Merging ground-based and spaceborne InSAR data to monitor earth dams

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Outline

- GB and SB-SAR
- GBSAR for dam monitoring
- Earth dam case study: GB and SB-SAR
- 3D displacement reconstruction
Azimuth synthetic (sub-)aperture

GBSAR systems use a sub-aperture $L < 4 \; \text{m}$

**SATELLITE**

\[
\lambda = 0.05 \; \text{m} \\
L = 10 \; \text{m} \\
H = 800 \; \text{km}
\]

Aperture = 4500 m

**GBSAR**

Horn antennas with 20° beamwidth

\[
\lambda = 0.018 \; \text{m} \\
D = 500 \; \text{m}
\]

Aperture = 170 m
Spatial resolution (GBSAR)

Range resolution:

\[ \Delta r_s = \frac{c \cdot 1}{2 \cdot B} \]

Azimuth resolution:

\[ \Delta x = \frac{R \cdot \lambda}{4 L \cos^2 \varphi} \]

depending on target distance \( R \), angular position \( \varphi \) with respect to the centre of the rail and its length (synthetic aperture \( L \))
Measuring dam displacements
Measuring dam displacements
Measuring dam displacements

Displacement $\Delta R$ measured by GBSAR

Down-stream displacement

Displacement $\Delta \mathbf{R}$ measured by GBSAR

$x_R$, $y_R$, $z_R$

GBSAR rail

$\mathbf{P}(x,y,z)$

Difficult to displace dams
Measuring dam displacements
Measuring dam displacements
Measuring dam displacements
Earth dam: GBSAR Installation sites
Earth dam (1-day GBSAR campaign)

Amplitude  Coherence  Phase

Earth dam (1-day GBSAR campaign)
Detail installation site (left)
Detail installation site (right)
Detail installation site (right)
Earth dam: CSK SAR data
Earth dam: CSK SAR data
Fig. 1. Sketch with the geometry of ascending and descending InSAR geometries with unit vectors (red) \( \mathbf{u}^a \) and (blue) \( \mathbf{u}^d \), radar incidence angles \( \vartheta^a \) and \( \vartheta^d \), and angles \( \beta^a \) and \( \beta^d \) related to ground-track azimuthal angles. The horizontal components of unit vectors \( \mathbf{u}^a \) and \( \mathbf{u}^d \) are also depicted. For the sake of clarity, the common vertical components of unit vectors are omitted.

Ascending and descending SB SAR data

The components of unit vectors $\mathbf{u}$ ($\mathbf{u}^a$ or $\mathbf{u}^d$), respectively, along the West-East, South-North, and vertical directions, are given in terms of the local radar incidence angles $\vartheta$ ($\vartheta^a$ or $\vartheta^d$) and ground-track azimuthal angles $\alpha$ ($\alpha^a$ or $\alpha^d$) as

$$
\begin{align*}
  u_E &= \sin \vartheta \sin \left(\alpha - \frac{\pi}{2}\right) \\
  u_N &= \sin \vartheta \cos \left(\alpha - \frac{\pi}{2}\right) \\
  u_Z &= \cos \vartheta
\end{align*}
$$

The three components of the terrain displacement velocity $\mathbf{v} = \{v_E, v_N, v_Z\}$ are usually estimated by minimizing the energy function

$$
E = \sum_{i \in \{a,d\}} \left( v_{PS}^i - u_E^i v_E - u_N^i v_N - u_Z^i v_Z \right)^2
$$

where $v_{PS}^a$ and $v_{PS}^d$ are the velocities along the ascending and descending orbits.
The first derivatives of energy $E$ with respect to each component of the unknown Terrain displacement velocity $v$ set to zero so obtaining the following linear equation:

$$
\mathbf{M} \cdot \mathbf{v} = \mathbf{a} \iff \begin{bmatrix}
  u^a_E v^a_E + u^d_E v^d_E \\
  u^a_E u^a_N + u^d_E u^d_N \\
  u^a_E u^a_Z + u^d_E u^d_Z \\
  u^a_N v^a_E + u^d_N v^d_E \\
  u^a_N u^a_N + u^d_N u^d_N \\
  u^a_N u^a_Z + u^d_N u^d_Z \\
  u^a_Z v^a_E + u^d_Z v^d_E \\
  u^a_Z u^a_N + u^d_Z u^d_N \\
  u^a_Z u^a_Z + u^d_Z u^d_Z 
\end{bmatrix} \begin{bmatrix}
  v_E \\
  v_N \\
  v_Z 
\end{bmatrix} = \begin{bmatrix}
  u^a_E v^a_{GPS} + u^d_E v^d_{GPS} \\
  u^a_N v^a_{GPS} + u^d_N v^d_{GPS} \\
  u^a_Z v^a_{GPS} + u^d_Z v^d_{GPS}
\end{bmatrix}
$$

The matrix $\mathbf{M}$ depends could be ill-conditioned for look an track angle values of Spaceborne SAR missions.
Earth dam: GB and SB-SAR data

\[
\begin{pmatrix}
\alpha_X & \alpha_Y & \alpha_Z \\
\beta_X & \beta_Y & \beta_Z \\
\gamma_X & \gamma_Y & \gamma_Z
\end{pmatrix}
\begin{pmatrix}
D_X \\
D_Y \\
D_Z
\end{pmatrix}
= 
\begin{pmatrix}
d_A \\
d_B \\
d_S
\end{pmatrix}
= 
\begin{pmatrix}
\frac{\lambda_{Ku}}{4\pi} \varphi_A \\
\frac{\lambda_{Ku}}{4\pi} \varphi_B \\
\frac{\lambda_X}{4\pi} \varphi_S
\end{pmatrix}
\]
Earth dam: GB and SB SAR data

\[
\begin{align*}
\mathbf{u}_r^L &= \begin{bmatrix}
\cos \vartheta_{GBSAR}^L & \cos \alpha_{GBSAR}^L \\
\cos \vartheta_{GBSAR}^L & \sin \alpha_{GBSAR}^L \\
\sin \vartheta_{GBSAR}^L & \\
\end{bmatrix} \\
\mathbf{u}_r^R &= \begin{bmatrix}
\cos \vartheta_{GBSAR}^R & \cos \alpha_{GBSAR}^R \\
\cos \vartheta_{GBSAR}^R & \sin \alpha_{GBSAR}^R \\
\sin \vartheta_{GBSAR}^R & \\
\end{bmatrix}
\end{align*}
\]
Geolocation and merging
Conclusions and future work

- An experiment has been carried out to merge GB and SB-SAR data to reconstruct the 3D displacement velocities.

- Results could be useful to set a protocol for the monitoring of dams.

- The future work will focus on using 3D displacement information provided by InSAR in dam modelling.