Assessment of the suitability of COSMO-SkyMed data to multi-temporal and multi-chromatic applications of radar-interferometry

FINAL WORKSHOP
“ACHIEVED RESULTS IN RESPONSE TO THE FIRST COSMO-SkyMed ANNOUNCEMENT OF OPPORTUNITY”

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SAR Interferometry

Coherent combination of two (or more) SAR images of the same area taken from slightly different directions:

\[
\Phi = -\frac{4\pi B_{\perp}}{c r_0 \sin \theta} (H \cdot f) \left(\frac{4\pi}{\lambda} v \cdot t\right)
\]

- **InSAR Absolute Phase**
- **Topography**
- **Movement**

**Multi-frequency Analysis**
- Frequency: \(f_0 \rightarrow f_{N_f}\)

**Multi-temporal Analysis**
- Time: \(t_0 \rightarrow t_N\)
Project objectives

• A systematization of the technical aspects related to the innovative Multi-Chromatic Analysis (MCA) in the context of repeat-pass interferometry and validation of the MCA for height retrieval with COSMO-SkyMed (CSK) data.

• Assessment of the suitability of CSK data to multi-temporal SAR interferometry, highlighting advantages and possible shortcomings of CSK mission with respect to the rest of present-day SAR data.

• A quantitative assessment of the nature of frequency-persistent scatterers (F-PS), in correlation to known temporal-PS targets.
Project status

The time scheduling of the project has been updated according to a delay of six months in the activities due to a correspondent delay of the CSK data procurement.
Test sites

• **ULURU monolith** (Australia), the topographic configuration as well as the surface coverage make this site well suited for MCA development and tuning. (S2: 8)

• **Zhouqu area** (Gansu Province, China) for experimenting the potentiality of CSK interferometric application to landslide monitoring. (S2: 25)

• Parkfield (USA), well suited for PSI investigations and comparison between PS and F-PS. (HI: 48, S2: 33)
Multi Chromatic Approach (MCA) is aimed at performing Phase Unwrapping (PU) and measuring ground elevation.
Multi-Chromatic Approach (MCA) principles

- Starting from the original idea of Madsen and Zebker, MCA involves the computation of a set of several equal-resolution interferograms from SAR sub-look images of bandwidth $B_p$ centred at different carrier frequencies $f_i$:

$$\Phi^W(x,y) = -2\pi \cdot k(x,r) - \frac{4\pi}{c} \cdot \Delta R(x,r) \cdot f_i = C_0(x,r) + C_1(x,r) \cdot f_i$$

- **Absolute phase measurement / Fringes classification**

$$k(x,r) = -\frac{C_0(x,r)}{2\pi}$$

- **Height measurement**

$$\Delta R(x,r) = -\frac{c}{4\pi} \cdot C_1(x,r)$$
Multi-Chromatic Approach (MCA) principles

- The basic MCA algorithm, for the height measurement, consists of performing standard InSAR processing on sub-band signals, followed by a point-wise estimation of $C_0$ and $C_1$ through a linear regression method.

- The height of any pixel is retrieved independently from the others and no phase unwrapping step is needed in the spatial domain. The resolution of the resulting interferogram depends on the spectral sub-band width, $B_p$.

- The inter-band coherence or the multi-frequency phase STD can be assumed as a quality index of the measurements:

$$
\sigma_\phi = \sqrt{\frac{1}{N_f} \sum_{i=1}^{N_f} [\Phi_i(x,r) - c_0(x,r) - c_1(x,r) \cdot f_i]^2}
$$

- Reliable measurement can be performed on the targets showing a good linear phase trend vs. frequency ($PS_{fd}$):

$$
PS_{fd} = \{(x,y) | \sigma_\phi (x,y) \leq \sigma_{th}^{\phi}\}
$$
MCA potentials

• Absolute phase/height retrieval (point-based PU, instead of conventional gradient-based PU)
• Support to standard (gradient-based) PU procedures
• Support to SAR image coregistration
• Coherent scatterers identification
• Absolute ranging
• MCA computes $C_0(x,y)$, $C_1(x,y)$, $\sigma_\phi(x,y)$:
  - Phase unwrapping: $\phi_{\text{MCA}}(x,y) = C_1(x,y) \cdot f_0 + \Phi_{\text{drg coreg}}(x,y)$ (if coregistration is performed once at full band)
  - Height retrieval: $H(x,y) = \phi 2H(x,y) \cdot \Phi_{\text{MCA}}(x,y)$
MCA parametric analysis

• A parametric analysis has been carried out with the aim of evaluating the impact of the MCA processing parameters ($B$, $N_f$, $B_p$, $B_e$) on the estimation performance.

• Results indicate that the estimation is improved mainly by using wider explored bandwidth, and secondly by using a wider bandwidth of the sub-look images or by increasing the number of sub-bands.

