MULTI-CHROMATIC ANALYSIS OF INSAR DATA: VALIDATION AND POTENTIAL

Fabio Bovenga, Vito Martino Giacovazzo, Alberto Refice, Nicola Veneziani, Raffaele Vitulli (ESA ESTEC)

bovenga@ba.issia.cnr.it
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• Multi Chromatic Analysis (MCA) background
• Implementation aspects.
• First validation on airborne and spaceborne SAR sensors.
• Comments and conclusions.
InSAR principles

\[ \Phi(x, r) = -\frac{4\pi}{c} \cdot \Delta R(x, r) \cdot f_c = -\frac{4\pi}{c} \left[ \frac{B_s H(x, y)}{R_0 \sin \theta} + \Delta R_{Atm}(x, r) + \Delta R_{def}(x, r) \right] \cdot f_c \]

\[ \Delta R = R_M - R_S \]

- Topography
- Atmosphere
- Deformation

\[ \text{Swath} \]

\[ \text{Ground range} \]
\[ \Phi(x, r) = \Phi^W(x, r) + 2\pi \cdot k(x, r) \]
• Madsen and Zebker:

\[ \phi_{\text{diff}} = \phi_+ - \phi_- = 2\pi \cdot \left( f_+ - f_- \right) \cdot t_d \]

\[ \phi_{\text{abs}} = \frac{f_0}{(f_+ - f_-)} \phi_{\text{diff}} \]

- \( \phi_{\text{abs}} \) is used to compute the \( K_{2\pi} \) necessary to recover the absolute phase
- Averaging is required to keep the noise low and attenuate effect of factor \( f_0 / (f_+ - f_-) \)
Multi-Chromatic Approach (MCA) principles

- MCA of InSAR processing 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 $f_i$:

$$\Phi = -\frac{4\pi}{c} \Delta R \cdot f_c \implies \Phi_i = -\frac{4\pi}{c} \Delta R \cdot f_i$$

$$f_i = f_c + df_i \in [f_i - B_i/2, f_i + B_i/2]$$

- Only wrapped phase values are known:

$$\Phi_i(x, r) = \Phi_i^W(x, r) + 2\pi \cdot k(x, r) \implies \Phi_i^W(x, r) = -2\pi \cdot k(x, r) + \Phi_i(x, r)$$
Multi-Chromatic Approach (MCA) principles

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

- \( k(x, r) = -\frac{C_0(x, r)}{2\pi} \) 
  Absolute phase measurement / Finges classification

- \( \Delta R(x, r) = -\frac{c}{4\pi} \cdot C_1(x, r) \) 
  Height measurement

**FFT along range**
- \( B = 100 \text{ MHz} \), \( f = 9.40 \text{ GHz} \)
- \( B_1 = 40 \text{ MHz} \), \( f_1 = 9.42 \text{ GHz} \)
- \( B_2 = 40 \text{ MHz} \), \( f_2 = 9.41 \text{ GHz} \)
- \( B_3 = 40 \text{ MHz} \), \( f_3 = 9.40 \text{ GHz} \)
- \( B_4 = 40 \text{ MHz} \), \( f_4 = 9.39 \text{ GHz} \)
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 for the MCA and 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 ($PS_{fd}$):

$$P_{fd} = \{(x, y) \mid \sigma_\phi(x, y) \leq \sigma^{th}_\phi \}$$
MCA on 100 MHz AES dataset (Langnau)

**AES**

$\sigma_{th} = 0.02$ rad
MCA potentials

- Height retrieval ($C_1$) / Finge classification ($C_0$)
- Support / enforce standard PU algorithms
- Absolute ranging from single SLC
- Coherent scatterers identification
MCA implementation

- First tested in simulation and applied on ERS data: satellite sensor available didn’t allow a reliable application.
- However, the technique appears optimally suited for the new generation of satellite sensors, which operate with larger bandwidths (TerraSAR-X or COSMO-SkyMed) → new impulse to the experimentation!
- First MCA implementation worked on RAW data and generate sub-bands images by focusing portions of the available bandwidth.
- But data policies of these missions do not foresee the delivery of RAW data thus imposing to perform the MCA starting from SLC images.
- MCA form SLC data has been investigate both theoretically and by processing real data.
MCA processing
MCA processing: coregistration

- ISSIA MCA processing chain is designed to have in input a couple of SLC images already co-registered to avoid increasing computational efforts related to the coregistration between Master and Slave images for each sub-bands.

