Delta-k Wideband SAR Interferometry for DEM Generation and Persistent Scatterers using TerraSAR-X

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Wideband Interferometry
– Estimate absolute phase without phase unwrapping

Standard Interferometry \( \phi = 4\pi \frac{f_c}{c} \Delta r \)
Delta-k Wideband Interferometry \( \phi_\Delta = \phi_2 - \phi_1 = 4\pi \frac{2f_0}{c} \Delta r \)

Example for TerraSAR-X: \( f_c = 9.65 \text{ GHz}, \lambda_c = 0.031 \text{ m}, B = 150 \text{ MHz} \)
Delta-k with \( b = 50 \text{ MHz} \) subbands: \( f_\Delta = 2f_0 = 100 \text{ MHz}, \lambda_\Delta = 3.1 \text{ m} \)

Height of Ambiguity increased by delta-k scaling factor \( k_\Delta = \frac{f_c}{2f_0} \approx 100 \)
DEM Generation – Salt Lake Salar de Arizaro, Argentina

Salt sea ~3500 m

Mountains ~4700 m
DEM Generation – Salt Lake Salar de Arizaro, Argentina

HoA 7.4 m/cycle

Acquisitions
15.07.2007, 26.07.2007
Stripmap 21 x 60 km
Carrier frequency 9.65 GHz
Range bandwidth 100 MHz
Resolution 1.8 x 3 m
Carrier HoA 7.4 m/cycle

Interferometric processing
36 interferometric looks
Resolution ~ 10 x 17 m

Fullband Coherence
Fullband Interferometric Phase
DEM Generation – Salt Lake Salar de Arizaro, Argentina

**HoA** 1076 m/cycle

**Subbands**
- Range bandwidth 33 MHz
- Simulated carrier 67 MHz, 4.5 m
- Resolution 4.5 x 3 m
- Delta-k scaling factor 145
- Delta-k HoA 1076 m/cycle

**Interferometric processing**
- 36 interferometric looks
- Resolution ~ 13 x 17 m

**Map**

**Fullband Coherence**

**Raw Delta-k Phase**
DEM Generation – Salt Lake Salar de Arizaro, Argentina

HoA 1076 m/cycle

Fullband Coherence

Smoothed Delta-k Phase

Smoothing filter
Resolution ~ 180 x 300 m
DEM Generation – Salt Lake Salar de Arizaro, Argentina

Scaled to Carrier Frequency, HoA 7.4 m/cycle

Resolution
MCF-PU ~ 10 x 17 m
Delta-k ~ 180 x 300 m

Fringe pattern over salt sea attributed to atmospheric delay effects – principally water vapour (see paper)

Comparison to SRTM DEM showed far fewer errors of a smaller magnitude using delta-k

MCF Phase Unwrapping

Delta-k absolute phase
Coherence

Remote Sensing Technology Institute


Institut für Methodik der Fernerkundung bzw. Deutsches Fernerkundungsdatenzentrum

200 m

MCF-PU Control

Raw Delta-k Phase

Smoothed Delta-k Phase

Salar de Arizaro
“lava tongue” feature
- MCF-PU incorrect
- Delta-k correct

SAR Intensity

MCF-PU Solution

Delta-k Absolute Phase

MCF-PU

Delta-k

SRTM C-band DEM
Delta-k with Custom Split Bandwidth Chirps

Standard Chirp

Custom Split Bandwidth Chirp

Transmitted

Lower subband

Upper subband

WASTED ENERGY/DOWNLINK BW

NO WASTED ENERGY/DOWNLINK BW

Received
Delta-k with Custom Split Bandwidth Chirps

- Range bandwidth $B$
- Subband bandwidth $b$
- $B/(2b)$ more subband energy/SNR
  - $b = B/3 \Rightarrow$ SNR increase 1.8 dB
  - $b = B/8 \Rightarrow$ SNR increase 6.0 dB

- TSX-1 commanded in experimental mode
- Manual focusing of subband L0 products

Spectrogram, custom chirp stripmap acquisition
range BW 300 MHz, subband BW 37.5 MHz
Delta-k with Custom Split Bandwidth Chirps
- DEM Generation, Salt Lake Salar de Uyuni, Bolivia