• At least $B=300$ MHz seems to be required to a reliable application.

• The technique appears optimally suited for the new generation of satellite sensors, which operate with larger bandwidths → COSMO-SkyMed
MCA on Uluru monolith

Tandem pairs acquired with ENHANCED SPOTLIGHT (B≥300MHz) acquired over the Uluru monolith, in central Australia along descending orbits.

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<th>ID</th>
<th>MASTER</th>
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<th>Bn (m)</th>
<th>Ha (m)</th>
<th>B (MHz)</th>
<th>Look</th>
<th>ΔRg</th>
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<td>28.4°</td>
<td>0.5</td>
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MCA on Uluru monolith

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MCA processing

• Split-band processing of MASTER and SLAVE to generate Nf sub-band images

\[ B = 325 \text{ MHz, } f_0 = 9.65 \text{ GHz (CSK)} \]
\[ N_f = 3 \div 15 \]
\[ B_p (df) = 20 \div 100 \text{ MHz} \]
\[ B_e = 180 \div 280 \text{ MHz} \]

• Generation of N_f InSAR phase fields
• Smoothing filtering of each sub-band phase field
• MCA analysis to compute \( C_0(x,y), C_1(x,y), \sigma_\phi(x,y) \):
  
  – **Phase unwrapping**: \( \phi_{MCA}(x,y) = C_1(x,y) \cdot f_0 + \Phi_{\text{drg\_coreg}}(x,y) \) (if coregistration is performed once at full band)
  
  – **Height retrieval**: \( H(x,y) = \phi 2H(x,y) \cdot \Phi_{MCA}(x,y) \)
MCA on Uluru monolith: CSK 03-04.09.2011

\[ \Phi_{MCA}^{UW}(x, r) = C_1(x, r) \cdot f_0 - \frac{4\pi}{\lambda} \delta r g_{coreg}(x, r) \]

**Absolute phase**
(after spatial filtering)

**Contribution from frequency analysis**
In order to validate this MCA-based absolute phase we compare the modulo $2\pi$ of this phase, $\Phi^W(x,r)$, wrt to the original interferogram, $\Phi_{MCA}^W(x,r)$.

The flattening is successful:
- There is less than one residual fringe on the whole flat area.
- On the monolith itself, there is also less than one residual fringe.
- Flattening fails where absolute phase derived through MCA is too noisy (due to decorrelation).
A calibration was required to remove the offset due to orbital errors as well as atmospheric signal which impact on the height computation.

Calibration was performed by exploring the SRTM DEM.

Smoothing filtering is also applied during calibration to reduce noise.
MCA on Uluru monolith: CSK 03-04.09.2011

- Offset removed though calibration
- Constraints have been applied on $\sigma_{\phi}$. 

![Graphs showing results of MCA on Uluru monolith](image-url)
MCA on Uluru monolith

- As reference DEM we used a post-processed 3-arc second (90 m) SRTM DEM provided by CGIAR-CSI.
- No-data regions due to insufficient textural detail (found especially in mountainous regions) are filled through interpolation.

MCA on InSAR phase provides information (except for a bias) where the coregistration fails.
In the same area the reference DEM used for comparison is not accurate due to steep slopes and coarse interpolation.
MCA on Uluru monolith
MCA on Parkfield test site

CSK Spotlight
- CSK_SCS_B_S2_02_VV_LD
- Master: 18.09.2010
- Master: 19.09.2010
- Bn = 112 m
- Bp = 75 m
- fo = 9.6 GHz (Λ=3.12 cm)
- B = 379 MHz
- Slant range res. = 0.5 m
- Azimuth res. = 1.1 m
- Ha ~ 44 m

SRTM

MCA_H_filt

σφ mask
MCA parametric analysis

- The theoretical parametric model has been also validated by processing ENANCED SPOTLIGHT CSK tandem couples acquired on ULURU test case.

- Results confirm that the estimation is improved mainly with wider explored bandwidth $B_e$, and secondly with wider sub-look bandwidth $B_p$ or more sub-bands $N_f$. 

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![Graphs showing parametric analysis results](image-url)
Advanced multi-temporal InSAR techniques (PSI, SBAS etc) allow detecting and monitoring with millimetre precision displacements occurring on targets exhibiting coherent radar backscattering (man-made structures, rock outcrops).
Multi-temporal Analysis

- In the framework of DInSAR applications it is worthwhile to investigate potential of the multi-temporal DInSAR processing of the high-resolution COSMO-SkyMedSAR data with respect to the thoroughly exploited medium resolution C-band SAR data.