- Co-registration step can be simply modeled as an shift in the space which introduce a phase ramp in the spectrum.

- When the sub-bands filtering is applied to the Slave image after interpolation, an additional phase term proportional to the frequency arises in the sub-band images:

\[
I_i^C(t) = FT^{-1}\left(FT(I_i^C) \cdot H_i(f)\right) = FT^{-1}\left(e^{-j2\pi f_i t} \cdot FT(I_i) \cdot H_i(f)\right) = FT^{-1}\left(e^{-j2\pi f_i t} \cdot FT(I_i)\right) = I_i(t - \Delta t)
\]

\[
\angle I_i^C(t) = \angle I_i(t - \Delta t) \propto e^{j2\pi f_i (t - t)} e^{-j2\pi f_i \cdot \Delta t}
\]
MCA processing: coregistration

- Then, the interferometric phase results:

\[ \Phi_i(p) = -2\pi \cdot (\Delta \tau(p) + \Delta t(p)) \cdot f_i = -\left( \frac{4\pi}{c} \Delta R(p) + \frac{2\pi}{f_s} sh_r(p) \right) \cdot f_i \]

- In order to infer the proper path difference it is needed to take into account the phase term related to the coregistration shift. This operation is trivial and not computationally expensive:

\[ INT_i(p) \rightarrow INT_i(p) \cdot e^{\frac{j2\pi}{f_s} sh_r(p) \cdot f_i} = I_{M,i} \cdot (I_{S,i})^* \cdot e^{\frac{j2\pi}{f_s} sh_r(p) \cdot f_i} \]

- The range shift matrix \( sh_r(p) \) is already available as side product of the coregistration step.
In order to avoid asymmetry in the spectrum, before the pass-band filtering a de-Hamming filter is applied to the SLC data which consists of weighting the range spectrum of the data by the function:

\[ H(f) = \frac{1}{\alpha - (1 - \alpha)\cos(2\pi f)} \]
MCA processing: height retrieval validation

- The InSAR phase can be expressed in terms of a reference phase ($\Phi_{\text{ref}}$) which accounts for both the difference between the slant range geometry and a reference ellipsoid and, the phase related with the elevation wrt this ellipsoid ($\Phi^H$):

\[
\Phi_i(p) = C_1 \cdot f_i = \Phi^H(p) + \Phi_{\text{ref}}(p) - \Phi^{sh}(p) \approx -\frac{4\pi}{c} \cdot f_i \cdot \left[ \frac{H(p)}{\Phi 2H} + \delta r \right]
\]

\[
\delta r = -\frac{c}{4\pi f_c} \Phi_{\text{ref}}(p) - \frac{c}{2 f_s} \Phi^{sh}(p)
\]

\[
H(p) = -\left[ \frac{c}{4\pi} \cdot C_1(p) + \delta r(p) \right] \cdot \Phi 2H(p)
\]

- In order to have available a topographic information in SAR geometry, the reference DEM has back-projected in slant range through standard InSAR processing chain: $H_{\text{DEM}}(x,r)$
A first validation started by using a TerraSAR-X dataset acquired on Langnau. This choice was driven by the possibility to obtain the data needed for validation by using a standard InSAR pre-processing.

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<th>Incid. Angle</th>
<th>Look/Pass Direction</th>
<th>Acquis. Date yyyy/mm/dd</th>
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MCA processing: TSX dataset
MCA Pre-processing: TSX dataset

[Images of radar data plots showing range and azimuth with color coding for SRTM Heights and InSAR Phase]
MCA processing: TSX dataset
MCA processing: TSX dataset

Kernel Spectrum around B/2

Image Spectrum around 0

\( \Phi_i(x,r) \)
MCA processing: TSX dataset

• To avoid phase aliasing along frequencies, the interferometric phase difference between adjacent sub-bands should not be higher than $\pi$:

$$|\Delta_{df} \Phi^\text{int}| = |\Phi^\text{int}(f) - \Phi^\text{int}(f + df)| < \pi$$

$$|\Delta_{df} \Phi^\text{int}| = \frac{4\pi}{c} df \cdot \left(\delta r + \frac{H}{\Phi 2H}\right) < \pi \rightarrow df_{\text{max}} < \frac{c}{4\left(\delta r + \frac{H}{\Phi 2H}\right)_{\text{max}}}$$

• TSX parameters:
  – $<\delta r>=0.31$ m , $<\phi 2H> = -2979$ , $H_{\text{max}} = 870$ m

• Experiment settings:
  – $df = 2.4$ MHz $< df_{\text{max}} \rightarrow N_{i} = 21$ , $B_{p} = 50$ MHz
MCA processing: TSX results

$\sigma_{\phi}^{th}=0.02 \text{ rad}$

A useful analysis for validate the output of the MCA processing is the inspection of the distribution of the pixels in $PS_{fd}$ superimposed on the SAR amplitude as well as on an optical image.

