Fusion of optical and PollInSAR data for land cover classification

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Summary

1. Who are we?
2. Remote sensing in case of crisis (Radar versus Optical Data)
3. Fusion of optical and PolInSAR data for land cover classification
4. The Data
5. Optical features
6. Polarimetric features
7. Polarimetric interferometric features
8. Fusion process
9. To conclude
1. WHO ARE WE?
The SIC: a Research Laboratory of the RMS

- A team of 25 competent researchers
- A team of experts working for the Defence and the Society on Defence, Security and environmental applications
- A doctoral School specialised in signal and image processing
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SIC Expertise

- Signal Processing (radar, polarimetric et interferometric SAR, STAP, SONAR)
- Images Processing (satellite and video, multispectral, hyperspectral, radar, sonar)
- Modelling (electromagnetism, infrared and radar)
- Pattern Recognition
- Data Fusion (low to high level)
- Crisis Management Systems
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- Data Fusion (low to high level)
- Crisis Management Systems
2. Remote sensing in case of crisis (Radar versus Optical Data)
Optical data
SAR Data
3. Fusion of optical and PolInSAR data for land cover classification

- Part of a research project funded by the Public Federal Service Scientific Policy (PolInSAR project with ULg and UCL)
- A research performed in three months by an excellent team:

  M. Shimoni, D. Borghys, R. Heremans and N. Milisavljević
Important Definitions

**1. Feature**: In computer vision and image processing the concept of feature refers to higher level pieces of information (as edges, corners, circular shapes, etc) the presence of which in the image must be investigated.

**2. Land cover feature**: type of ‘materials’ covering the soil, such as vegetation, bare soil, forest etc.

**3. Low level fusion (data fusion)**: methods to combine several sources of raw data to produce new raw data with improved information quality.

**4. Intermediate level fusion (feature level fusion)**: methods to combine various features.

**5. High level fusion (decision fusion)**: methods to combine decisions (hard fusion) or guesses/confidence (soft fusion), coming from several experts.
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PolSAR, PolInSAR and Multispectral fusion  
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Research goals

To fuse different frequency ESAR PolSAR and PolInSAR data with Daedalus optical data for land cover classification.
4. The Data
Optical data set, collected by DLR (EC/SMART)

Test site: Glinska Poljana, Croatia;
Date: 6 to 10 August 2001.

<table>
<thead>
<tr>
<th>Channel number</th>
<th>Spectral range ($\mu m$)</th>
<th>Resolution</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>0.44-0.53</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.51-0.62</td>
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<tr>
<td>5</td>
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<tr>
<td>6</td>
<td>0.67-0.80</td>
<td>0.8 - 1.0 m</td>
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<td>7</td>
<td>0.73-1.00</td>
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</tr>
<tr>
<td>8</td>
<td>0.85-1.10</td>
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</tr>
<tr>
<td>9</td>
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<tr>
<td>10</td>
<td>1.95-2.42</td>
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<tr>
<td>11</td>
<td>8.20-14.0</td>
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Daedalus multispectral data
Polarimetry (courtesy of E. Pottier)
Characteristics of ESAR data

<table>
<thead>
<tr>
<th>Band</th>
<th>Polarization</th>
<th>Resolution in range</th>
<th>Resolution in azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>vv, hh, hv, vh</td>
<td>2.0 m</td>
<td>0.8 m 2.0 m</td>
</tr>
<tr>
<td>P</td>
<td>vv, hh, hv, vh</td>
<td>4.0 m</td>
<td>1.6 m 4.0 m</td>
</tr>
</tbody>
</table>

L-band (1.3 GHz) Polarimetric data (from left to right: hh, hv, vh and vv polarizations).

+ Repeat pass interferometry
Polarimetry + Interferometry (courtesy of E. Pottier)
Ground truth data set

- Global location and local environment;
- General geographic description;
- Geomorphologic structure;
- Representative land use;
- General soil characteristics;
- General pictures.

**Supervised classification:** ground truth data are used to construct the training and validation data sets.
Pre-processing

**Optics:** Radiometric and atmospheric correction

**Registration:** The *P-band* SAR data and the *optical* data were registered to the *L-band* SAR data using second-degree polynomial transformation and with sub-pixel precision.
5. Optical features extraction
Optical features

10 Daedalus bands
Optical features

10 Daeadalus bands

10 PCA bands
Optical features

10 Daeadalus bands

10 PCA bands

6 Directional filters: $45^\circ, 60^\circ, 90^\circ, 180^\circ, 270^\circ, \text{sum.}$

26 Optical Features
6. SAR Polarimetric (PolSAR) features
PolSAR features

SAR complex backscattering coefficients (module and phase) are represented in each pixel by the scattering matrix $S$:

$$S = \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix}$$

In the monostatic case

$$S_{vh} = S_{hv}$$
PolSAR features: the PolSAR coherence

The polarimetric coherence is defined as the absolute value of the complex correlation coefficient between the different polarisations.

