSTA RICA

- HyMap imagery acquired over a west side of San Jose, Costa Rica, in 2005
- Main land covers include:
  - Photosynthetic vegetation
  - Non-photosynthetic vegetation
  - Bare soil

EVALUATION METHODOLOGY: RECONSTRUCTION

\[ Y \in \mathbb{R}^{B \times P} = [y_1, \ldots, y_i, \ldots, y_B]^T = [y_1, \ldots, y_j, \ldots y_P] \]

- Peak signal to noise ratio (PSNR)
  \[
  \text{PSNR} = \frac{1}{B} \sum_{i=1}^{B} 10 \log_{10} \left( \frac{\max(y_i)^2}{\|y_i - \hat{y}_i\|_2^2/P} \right)
  \]

- Spectral angle mapper (SAM)
  \[
  \text{SAM} = \frac{1}{P} \sum_{j=1}^{P} \arccos \left( \frac{y_j^T \hat{y}_j}{\|y_j\|_2 \|\hat{y}_j\|_2} \right)
  \]

Quality Measures

- \( B \): # of bands
- \( P \): # of pixels
- \( y_i \): \( i \)-th band
- \( y_j \): \( j \)-th pixel

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)
\[ \text{RMSE} = \sqrt{\frac{1}{MP} \left\| \mathbf{A} - \hat{\mathbf{A}} \right\|_F^2} \]

Abundance matrix:
\[ \mathbf{A} \in \mathbb{R}^{M \times P} \] (M: # of endmembers)

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

VISUAL COMPARISON: COLOR COMPOSITE & SAM

Reference  SREM  Ours

RGB = (2209, 2098, 627) nm

SAD (degree)

Setting of our method
Distance metric: SAD
K: 7
Impact of Spectral Enhancement on Unmixing

Reference
Sentinel-2
SREM
Ours

Photosynthetic vegetation
Non-photosynthetic vegetation
Bare soil

Endmembers

IMPACT OF SPECTRAL ENHANCEMENT ON UNMIXING

Reference: Sentinel-2, SREM, Ours

Endmembers

Photosynthetic vegetation

Non-photosynthetic vegetation

Bare soil

NUMERICAL EVALUATION

Accuracy of reconstruction and unmixing

<table>
<thead>
<tr>
<th></th>
<th>PSNR (dB)</th>
<th>SAM (deg)</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>$\infty$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S2</td>
<td>---</td>
<td>---</td>
<td>0.108</td>
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<tr>
<td>SREM</td>
<td>46.86</td>
<td>1.454</td>
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<tr>
<td>Ours</td>
<td>50.01</td>
<td>0.830</td>
<td>0.064</td>
</tr>
</tbody>
</table>

* S2: Sentinel-2

PSNR plot

SAM histogram

Reconstruction Unmixing
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

- 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

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
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