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Republic of Poland



JAGIELLONIAN UNIVERSITY
IN KRAKÓW



EUROPEAN SPACE AGENCY

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FRINGE 2026

A Consensus Analysis on Range Split-Spectrum Approaches for Ionospheric Phase Estimation in DInSAR Applications

Claudio De Luca; Marianna Franzese; Giorgio Gomba and Riccardo Lanari Riccardo

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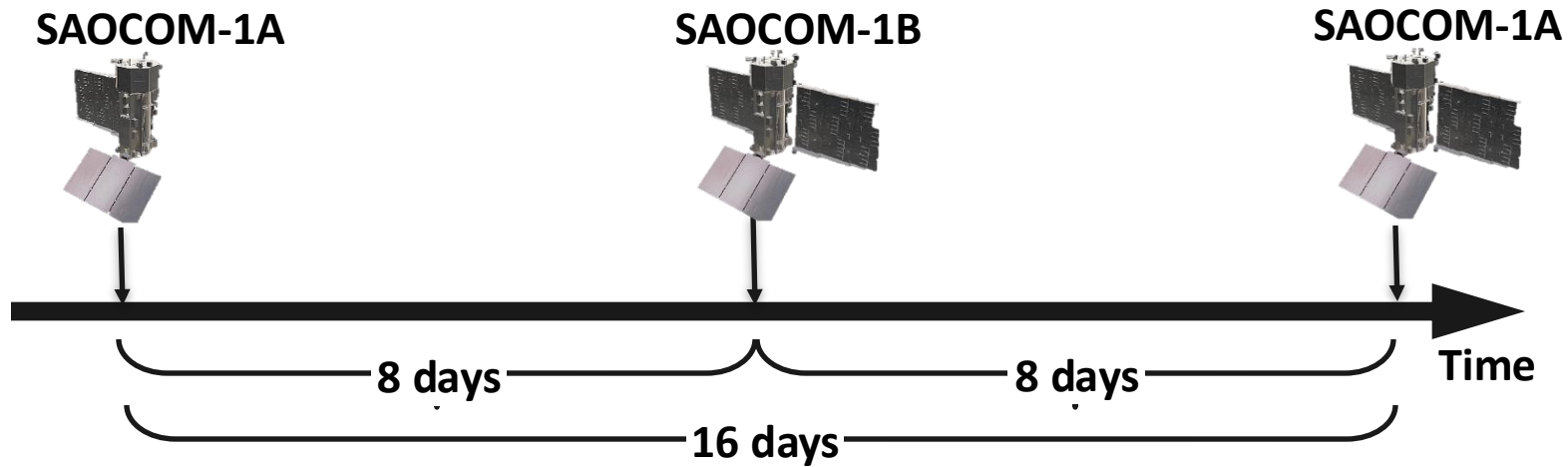


→ THE EUROPEAN SPACE AGENCY

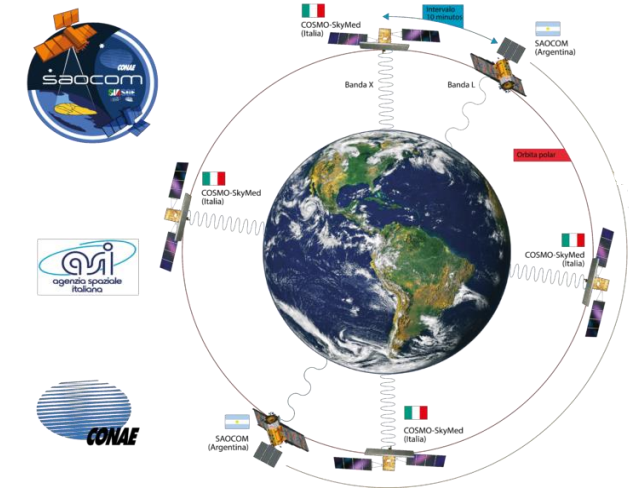
Outlines

- Area of interest and exploited L-band data
- Ionospheric effects on L-band DInSAR analysis
- RSS-based method for ionospheric phase retrieval in range component
- RSS-based method criticalities
- **PRIME-RSS** algorithm for an effective estimation of ionospheric range phase component
- **PRIME-RSS** algorithm performance in alternative RSS-based method formulation
- Final remarks