Targets in $PS_{fd}$ drop mainly on pixels which show high amplitude values or, in the optical image, on resolution cell which correspond to man made objects (as buildings).
MCA processing: TSX results

- Trends before shift compensation for pixel with $\sigma_\phi=0.0038\ rad$
MCA processing: TSX results

- The trends show the effect of shift compensation for pixel with $\sigma_\phi = 0.0038 \text{ rad}$
MCA processing: TSX results

- Pixels with $\sigma_\phi<0.5\ rad$ cover the built area of the town.
MCA processing: TSX results

- In order to validate the results, we use external DEM back projected onto SAR Master geometry: \( H_{DEM}(x, r) \).
- The difference between these height values is due to a deviation of the interferometric phase \( \Phi \) wrt the expected value \( \hat{\Phi} \):

\[
\Phi^R(x, r) = \Phi(x, r) - \hat{\Phi}(x, r) = \Phi^{APS}(x, r) + \Phi^{proc}(x, r) + \Phi^{noise}(x, r)
\]

- In the present case it is not possible to discriminate between the different contributions to the residual phase.
- Temporal decorrelation (\( B_t = 33 \) d) \( \rightarrow \) increase the noise level.
- Additional path induced by the atmosphere \( \rightarrow \) bias in the estimation of absolute height (a variation of \( \lambda/2 \) causes an error of 50 m in \( H \)).
MCA processing: TSX results

Height error distribution at $\theta < 0.02$ (pick value = -79 m)

Expected-estimated heights - pick value = -229 m (no $\theta$, no APSc)
MCA processing: TSX results

- Possible rough atmospheric signal estimation by using standard pre-processing side products and SRTM DEM (90x90 m)

\[ \Phi^R(x, r) = C_1(x, r) \cdot f_c + \left( \Phi^{sh}(x, r) - \Phi^{ref}(x, r) \right) - \hat{\Phi}^H(x, r) \approx \]
\[ \approx C_1(x, r) \cdot f_c - \frac{4\pi \cdot f_c}{c} \left[ \Delta R_h(x, r) - (\Delta R_{sh}(x, r) - \Delta R_{ref}(x, r)) \right] \]

The spectral density shows an average trend close to \( f^{-5/3} \) which is typical of signals related to the wet component of the troposphere.
MCA processing: TSX results

- Performing the estimation on very coherent targets by means of a severe threshold on $\sigma_\phi (<0.008)$ we obtained best measures which differ from expected SRTM heights of about few meters after a rough atmospheric compensation.

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MCA processing: TSX results

- The true problem remains the difficulty to separate different sources of phase signals without the help of ancillary data or further temporal analysis.

- Also the bandwidth value represents a limiting factor in the MCA performance.

- In order to evaluate the impact of this parameter on height retrieval through MCA processing, the airborne airborne AES-1 dataset has been used: it is not affected by neither atmospheric distortion nor temporal and geometrical decorrelation and, provides the possibility to explore different values of bandwidth from 100 to 400 MHz.

- The experiment showed that a bandwidth of least 300 MHz seems to be required in order to obtain reliable results height measurements.
MCA processing: AES-1 results

- **Dataset** acquired by airborne **AES-1 sensor** appears very promising for MCA testing

- A multi-channel In-SAR sensor operating at X-band, with a total radar bandwidth of 400 MHz resulting from four non-overlapping channels, each 100 MHz wide, whose central frequencies are in GHz \{9.4, 9.5, 9.6, 9.7\}.

- For this dataset the normal baseline \( B_\perp = 0.75 \text{ m} \) thus ensuring a very limited geometrical decorrelation effect.