- In particular, two specific questions come up:
  
  1. How do the characteristics of the new SAR sensors impact on PS processing?
  
  2. Can the minimum number of SAR images required to obtain reliable PSI results be lower for high resolution data with respect to medium resolution data?

\[ \lambda, B, dt \longrightarrow N_i, N_{PS} \]
Multi-temporal Analysis

• Through a simple theoretical model, it is possible to take into account the differences in wavelength, resolution and revisit time between **X-band high resolution** and **C-band medium resolution** sensors.

\[
\sigma_v \approx f_1(N_i, T) \cdot \frac{\lambda}{4\pi} \sigma_\phi = f_1(N_i, T) \cdot \sigma_d = f_1(N_i, T) \cdot f_2(B, \lambda, \sigma_0, \theta)
\]

**N\_i** → We demonstrated that with the **higher resolution**, new generation X-band sensors, reliable estimates of the displacement rates are possible using **fewer SAR scenes** than in the case of C-band medium resolution data.

**N\_PS** → The high resolution leads to PS spatial density **between five and ten times greater** than that derived by medium resolution data.
The Zhouqu area is located in the central part of the China (Gansu region) along Bailong river and it results very interesting for landslides investigation.
The geomorphology/geology of the Zhouqu area.

- Seismically active area (high, even >7, magnitude earthquakes), fault controlled landscape, very high relief.

- The highest peak reaches over 3000 m, the lowest point is the main river at about 1340 m elevation. Very steep mountain terrain (upper slopes gradients exceeding 35°).

- Tree cover only at the highest elevations.

- Relatively dry climate, but with monsoon-like late spring-summer.

- Geology/Lithology make the area susceptible to slope instability: loess, limestones, argillites/shales, igneous and metamorphic rocks.
• In the area, there are several active landslides, moving slowly and can block the Bailong River at any time.
• In August 2010, debris flows destroyed about 200 houses, causing the deaths of more than 1500 people, in the town of Zhouqu. The Sanyayu catchment generated the largest debris flows.

Satellite images showing Zhouqu before (left) in July, 2008 and after the recent landslide (right), taken on August 8, 2010 (from the State Bureau of Surveying and Mapping).

(STR/AFP/Getty Images)
PSI SPINUA Processing - Zhouqu

- 22 CSK HIMAGE acquisitions.
- Pass: Descending.
- Polarization: HH.
- Look side: Right; Beam: HI_09, θ:40°
- The topographic range is ~ 2km.

- Steep topography, low urbanisation and scarce number of images make difficult the processing.
PSI SPINUA Processing - Zhouqu
• SPINUA adopts some ad hoc solutions (robust patch-wise processing scheme) which enable to get fast results, on small areas by processing also scarcely populated stack of SAR images.

• InSAR processor has been updated in order to handle:
  – Left-looking acquisitions
  – Rough topography and long baselines (DEM-assisted coregistration)
  – The high variability of Doppler centroid along azimuth direction in enhanced spotlight acquisitions (resampling, common-band filtering)
  – PRF changes between master and slave acquisitions (stripmap/spotlight)
1. Large (well over 1 km long), deep, active landslide (known – inspected in 2009 and 2011); arrows indicate the direction of movement.
2. Landslide zone or landslide complex (with superimposed, coalescing movements), on the GE image can note 2 active landslides (known - visited 2009 e 2011).
3. Area characterized by the presence of more or less recent landslides; signs of recent slope instability were noted during a visit in 2011.
4. A large, composite/complex landslide; we did not know about it, but one can recognize it on GE image.
Conclusions

• Multi-Chromatic Analysis (MCA)
  - It was shown that **MCA is able to derive a reliable unwrapped interferometric phase surface** (with some spatial smoothing) where, due to the steep terrain slopes, conventional 2D PU results critical.
  - The **absolute measurements (phase / height)** are affected by atmospheric artefacts as well as orbital errors. Calibration procedures through independent measurements (e.g. reference points) are required. Surface model has been obtained also on steep terrain slopes (ULURU).
  - The impact of the processing parameters ($B$, $N_f$, $B_p$, $B_e$) have been evaluated through modeling and CSK processing.

• Multi-temporal analysis
  - SPINUA PSI algorithm was updated to handle CSK specifics and applied to detect displacements induced by slope instabilities in an complex area (steep slopes, low urbanisation, few CSK HI acquisitions).
  - Results confirm the indications coming from theoretical analysis as well as previous studies: thanks to the higher resolution of CSK, reliable displacements are derived even by processing few SAR scenes. **A practical implication is that, also thanks to the short repeat cycle of CSK constellation, landslide assessment and hazard monitoring results can be obtained in a shorter time, which is particularly relevant in high risk cases.**
Ongoing activities and future works

- Multi-temporal analysis for atmospheric artefacts reduction.
- Investigation of the impact of the scattering nature on the frequency behaviour ($PS_{fd}$ vs $PS$).
- Performing MCA on single SAR image to infer atmospheric delay and to perform absolute ranging.
Thank you!