e.g. the coherence between the $hh$ and the $vv$ polarisations is given by

$$\rho_{hh/vv} = \frac{\langle S_{hh}S_{vv}^* \rangle}{\sqrt{\langle S_{hh}S_{hh}^* \rangle \langle S_{vv}S_{vv}^* \rangle}}$$
The other PolSAR features are obtained by vectorization $V(\cdot)$ of the scattering matrix $S$ in each pixel:

$$S = \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \Rightarrow k = V(S) = \frac{1}{2} \text{Trace}\{S[\Psi]\}$$

where $k$ is called the target vector, and $\Psi$ is a set of $2 \times 2$ complex basis matrices, constructed as an orthonormal set under a hermitian inner product, corresponding to elementary backscattering processes.
PolSAR features: the Pauli decomposition

\[ \Psi = \left\{ \sqrt{2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \sqrt{2} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \sqrt{2} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \right\} \]

\[ k = \frac{1}{\sqrt{2}} [S_{hh} + S_{vv}, S_{hh} - S_{vv}, 2S_{hv}]^T \]

which allows to define the coherence matrix \( T \)

\[ T = k.k^T \]

Diagonal terms of \( T \) correspond to the squared components of \( k \) and are closely related to physical and geometrical properties of the scattering mechanism:

\[ |S_{hh} + S_{vv}|^2 \text{ odd bounce scattering} \]
\[ |S_{hh} - S_{vv}|^2 \text{ double bounce scattering} \]
\[ 2|S_{hv}|^2 \text{ volume scattering} \]
PolSAR features: the lexicographic decomposition

\[
\Psi = \left\{ 2 \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, 2\sqrt{2} \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, 2 \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \right\}
\]

\[
\tilde{k} = \begin{bmatrix} S_{hh}, \sqrt{2}S_{hv}, S_{vv} \end{bmatrix}^T
\]

which allows to define the covariance matrix \( C \)

\[
C = \tilde{k}\tilde{k}^T
\]

Diagonal terms of \( C \) correspond to the squared components of \( \tilde{k} \) and their sum is closely related to the total power scattered by the target.
The objective of the coherent decompositions is to express the scattering matrix $S$ measured by the radar as a combination of the scattering responses of $k$ simpler objects

$$S = \sum_{i=1}^{k} c_i S_i$$

Two coherent decompositions are used in this project: the Pauli decomposition and the Krogager decomposition
PolSAR features: coherent Pauli decomposition

In a monostatic case the Pauli decomposition is given by

\[ S = \alpha S_a + \beta S_b + \gamma S_c \]

where \( S_a \) corresponds to a sphere, a plate or a trihedral, \( S_b \) to a dihedral oriented at 0° and \( S_c \) to a diplane oriented at 45°

Pauli parameters \(|\alpha|\), \(|\beta|\) and \(|\gamma|\) respectively in red, green and blue
PolSAR features: coherent Krogager decomposition

The Krogager components account for an orientation $\theta$

\[ S = e^{i\phi} \left\{ e^{i\phi_s} k_s \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + k_d \begin{bmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{bmatrix} + k_h e^{\pm j2\theta} \begin{bmatrix} 1 & \pm j \\ \pm j & 1 \end{bmatrix} \right\} \]

Krogager parameters $k_s$, $k_d$ and $k_h$ respectively in red, green and blue
Objective: to characterize "distributed scatterers". This type of scatterers can only be characterized statistically due to speckle noise. Therefore, one uses the covariance $\langle C \rangle$ and coherence $\langle T \rangle$ matrices, computed on $7 \times 7 = 49$ neighbouring pixels. These two representations of the polarimetric information are equivalent. The decomposition theorems can be expressed as

$$\langle C \rangle = \sum_{i=1}^{k} p_i C_i$$

and

$$\langle T \rangle = \sum_{i=1}^{k} q_i T_i$$

The incoherent decompositions used in this project are: the decomposition of Freeman, Huynen, Barnes, Cloude and Pottier, Cloude and Holm
The Freeman decomposition models the covariance as the contribution of three scattering mechanisms: \textit{double-bounce (Dbl)}, \textit{volume scattering (Vol)} and \textit{surface scattering (Odd)}.
Huynen uses a particular parametrization of the coherence matrix $\langle T \rangle$, considering three different contributions to the total scattered power.
PolSAR features: incoherent Barnes decomposition

Barnes considers an orthogonal transform of the Huynen decomposition to obtain three new components.
PolSAR features: incoherent Cloude decomposition