- The two antenna acquire simultaneously:
  - NO temporal decorrelation
  - NO atmospheric contribution to the interferometric phase are avoided

\[
\Phi^R(x, r) = \Phi^{APS}(x, r) + \Phi^{proc}(x, r) + \Phi^{noise}(x, r) \xrightarrow{\sigma_\Phi \to 0} \Phi^{proc}(x, r)
\]
MCA processing: AES-1 results
MCA processing: AES-1 results

- **However**, for airborne dataset is not possible to perform InSAR pre-processing by using standard InSAR chain designed for satellite missions → $\Phi^{ref}(x,r), \Phi^{2H}(x,r), H_{DEM}(x,r)$ are not determined properly.

- Moreover, the analysis of the data pointed out the presence of a delay introduced by the hardware between M and S. Since, the analysis of the ancillary data did not allow to define the actual value of this delay, it result impossible to perform absolute interferometric phase estimation.

- For these reasons the experiment with AES data was performed by analysing the data in slant range geometry without a direct comparison wrt the SRTM height profile.

- Anyway, this limitation didn’t prevent to verify how the MCA performances depend on the available bandwidth.
MCA processing: AES-1 results

Reflectivity image

AES-1 interferometer - Fringe pattern at 100 MHz range bandwidth

11 fringes
MCA processing: AES-1 results

\( K(x,r) \)

11 \( K \) values

\( B = 400 \text{ MHz} \)

\( B = 300 \text{ MHz} \)

\( B = 200 \text{ MHz} \)

\( B = 100 \text{ MHz} \)
MCA processing: AES-1 results

\[ K(x,r) \]

- \( B = 400 \text{ MHz} \sigma < 0.045 \text{ rad} \)
- \( B = 300 \text{ MHz} \sigma < 0.03 \text{ rad} \)
- \( B = 200 \text{ MHz} \sigma < 0.015 \text{ rad} \)
- \( B = 100 \text{ MHz} \sigma < 0.005 \text{ rad} \)
MCA processing: parametric analysis

- Relevant parameters: $B$, $N_f$, $B_p$, $B_e$
- Estimation of the expected noise as function of the processing parameters.

\[
\Delta R(x,r) = -\frac{c}{4\pi} \cdot C_1(x,r)
\]
\[
k(x,r) = -\frac{C_0(x,r)}{2\pi}
\]
\[
\sigma_{c_i} = \sqrt{\frac{N_f}{N_f \sum_{i=1}^{N_f} (f_i)^2 - \left(\sum_{i=1}^{N_f} f_i\right)^2}} \sigma_{\Phi}
\]
\[
\sigma_{c_o} = \sqrt{\frac{\sum_{i=1}^{N_f} (f_i)^2}{N_f \sum_{i=1}^{N_f} (f_i)^2 - \left(\sum_{i=1}^{N_f} f_i\right)^2}} \sigma_{\Phi}
\]

- In the hypothesis of ideal metallic planar reflector:

\[
\sigma_{\Phi} = \frac{1}{\sqrt{2 \cdot SCR}}\quad SCR = \frac{4\pi \cdot A^2}{\sigma_0 A_{\text{clutter}}}
\]

where

- $\sigma_0 = \text{normalised radar cross section (} = 1\)$
- $A_{\text{clutter}} = \text{area of the resolution cell}$
- $A = \text{area of the metallic planar reflector (} 0.5 \times 0.5 \text{ m}^2 \)$
MCA processing: parametric analysis
MCA processing: parametric analysis
MCA processing: parametric analysis
MCA processing: comments

• It can be noted that the K values map obtained by processing a bandwidth of 400 MHz reproduces properly the fringe pattern.

• At least a 300 MHz bandwidth seems to be required to provide reliable results.

• For B=100 MHz the correlation with the fringe pattern disappears. This value appears inadequate for reliable height inference.

• Therefore, this experiment confirms that, in the case of TSX dataset, where the phase information is corrupted by temporal and geometrical decorrelation and by the presence of atmospheric signal, a bandwidth of 100 MHz leads to unreliable height.

• The results are confirmed by the parametrical analysis obtained through theoretical modeling.
MCA processing: work in progress

- Experiment with TSX 300 MHz bandwidth Spotlight acquisition.
- Experiment with COSMO-SkyMED 130 MHz bandwidth on desert area.
- More reliable figure for frequency coherent target ($\sigma_\Phi$ is not robust)
- Multi-temporal dataset exploration for estimate the atmospheric influence.
The End

Thank you

- Work supported by ESA ESTEC Contr. N. 21319/07/NL/HE.
- TerraSAR-X images are provided by DLR under a Scientific Use License for the proposal MTH0397.
- Sample AES-1 data is courtesy of SARMAP