Ice surface velocities using SAR

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Outline

Synthetic Aperture Radar (SAR) theory
  Coverage / geometric resolutions / geometric distortions
  Surface properties / speckle / SAR glacier zones
  Advantages / disadvantages

Offset tracking
  Preprocessing / cross correlation / post processing
  Examples from Svalbard
  Preview of practical

Interferometric SAR
  Processing steps of 2-Pass D-InSAR of ERS-1/2 tandem pair

Take aways
Imaging geometry / Acquisition modes

Microwave sensors: Side-looking radar

Acquisition modes

Airbus Defence and Space [2014]

K. Langley, 2007
Figure 2.10: SAR intensity images of Kronebreen:
(a) Radarsat-2 Ultrafine Mode, 18th October 2013, 2 m geometric resolution.
(b) Radarsat-2 Wide Mode, 9th October 2013, 20 m geometric resolution.
(c) TerraSAR-X StripMap, 27th April 2008, 2 m geometric resolution.
(d) Radarsat-2 Wide Fine Mode, 23rd November 2015, 8 m geometric resolution.
Microwave sensors and their technical specifications: frequency, wavelength, waveband (modified after Richards, 2009).
SAR Theory - Speckle

SAR

Optical

Resolution cell

Re

Im

Kääb

Kääb
Interferometric SAR theory

Single Look Complex

Amplitude $|s|$

Phase $\varphi$

$$s = a + ib$$
$$s = |s| (\cos \varphi + i \sin \varphi)$$
$$= |s| (\cos(\varphi + 2k\pi) + i \sin(\varphi + 2k\pi))$$
$$s = |s| e^{i\varphi}$$

$a$: real part; $b$: imaginary part

$\varphi$: phase angle; $|s|$: magnitude, amplitude
SAR glacier zones

1. Onset of cold season
2. Freeze-up in firm
3. Winter rain event
4. Change in surf. prop.
5. Glacier facies (winter)
6. Onset of melt season
7. Transient snow lines
8. End of summer snowline
9. Length of melt season
10. Dry-to-wet snow line
11. Glacier front

SAR backscatter time series from RS-2 and Sentinel-1

Winsvold et al., 2018
Geometric distortions

Foreshortening

Layover

Shadow

azimuth
range
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Take aways
SAR offset and speckle tracking

Scheme of the offset tracking workflow:

1. Co-registration of two single-look complex (SLC) images e.g. using orbital parameters or correlation
2. Offset tracking (correlation)
3. Geocoding of the velocity map
4. Filtering of the velocity map
   - manual filtering based on amplitude and direction
   - automated filtering (e.g. maximum velocity, standard deviation)
Principle of offset tracking / image matching
From: Kääb [2005], modified

Cross-correlation in the spatial domain

$$CC(i, j) = \frac{\sum_{k,l}(s(i + k, j + l) - \mu_s)(r(k, l) - \mu_r)}{\sqrt{\sum_{k,l}(s(i + k, j + l) - \mu_s)^2 \sum_{k,l}(r(k, l) - \mu_r)^2}}$$

$i,j$ indicates the position in the search area,
$k,l$ the position in the reference area,
$r$ the pixel value of the reference chip,
$s$ the pixel value of the search chip
$\mu_r$ the average pixel value of the reference chip
$\mu_s$ the average pixel value of the search chip.

$->$ peak of the cross-correlation surface indicates
the displacement between the images

Cross-correlation in the frequency domain

$$CC(i, j) = IFFT(F(u, v)G^*(u, v))$$

$F(u,v)$ is the FFT of the matching window from the image at time $t=1$,
$G(u,v)$ is the FFT of the matching window from the image at time $t=2$,
$*$ denotes the complex conjugated and IFFT is the Inverse Fast Fourier Transform.
Basin-3 / Basin-2

Photo: Thorben Dunse
Landsat 8 OLI (29 May 2013)
Surface velocity of Basin-3 from SAR (2012 -2016)
Surface speed of Basin-3

Maximum speed: 18.8 m d$^{-1}$
Dec 2012 / Jan 2013
The beginning...

Crevasse formation on Basin-3 in 2004–2012 from GPR

Dunse et al., 2015

GPS velocity - Basin-3 (2008 - 2012)

Surface velocity April/May 2012

Dunse et al., 2015
Surface velocity of Basin-3 from GPS
Hydro-thermodynamic feedback

Phase 1: Initiation of spatially confined fast flow
Surface melt reaches the bed within an initiation zone

Phase 2 & 3: Multi-annual mobilization of reservoir, weakening of sticky spots / cold-ice plug

Summer melt promotes cryo-hydraulic warming, basal lubrication and sediment deformation

Annual hydro-thermodynamic feedback

Expansion of basal area subjected to surface melt, expansion of fast flow

Crevasse formation, meltwater routing to bed

Enhanced ice flow, longitudinal extension

Surge cycle of Basin-3

Surge
Failure of cold-ice plug

Quiescent phase

1870 1990s <2008

Quiescent phase

autumn 2012...
Stonebreen, Edgeoya

SE-Svalbard
toposvalbard

Sentinel-1 winter 2015 / Autumn 2015

Strozzi et al., 2017
Nathorstbreen surge

Maximum velocity > 40 m/day
→ Eventually the fastest glacier on Earth at that time
→ No offset tracking possible (→ advance)
Frontal ablation of Basin-3
April 2012 - July 2016

