Results of **UAVSAR** Airborne SAR Repeat-Pass Multi-Aperture Interferometry

Bryan Riel, Ron Muellerschoen
Jet Propulsion Laboratory, California Institute of Technology

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Measuring deformation using radar interferometry uses two passes separated by time intervals ranging from minutes to years to access motion along the radar line-of-sight between observations.

State-of-the-art data fusion of precise GPS positions and aircraft INU data still leaves residual phase errors in the SAR interferogram.
Baseline Estimation – Range Estimates

- Range and azimuth displacements between the images of the two passes can be used to obtain baseline correction.

- Two methods of displacement construction will be discussed
  - ampcor – Amplitude Correlation
  - MAI – Multi-Aperture Interferometry

- Components of the baseline offsets in the cross-track ($B_C$) and vertical ($B_H$) direction can be obtained by minimizing the performance functional $J_R$

$$J_R(B_C(k), B_H(k)) = \sum_{i \in k} \left| \frac{\lambda}{4\pi} \phi_i - B_C(k)L_C - B_H(k)L_H \right|^2$$

where $L_C$ and $L_H$ are the components of the look vector at instance $i$
Baseline Estimation – Azimuth Estimates

- Range and azimuth displacements between the images of the two passes can be used to obtain baseline convergence angles.
  - Baseline convergence angles $\tan \gamma$ and $\tan \delta$ can be obtained by minimizing the performance function $J_A$

$$J_A \left( \frac{dB_C(k)}{dS}, \frac{dB_H(k)}{dS} \right) = \sum_{i \in k} \left| \sin \alpha - \frac{\langle \overline{T - P_1 - B(k), M(k) \cdot \hat{n}} \rangle}{|\overline{T - P_1 - B(k)}|} \right|^2$$

where $\alpha$ is the electronic steering angle, $\hat{n}$ is the imaging plane normal, $T$ and $P_1$ are the target and platform locations and

$$\overline{B(k)} = \left( \frac{\text{azimuth spacing}}{4\pi}, \phi_a(i), B_C(k), B_H(k) \right)$$

$$M(k) = \begin{pmatrix} 1 & -\gamma(k) & \delta(k) \\ \gamma(k) & 1 & 0 \\ -\delta(k) & 0 & 1 \end{pmatrix}$$

NB: scaling by (azimuth spacing / 4 / $\pi$) to be explained

Baseline Estimation Process

- Integrating the baseline convergence angles $\tan \gamma$ and $\tan \delta$ produces estimates of the baseline offsets.
  - Estimates of cross-track baseline offsets ($B_C$) and vertical baseline offsets ($B_H$) as determined from $J_R$ are used as the constants of integration.
Multi-aperture Interferometry Overview

- Range and azimuth displacements can be generated from cross-correlation of amplitude images.
  - Sub-pixel precision can be obtained by oversampling the data during cross-correlation.
  - Computation is performed on small patches of the images resulting in offset measurements in both Range and Azimuth directions.
    - Range estimates and Azimuth estimates are correlated.
  - Method depends on speckle correlation--not image correlation.
  - “ampcor”

- Range and azimuth displacements can also be generated from phase differences in the images.
  - Generate forward and backward SLC’s which correspond to positive and negative Doppler frequencies.
  - Computation is performed on large patches of data resulting in offset displacements in Azimuth direction.
    - Additionally requires phase unwrapping.
    - Range offsets derived directly from the interferogram of the scene and therefore uncorrelated with the azimuth estimates.
      - But also requires phase unwrapping.
  - Proves to work well with scenes of low contrast such as ice.
  - Multi-Aperture Interferometry or MAI
MAI Technique – Geometry

Sub-aperture processing produces forward and backward looking interferograms:

\[
\Phi_{\text{forward}} = -\frac{4\pi}{\lambda} \Delta S \sin(\theta_{sq} + \beta)
\]

\[
\Phi_{\text{backward}} = -\frac{4\pi}{\lambda} \Delta S \sin(\theta_{sq} - \beta)
\]

\[
\Phi_{\text{MAI}} = \Phi_{\text{forward}} - \Phi_{\text{backward}} = -\frac{8\pi}{\lambda} \Delta S \cos\theta_{sq} \sin\beta
\]

where \( \beta \) is the fraction of the full beamwidth \( \alpha \) and \( \Delta S \) is a displacement in the along track.

