Application of polarimetric information to the atmospheric phase screen compensation for GB-SAR in a mountainous area

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28 January–1 February 2019 | ESA–ESRIN | Frascati (Rome), Italy
Background

- Ground-Based Synthetic Aperture Radar (GB-SAR)
  - Fixed-point observation
  - Not necessary to attach the sensor
- Landslide affected mountainous cliff located in Minami-Aso, Kumamoto, Japan
  - Jan. 2017 – current
  - Providing early warning
  - Real time measurement
Atmospheric Phase Screen in GB-SAR

- Problem in DInSAR
  - Model-based approach
  - Soft topography
    \[ \Delta \phi_{\text{atm}} = k_0 r (\Delta n) \]
  - Steep topography
    \[ \Delta \phi_{\text{atm}} = \beta_1 r + \beta_2 rh + \ldots \]
Atmospheric Phase Screen in GB-SAR

- **Turbulent APS – Kriging interpolation**

**Reason**
- Due to the extreme weather condition
- Inhomogeneity of refractivity index

**Solution**
- Applying spatial statistics to mitigate the turbulent APS
- Kriging interpolation

\[
\gamma(l) = \frac{1}{2N(l)} \sum_{i=1}^{N(l)} (z(x_i) - z(x_i + l))^2
\]

\[
z_{est} = \sum_{i=1}^{n} b_i z_i
\]
Atmospheric Phase Screen in GB-SAR

- Procedure of APS compensation
  - Model-based compensation
  - Kriging interpolation

![Diagram showing model-based compensation and Kriging interpolation](image-url)
Atmospheric Phase Screen in GB-SAR

Problem

15min. time interval

\[ \gamma > 0.98 \rightarrow \text{Coherent Scatterer (CS)} \]

Scattering heterogeneous area suffer less number of CS

APS estimation is inaccurate in sparse CS location
How does the polarimetric information contribute to GB-SAR measurement?

1. Increase the CSs by polarimetric optimization

2. Detect the land morphological changed area without APS compensation
Outline

1. Background

2. Atmospheric phase screen in GB-SAR

3. Two-step polarimetric optimization

4. Polarimetric Anomaly detection

5. Conclusion
Two-step polarimetric optimization

- Proposed optimization

**Similarity test**
Enhance the coherence especially at scattering heterogeneous area

**Polarimetric optimization**
Enhance the coherence in whole area

\[ \gamma_{ESM} = \gamma(w) = \frac{w^H \Omega \omega_{12} w}{\sqrt{w^H T_{11} w} \sqrt{w^H T_{22} w}} \]
Two-step polarimetric optimization

- Similarity test – PolSAR covariance matrix likelihood ratio test statistic

\[ X, Y : \text{Covariance matrix} \rightarrow \text{Wishart distributed} \]

\[ X \in W(q, n, C_x) \quad Y \in W(q, m, C_y) \]

\[ H_0 : C_x = C_y \quad H_1 : C_x \neq C_y \]

Null hypothesis \quad Alternative hypothesis

Logarithm of the test statistic

\[ \ln Q = n(2q \ln 2 + \ln |X| + \ln |Y| - 2\ln |X + Y|) \]

where \( q = 3 \) : PolSAR

\( n = m \) : ENL

if \( \ln Q > \text{threshold} \)

Choose as averaging candidates

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Two-step polarimetric optimization

- Results – CS distribution
  - HH Boxcar: 46123
  - ESM Boxcar: 61754
  - ESM SimTest (Two-step pol. opt.): 62227

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\[ \gamma > 0.98 \]
Two-step polarimetric optimization

- Results – Kriging APS compensation
  Result of one interferometric pair
1. Background

2. Atmospheric phase screen in GB-SAR

3. Two-step polarimetric optimization

4. Polarimetric anomaly detection

5. Conclusion
Polarimetric anomaly detection

- Terrain morphological change detection including the APS correction effect

Conventional method

\[
\Delta \phi_{HH}(t_1,t_2) = \phi_{atm} + (\phi_{def} + \phi_{t\_HH})
\]

\[
\Delta \phi_{APS\text{comp}}(t_1,t_2) = (\phi_{def} + \phi_{t\_HH})
\]

Estimate and remove

APS independent descriptor

\[
\Delta \phi_{HH}(t_1,t_2) = \phi_{atm} + (\phi_{def} + \phi_{t\_HH})
\]

\[
\Delta \phi_{VV}(t_1,t_2) = \phi_{atm} + (\phi_{def} + \phi_{t\_VV})
\]

\[
\Delta \phi_{HH} - \Delta \phi_{VV} = \phi_{t\_HH} - \phi_{t\_VV}
\]

\[\rightarrow\text{APS independent descriptor}\]

Possible to distinguish the anomaly location without APS compensation
Surface topography was changed by filling soil

understand how the APS independent descriptor detects the land morphological change without APS compensation
Polarimetric anomaly detection