This decomposition is based on the three eigenvalues ($\lambda_1$, $\lambda_2$ and $\lambda_3$ with decreasing magnitude) of the coherence matrix $\langle T \rangle$, and defines the Entropy $H$, the anisotropy $A$, the angle $\alpha$ and the asymmetry $AS$ as follows:

$$H = -\sum_{i=1}^{3} p_i \log(p_i) \quad \text{where} \quad p_i = \frac{\lambda_i}{\sum_{k=1}^{3} \lambda_k}$$

$$A = \frac{\lambda_2 - \lambda_3}{\lambda_2 + \lambda_3}$$

$$\alpha = \sum_{i=1}^{3} p_i \alpha_i \quad (\alpha_i: \text{parameters of the eigenvectors})$$

$$AS = \frac{\lambda_1 - \lambda_2}{1 - 3\lambda_2}$$
PolSAR features: incoherent Cloude decomposition

$H$, $A$ and $\alpha$ decomposition

Asymmetry
PolSAR features: incoherent Holm decomposition

The Holm decomposition is also based on the three eigenvalues ($\lambda_1$, $\lambda_2$ and $\lambda_3$ with decreasing magnitude) of the coherence matrix $\langle T \rangle$, but defines the following three parameters $\lambda_1 - \lambda_2$, $\lambda_2 - \lambda_3$ and $\lambda_3$ instead of $H$, $A$ en $\alpha$.

$\lambda_1 - \lambda_2$, $\lambda_2 - \lambda_3$ and $\lambda_3$ decomposition
PolSAR features: summary

- PolSAR coherences
- Pauli decomposition
- Krogager decomposition
- Freeman decomposition
- Huynen decomposition
- Barnes decomposition
- H'\(\alpha\) decomposition
- Asymmetry
- Holm decomposition
PolSAR features: summary
7. SAR Polarimetric interferometric (PolInSAR) features
**PolInSAR features**

**PolSAR:**
- sensitive to scatter. mech.
- influenced by shape, orientation, dielectric properties

**InSAR:**
- $\Delta \phi \rightarrow$ height and tomography
- 3D information

**PolInSAR:** computation of interferometric phases and coherences for different scattering mechanisms
SAR interferometric coherence

Two polarimetric image sets (A and B) corresponding to two different view angles. The resulting target vector $k_6$ is obtained by stacking target vectors $k_A$ and $k_B$ of polarimetric image sets A and B.

$$k_A = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{hh}^A + S_{vv}^A \\ S_{hh}^A - S_{vv}^A \\ 2S_{hv}^A \end{bmatrix} = |k_A| w_A$$

and

$$k_B = \frac{1}{\sqrt{2}} \begin{bmatrix} S_{hh}^B + S_{vv}^B \\ S_{hh}^B - S_{vv}^B \\ 2S_{hv}^B \end{bmatrix} = |k_B| w_B$$

where $w_A$ and $w_B$ are unitary complex vectors taking their values on the unit complex sphere and can be interpreted as scattering mechanisms.
SAR interferometric coherence

The new estimation over \( n = 7 \times 7 \) pixels of the expected polarimetric coherence matrix \( \langle T_6 \rangle \) is given by

\[
\langle T_6 \rangle = \frac{1}{n} \sum_{k=1}^{n} k_6 k_6^* T
\]

or by

\[
\langle T_6 \rangle = \begin{bmatrix}
\langle T_{AA} \rangle & \langle \Omega_{AB} \rangle \\
\langle \Omega_{AB}^* \rangle & \langle T_{BB} \rangle
\end{bmatrix}
\]

The complete polarimetric interferometric information is included in the complex submatrix \( \langle \Omega_{AB} \rangle \) of \( \langle T_6 \rangle \). This submatrix is used to define the complex coherence.
Complex coherence cloud

Different scattering mechanisms are chosen randomly: 100 complex unit vectors $\mathbf{w}_A$ and $\mathbf{w}_B$ are selected randomly on the unit complex sphere, and 100 different complex coherence values $\gamma$ are computed in each pixel:

$$\gamma = |\gamma|e^{i\phi} = \frac{\mathbf{w}^*_A \langle \Omega_{AB} \rangle \mathbf{w}_B}{\sqrt{\mathbf{w}^*_A \langle T_{AA} \rangle \mathbf{w}_A \cdot \mathbf{w}^*_B \langle T_{BB} \rangle \mathbf{w}_B}}$$