For \( N \) subapertures:

\[
\beta = \frac{\alpha}{2N} \quad \text{and} \quad \alpha = \frac{\lambda}{L_a} \quad \text{and} \quad L_a \quad \text{is the effective antenna length}
\]

\[
\therefore \quad \Delta S = -\Phi_{\text{MAI}} \frac{2NL_a}{8\pi} \quad \text{for small} \quad \theta_{sq} \quad \text{and small} \quad \beta
\]

For a azimuth resolution of 3 meters, \( L_a \) is 6 meters, and with 2 sub-apertures:

\[
\Delta S = -\Phi_{\text{MAI}} \ast (3 / \pi) \text{ meters}
\]

\[
\phi_a(i) = (4\pi \Delta S) / (\text{azimuth spacing})
\]

MAI Technique – Two Possible Approaches

- 4 additional images are required
  - 1.) forward looking image of pass 1, call it $S_1^f$
  - 2.) backward looking image of pass 1, call it $S_1^b$
  - 3.) forward looking image of pass 2, call it $S_2^f$
  - 4.) backward looking image of pass 2, call it $S_2^b$

\[ \Phi_{MAI} = \arg\left\{ (S_1^f S_2^*) (S_1^b S_2^*)^* \right\} \]

- Instead, filter the focused images in the azimuth direction
  - Construct a FIR filter with pass band equal to the width of a single sub-aperture ($\alpha/N$)
  - Shift in the frequency domain to pass either the positive or negative frequencies associated with the Doppler centroid
  - NB: Each filter will be range dependent due to look angle variation over the range swath
MAI Technique – convolve SLC with FIR filter

- In time domain, construct forward looking filter $h^f$ and backward looking filter $h^b$

\[
h^f(j; r) = C_j e^{4\pi j(0.25)} e^{4\pi j f_0}
\]

\[
h^b(j; r) = C_j e^{4\pi j(-0.25)} e^{4\pi j f_0}
\]

where \(f_0(r) = \frac{2(\text{azimuth spacing})L_s(r)}{\lambda}\)

and \(L_s(r)\) is the component of the look vector in the along track direction
Controlled Example

- Use same data in repeat pass mode – but perturb platform motion.  
  use real-time vs. post-processed GPS data

2 $\pi$ wrap interferogram

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Amplitude image

32 km
Baseline Estimates from Minimizing $J_R$ and $J_A$
Interferograms from Baseline Estimates...

- Using ampcore displacements
- Using MAI displacements
- Using truth displacements

Increasing range

π/2 wrap interferogram
Range and Azimuth Displacements
Examples—processing sample RPI cases with MAI

SanAnd_26501_10027-001_10028-000_0001d_s01_L090HH_02
(10027: 2 deg avg yaw, 10028: 4 deg avg yaw)

ampcor

Near range fringing appears to be reduced.
Phase variations closer to mean 0.
Examples—processing sample RPI cases with MAI

Laurnt_18801_09054-005_09056-005_0002d_s01_L090HH_01
(09054: 7 deg avg yaw, 09056: 4 deg avg yaw)

Smaller Residual Phase
Examples—processing sample RPI cases with MAI

harvrd_18505_09060-005_09065-004_0004d_s01_L090HH_01
(09060: avg -1deg yaw, 09065: avg 9deg high yaw)

ampcor

MAI
Near range fringing reduced
Examples—processing sample RPI cases with MAI

harvrd_18501_09063-002_09065-006_0001d_s01_L090HH_01
(09063: -0.6 avg yaw, 09065: -0.5 avg yaw)

ampcor

MAI
Flatter interferogram
Summary

• Demonstrated that Multi-Aperture Interferometry can produce azimuth displacements comparable to amplitude correlation displacements.
  – Method has not been adopted for production of repeat-pass interferometry at JPL.

• Possible advantage of MAI is that the range displacements are uncorrelated from the azimuth estimates.
  – Range offsets come directly from unwrapped interferogram.

• Additional sub-banding techniques are also being investigated for improved residual motion recovery.