Area of Interest and exploited L-band SAOCOM-1 constellation



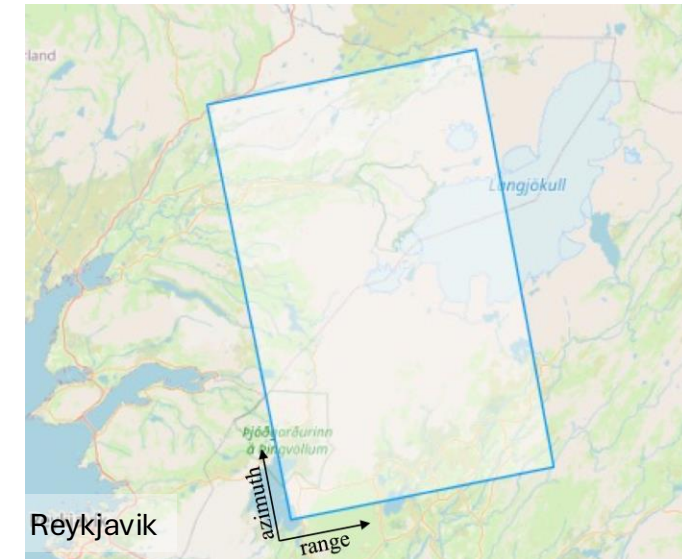
SIASGE system



The Argentinian L-band constellation SAOCOM-1A and 1B and the Italian X-band COSMO-SkyMed one share the same orbits, forming the SIASGE system.

- **Spatial resolution (Stripmap mode):** **10 m x 5 m** (Single e Dual Pol) 10 m x 6 m (Quad Pol)
- **Footprint:** **40-60 km** (Single e Dual Pol) 20-30 km (Quad Pol)
- **Frequency:** **L-Band** ($\lambda \cong 23.5$ cm)

Area of Interest



Ionospheric effects on ground displacement components

AZIMUTH DIRECTION

$$\Delta x_{iono} = \frac{2K}{f^2} \frac{\partial TEC}{\partial x} R_0$$

- $\partial TEC / \partial x$ is the gradient of the TEC along the azimuth direction;
- R_0 represents the distance at the closest approach.

- Different **azimuth shift** in the primary and secondary acquisitions produce **misregistration effects**.
- The impact of this misregistration degrades the performance of techniques for estimating the **deformation component** along the azimuth direction:

➤ Multiple Aperture Interferometry (MAI)

➤ Pixel Offset Tracking (POT)

➤ Re-focusing procedure

SLANT RANGE DIRECTION

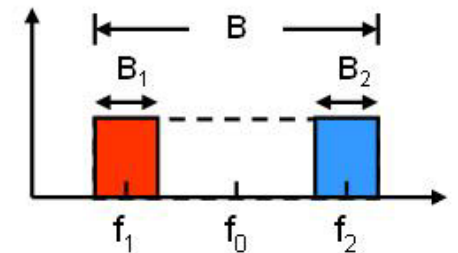
$$\Delta \Phi_{iono} = -\frac{4\pi K}{cf} \Delta TEC$$

- $K = 40,31 \text{ m}^3/\text{s}^2$;
- c is the speed of light in vacuum;
- f is the carrier frequency;
- ΔTEC represents the differential TEC.