**Acquisitions**
08.03.2008, 30.03.2008
Stripmap 8.7 x 83 km
Carrier frequency 9.65 GHz
Range bandwidth 300 MHz
Carrier HoA 28 m/cycle

**Subbands**
Range bandwidth 37.5 MHz
Resolution 4 x 3 m

**Interferometric processing**
36 interferometric looks
Subband resolution 6.7 m x 14 m

Salt sea ~3650 m
Mountains ~5500 m

**Delta-k Phase**
Delta-k processing
Delta-k scaling factor 37
Delta-k HoA 1027 m/cycle
Resolution 64 x 240 m

Wikipedia

Wideband Persistent Scatterer Interferometry (PSI)

- PSI provides accurate height and deformation estimates for a single PS relative to a reference point.
- Combines 100s – 1000s of PSs in a network to estimate all topographic and deformation parameters simultaneously (spatial phase unwrapping).
- Phase unwrapping → unwrapping error & error propagation.
- Delta-k can provide height estimates without phase unwrapping:
  - No possibility of error propagation.
  - Simple method, no network required → little computational complexity.
- Explore theoretical / practical aspects of delta-k for PSI.
Wideband PSI – Interferometric Stack Description

- 25 x 300 MHz HS acquisitions
  22.11.2007 – 31.03.2009
- Subband bandwidth \( b = 100 \) MHz
  Delta-k scale factor \( k_\Delta \approx 48 \)
- 24 slaves coregistered to common master
- Focus on Eiffel tower - many strong scatterers
Wideband PSI – Theory

- Differences to DEM generation / distributed scatterers
  - Interested in a single PS only → do not smooth delta-k phase
  - SCR << SNR → performance dependent on SCR not SNR

- Optimal subband bandwidth still $b = B/3$

**Equation:**

$$\frac{1}{\sqrt{2\pi}} \frac{f_C}{B} \frac{1}{1 - b/B} \frac{1}{\sqrt{SCNR}} [\text{cycles}]$$

**Graph:**

- SNR > 33 dB: 10⁴ pixels
- SCR > 33 dB: ~0 pixels

**Parameters:**

- $f_C = 9.65 \text{ GHz}$
- $B = 300 \text{ MHz}$
- $b = 100 \text{ MHz}$

**Legend:**

- SNR
- SCR

- [dB]

**Note:**

$\frac{1}{4}$ cycle

33 dB
Wideband PSI –
Conventional PSI Processing

- GENESIS-PSI developed at DLR, IMF

- Involves many complicated steps including:
  PS detection, generation of reference network and arcs, lambda method for estimation on arcs, SVD network inversion

Reference Network PSs and Arcs
Wideband PSI –
Single Delta-k Interferogram Height Estimate

- Obtain height estimate by scaling delta-k phase from a single delta-k interferogram with delta-k HoA
- Maintains temporal resolution
- Increase in $\sigma \approx \sqrt{2k_\Delta} \approx 68$
- Only possible for very strong scatterers

23 m/cycle

1024 m/cycle

$P(y|x, M)P(x|M)$
Wideband PSI –
Single Delta-k Interferogram Height Estimate

- Reduce error in single delta-k interferogram height estimate by smoothing delta-k phase as for DEM generation
- Only intended for quick and simple validation
- Loss in resolution (~16 x 21 m) defeats purpose of PSI where focus is on single scatterers

23 m/cycle

1024 m/cycle
Wideband PSI –
Least Squares Delta-k Height Estimate

Phase $\propto$ height through height-to-phase ratio, perform LS linear regression for single pixel

$$\phi_\Delta[k] = h2 p_\Delta[k] \times h, \quad k = 1, \ldots, K$$

- More accurate and robust estimates
  - Atmospheric error averages out over stack
  - Factor reduction in $\sigma \approx 2.3$

- Loss of temporal resolution

- Amend regression model for time varying deformation? deformation $\sigma \approx$ deformation
  Difficult for single PS – must average over several PSs

23 m/cycle
Conclusion

- Wide bandwidth of TerraSAR-X allows use of delta-k absolute phase estimation without error prone phase unwrapping

- DEM Generation: Delta-k can be used to validate / support phase unwrapping, especially if custom chirps are used to increase the SNR

- PSI: Application limited to only the strongest PSs. As system bandwidths increase and SCRs decrease, delta-k for PSI will become more attractive.