- Qualitative comparison

APS compensated retrieved displacement by HH

APS independent descriptor
Conclusion

- Two-step polarimetric optimization
  - Two-step polarimetric optimization is proposed
  - Increase of the number of CS is confirmed
  - Polarimetric information achieve more accurate APS compensation than single polarization

- Polarimetric anomaly detection
  - The concept of detecting the land morphological change without APS compensation for a GB-SAR is presented.
  - The time-series result of APS independent descriptor is in agreement with the APS-compensated DInSAR result.
  - Possible applications are landslide, snowfall, and rock fall
Thank you for your attention!
Multiple Regression Model

\[
\phi_{\text{atm}} = 10^{-6} \frac{4\pi f_c}{c} \int_{r_n} N(r, t) \, dr
\]

\[
\phi_{\text{atm}} = 10^{-6} \frac{4\pi f_c}{c} \int_{r_n} N(h) \, dr
\]

\[
= 10^{-6} \frac{4\pi f_c}{c} \left( N_s(t) + N_1(t) h \right) \, dr
\]

\[
= 10^{-6} \frac{4\pi f_c}{c} \left( N_s(t) r_n + \frac{N_1(t)}{2} r_n h_n \right)
\]

Atmospheric phase

\[
N(h) = N_s e^{-\alpha h}
\]

\[
= N_s - N_s \alpha h
\]

\[
= N_s + N_1 h
\]

First two terms of Taylor series, exhibiting linear behavior of \( N \)

Atmospheric phase difference

\[
\Delta \phi_{\text{atm}} = 10^{-6} \frac{4\pi f_c}{c} \left( N_s(t_2) - N_s(t_1) \right) r_n + \left( N_1(t_2) - N_1(t_1) \right) \frac{r_n h_n}{2}
\]

\[
= \beta_1 r_n + \beta_2 r_n h_n
\]
Two-step polarimetric optimization

Equal Scattering Mechanism (ESM)

\[ \gamma^{ESM} = \gamma(w) = \frac{w^H \Omega_{12} w}{\sqrt{w^H T_{11} w} \sqrt{w^H T_{22} w}} \]

\[ T = \frac{T_{11} + T_{22}}{2} \]

\[ A = T_{11}^{-1/2} \Omega_{12} T_{22}^{-1/2} \]

Obtain optimal polarization with less iteration

ESM procedure

\[ \gamma^{ESM} = \gamma(w) = \frac{w^H \Omega_{12} w}{\sqrt{w^H T_{11} w \sqrt{w^H T_{22} w}}} \]

: Equalize the polarization between Master and Slave

\[ T = \frac{T_{11} + T_{22}}{2} \]

: Calculate the numerical radius of this matrix which is the maximum eigenvalue corresponding to optimal projection vector.

\[ A = T^{-1/2} \Omega_{12} T^{-1/2} \]
Atmospheric Phase Screen in GB-SAR

**Kriging procedure**

**Variogram derivation**

\[
\gamma(l) = \frac{1}{2N(l)} \sum_{i=1}^{N(l)} (z(x_i) - z(x_i + l))^2
\]

The weights can be found from kriging equation:

\[
\mathbf{b} = \left[ \begin{array}{c} b_1 \\ \vdots \\ b_n \\ \lambda \end{array} \right] = \left[ \begin{array}{cccc} C_{11} & \ldots & C_{1n} & 1 \\ \vdots & \ddots & \vdots & \vdots \\ C_{n1} & \ldots & C_{nn} & 1 \\ 1 & 1 & 1 & 0 \end{array} \right]^{-1} \left[ \begin{array}{c} C_{1x} \\ \vdots \\ C_{nx} \\ 1 \end{array} \right]
\]

where

\[
C_{ij} = C(0) - \gamma_{ij}
\]

**Estimation of APS**

\[
z_{est} = \sum_{i=1}^{n} b_i z_i
\]
Two-step polarimetric optimization

- Results – Kriging APS compensation
  Cumulative result (4 DInSAR pairs)
Two-step polarimetric optimization

Results – Bicubic spline interpolation

HH Boxcar

ESM SimTest (Two-step pol. opt.)

Interferometry after APS comp.

Range [m]

Azimuth [m]

Cubic spline x axis

Cubic spline y axis

Bicubic spline interpolation
Polarimetric anomaly detection

- APS of three polarizations
  - HH
  - HV
  - VV
Polarimetric anomaly detection

Qualitative comparison
APS compensated retrieved displacement

\[ \ln Q \]
Threshold determination

- The theoretical thresholds can be determined at a given probability of $\ln Q$.
- The distributions of $\ln Q$ is functions of the number of looks $n$ and the covariance matrix dimension $q$. In a simple and empirical fashion, the threshold can be estimated as

$$Th = -\sqrt{\frac{qD}{n}}$$

$D$ is adjusting parameter where we set as 10