<table>
<thead>
<tr>
<th>Frontal ablation components</th>
<th>(Gt yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice mass flux, (Q_{fg})</td>
<td>7.8 ± 2.7</td>
</tr>
<tr>
<td>Terminus mass change, (Q_t)</td>
<td>2.6 ± 0.8</td>
</tr>
<tr>
<td>Terminus-seawater replacement, (Q_{tsw})</td>
<td>2.1 ± 0.7</td>
</tr>
<tr>
<td>Total frontal ablation</td>
<td></td>
</tr>
<tr>
<td>Mb perspective, (Q_{mb} = Q_{fg} - Q_t)</td>
<td>5.2 ± 1.9</td>
</tr>
<tr>
<td>SLR perspective, (Q_{sl} = Q_{mb} + Q_{tsw})</td>
<td>7.3 ± 2.6</td>
</tr>
</tbody>
</table>

Total Svalbard

6.8 ± 1.7 Gt yr\(^{-1}\)
(Blaszczyk et al., 2009)

2 l drinking water
for every human being – daily!
SAR practical – Sentinel-1 offset tracking of Basin-3 using the ESA SNAP Sentinel-1 Toolbox
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Take aways
2-pass D-InSAR workflow

ASC pair → Raw → SLC → Co-registration → Interferograms

DESC pair → Raw → SLC → Co-registration → Interferograms

DEM → Subsetting → Co-registration of DEM to SAR → Simulation of unwrapped topographic phase

Differential interferograms → Baseline refinements → Adaptive filtering

Unwrapping → Displacement maps

Combination ASC / DESC → UTM

Accuracy assessment
Interferometric SAR theory

Single Look Complex

\[ s = a + ib \]
\[ s = |s| (\cos \varphi + i \sin \varphi) \]
\[ = |s| (\cos(\varphi + 2k\pi) + i \sin(\varphi + 2k\pi)) \]
\[ s = |s| e^{i\varphi} \]

\( a \) : real part; \( b \) : imaginary part
\( \varphi \) : phase angle; \( |s| \) : magnitude, amplitude
Interferometric SAR theory

Interferometric SAR (Radar interferometry, InSAR)
Interferometric SAR (Radar interferometry, InSAR)

$\Delta \phi$: interferometric phase

$\Delta \phi = 100^\circ$

$\Delta \phi = 0^\circ$
Interferometric SAR theory

Interferometric SAR (Radar interferometry, InSAR)
Interferometric SAR theory

Interferometric SAR (Radar interferometry, InSAR)

- $f$ (topography)
Interferometric processing of ERS-1/2 tandem pair

Interferogram ASC

Interferogram DESC

* ERS-1/2 data from ESA / Romsenter PRODEX project “ICEDIVIDE”
DEM preparation

DEM hill shade

Simulated SAR image

SAR height

Simulated unwrapped phase
Subtraction of topographic phase

Interferogram #2

Differential Interferogram
Unwrapping

Phase unwrapping: up-slope example

Wrapped phase
Unwrapping

Phase unwrapping: up-slope example

2 ambiguities:
• $\pi$ - ambig
• Integration constant
Unwrapping

Phase unwrapping: up-slope example

2 ambiguities:
• \( \pi \) - ambiguities
• Integration constant

Only \( \Delta h \) or displacement < 2\( \pi \) between two pixels can be measured

Real terrain?

Unwrapped phase

Wrapped phase

Real terrain?
Unwrapping

Phase unwrapping: noise

2 ambiguities:
• $\pi$ - ambig.
• Integration constant

Only $\Delta h$ or displacement $< 2\pi$ between two pixels can be measured

$$\frac{\partial \phi}{\partial z} = \frac{4\pi}{\lambda} \frac{B_z}{y' \sin \theta}$$

Wrapped phase
Unwrapping

Differential interferogram

Differential unwrapped interferogram
2-pass D-InSAR workflow

ASC pair

- Raw → SLC
- Co-registration
- Interferograms
  - Differential interferograms
    - Baseline refinements
      - Adaptive filtering
        - Unwrapping
          - Displacement maps
            - Combination ASC / DESC → UTM

DESC pair

DEM

- Subsetting
  - Co-registration of DEM to SAR
    - Simulation of unwrapped topographic phase

Accuracy assessment
Velocity map – line of sight
2D velocity map
Icedivide between Kongsbreen and Monacobreen

**Speed (m/d)**

**Direction (N = 0°, clockwise)**

Influence of the surge?
InSAR Accuracy (bedrock displacement in meter) of Jostedalsbreen 20/21 Jan 1996 – 6/7 Mar 1996

<table>
<thead>
<tr>
<th></th>
<th>V_median</th>
<th>V_mean</th>
<th>V_std</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTM</td>
<td>0.00552</td>
<td>0.00764</td>
<td>0.00732</td>
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<tr>
<td>ASC</td>
<td>0.00372</td>
<td>0.00606</td>
<td>0.00702</td>
</tr>
<tr>
<td>DESC</td>
<td>0.00381</td>
<td>0.00636</td>
<td>0.00728</td>
</tr>
</tbody>
</table>
Take aways

SAR Limitations
• Side-looking sensor (complicated image geometry)
• Backscatter difficult to interpret visually
• Some penetration into the ground
• Sensitive coherence (repeat pass)
• Much analysis know-how necessary

Offset tracking
• robust method for fast moving glaciers
• Accuracy ~1/10 of a pixel

InSAR
• for slow displacements
• accuracy in the range of cm
• many parameters to tune
Thank you!