Coherence cloud in the complex plane for two different pixels.
Optimal coherence
Finding the scattering mechanism providing with the highest interferometric coherence. Analytical solution:

\[ \langle T_{BB}^{-1} \rangle \langle \Omega_{AB}^* T \rangle \langle T_{AA}^{-1} \rangle \langle \Omega_{AB} \rangle w = \nu w \]

which gives the eigenvalues \( \nu_1 \geq \nu_2 \geq \nu_3 \)
Lee’s optimal coherence

\[ A_1 = \frac{\nu_1 - \nu_2}{\nu_1} \quad (0 \leq A_1 \leq 1) \]

\[ A_2 = \frac{\nu_1 - \nu_3}{\nu_1} \quad (0 \leq A_2 \leq 1) \]
Neumann decomposition

The coherence cloud is characterized by 5 parameters:

- the position of the centre of gravity ($|\gamma|$ and the angle $\phi$ replaced here by $\text{Std}(\phi)$)
- the long and short axes ($\lambda_1$ and $\lambda_2$)
- the orientation of the ellipse (replaced here by $\text{Std}(|\gamma|)$)

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PolSAR, PolInSAR and Multispectral fusion

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Neumann decomposition

\[
\begin{array}{|c|c|c|}
\hline
| \gamma | & \lambda_1 & \lambda_2 \\
\hline
\text{Std}(|\gamma|) & \text{Std}(\phi) \\
\hline
\end{array}
\]
They define three new parameters from the ellipse parameters:

- **the Pseudo ellipticity** $\chi$
  $$\chi = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2}$$

- **Coherence/Phase Std relationship** $\rho$
  $$\rho = \frac{\text{Std}(|\gamma|)}{\text{Std}(|\gamma|) + \text{Std}(\phi)/\pi}$$

- **the outward tendency** $\theta = \chi \rho |\gamma|$
Complete feature sets

**PolSAR**
- PolSAR coherences
- Pauli decomposition
- Kohgeiger decomposition
- Freeman decomposition
- Huyven decomposition
- Barnes decomposition
- HAVe decomposition
- Asymmetry
- Holm decomposition

25 L-band PolSAR Features
25 P-band PolSAR Features

**PolInSAR**
- Optimal coherences
- Mean magnitude
- Eigenvalue $\lambda_2$
- Eigenvalue $\lambda_3$
- $\text{Stdv of the magnitude} |\mu|$
- $\text{Stdv of the phase} |\phi|$
- Neumann decomposition
- Lee Classifier $A_1$
- Lee Classifier $A_2$
- Directional filter

13 L-band PolInSAR Features
13 P-band PolInSAR Features

**Optical**
- Daedalus bands
- PCA234
- Directional filter

26 Optical Features
8. Fusion
Fusion methods

- Feature-level fusion by logistic regression (LR)
- Decision-level fusion based on:
  - fuzzy logic
  - spatial regularisation using classification results of LR
Feature selection and fusion with multiple logistic regression

Objective:

*To distinguish each class (target t) from all others (background)*

**Method** (supervised classification)

- Compute the feature images $F_i(m, n)$
- Find optimal combination of features for detecting a given class for the learning set (find the $\beta_i$ and eliminate the features which are not relevant)
- Logistic Regression

$$p_{m,n}(t/F) = \frac{\exp\{[\beta_0 + \sum_i F_i(m, n)\beta_i]\}}{1 + \exp\{[\beta_0 + \sum_i F_i(m, n)\beta_i]\}}$$

- Apply the combination to complete set of feature images
Decision level fusion

Fuzzy logic based fusion: Method

- fuses classification results of LR
- discounting of weights for each classifier (by the accuracy obtained in the confusion matrix of the LR results on the learning set)
- maximum rule
- spatial regularisation by majority voting
Classification results: confusion matrix

Ground truth validation set
Confusion L-PolSAR + L-PolInSAR
Confusion P-PolSAR + P-PollnSAR
Confusion LP-PolSAR + LP-PolInSAR = All SAR
Confusion All SAR + Daedalus

ALL SAR

Daedalus

ALL SAR + Daedalus

Aban Resid Forest Past. Wheat Barley Corn Bare River Roads

Aban Resid Forest Past. Wheat Barley Corn Bare River Roads

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Pauli

LR

Residence areas

Roads

River

Forest

Pastures

Wheat

Barley

Corn

Bare soil

Abandoned areas
9. Conclusions
Conclusions

- For both fusion methods the overall accuracy for the fused feature sets is better than the accuracy for the separate feature sets;
- Features from different SAR frequencies are complementary and their fusion is adequate for land cover classification;
- PolInSAR and PolSAR features are complementary and both essential for producing an accurate classification of different land cover types as man-made object, water bodies, forest, crops and bare soils;
- Optical data complement SAR data but are not necessary for the production of an accurate land cover classification;
- The global fusion performances of the fuzzy-based approach are slightly better than the feature fusion using the logistic regression for most of the feature set combination.