Interferometric Phase $\Delta \Phi = \Delta \Phi_{non-disp} + \Delta \Phi_{iono}$

$$\Delta \Phi_{non-disp} = \Delta \Phi_{topo} + \Delta \Phi_{defo} + \Delta \Phi_{atm}$$

**RANGE
SPLIT-SPECTRUM
METHOD**

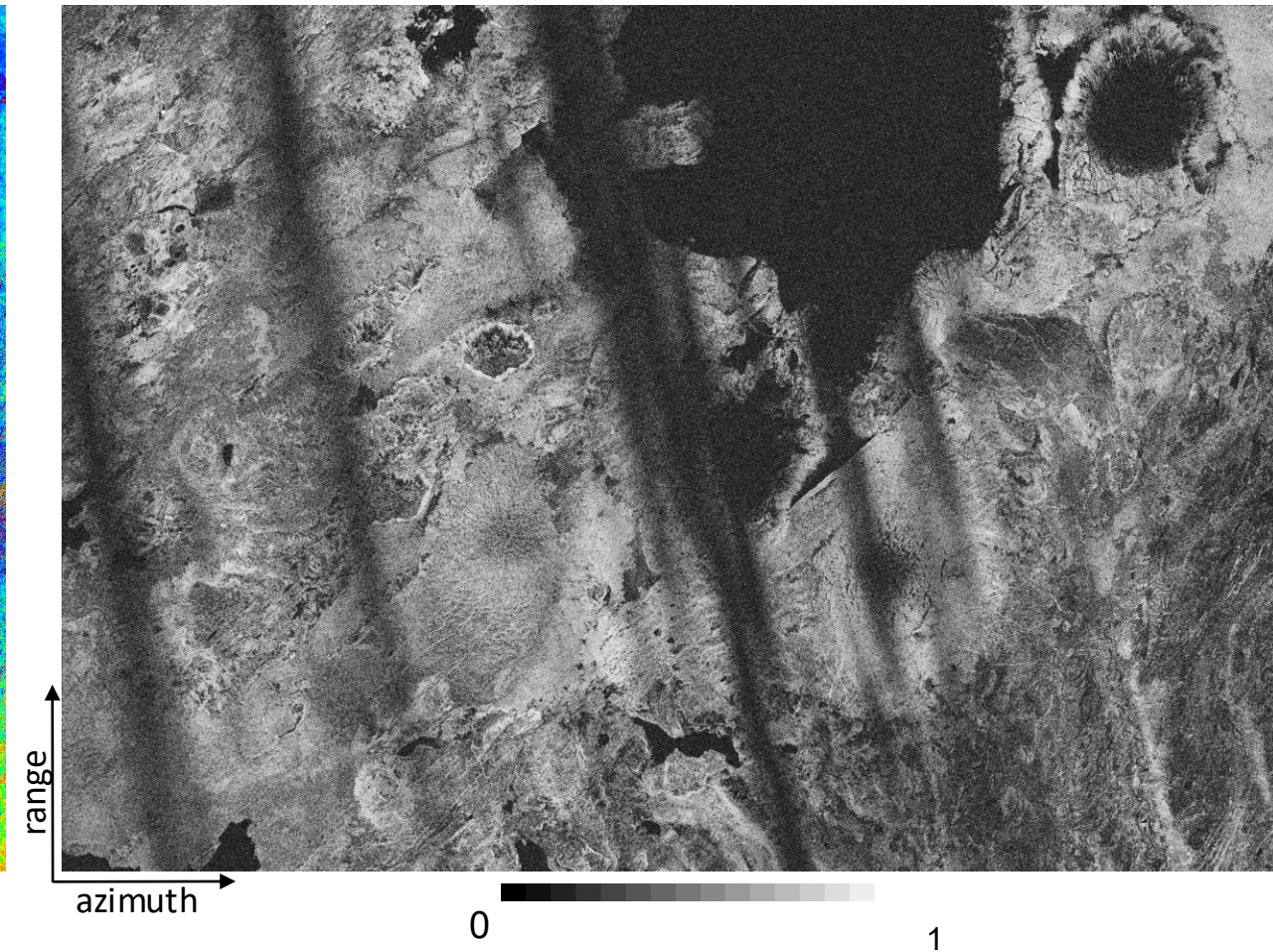
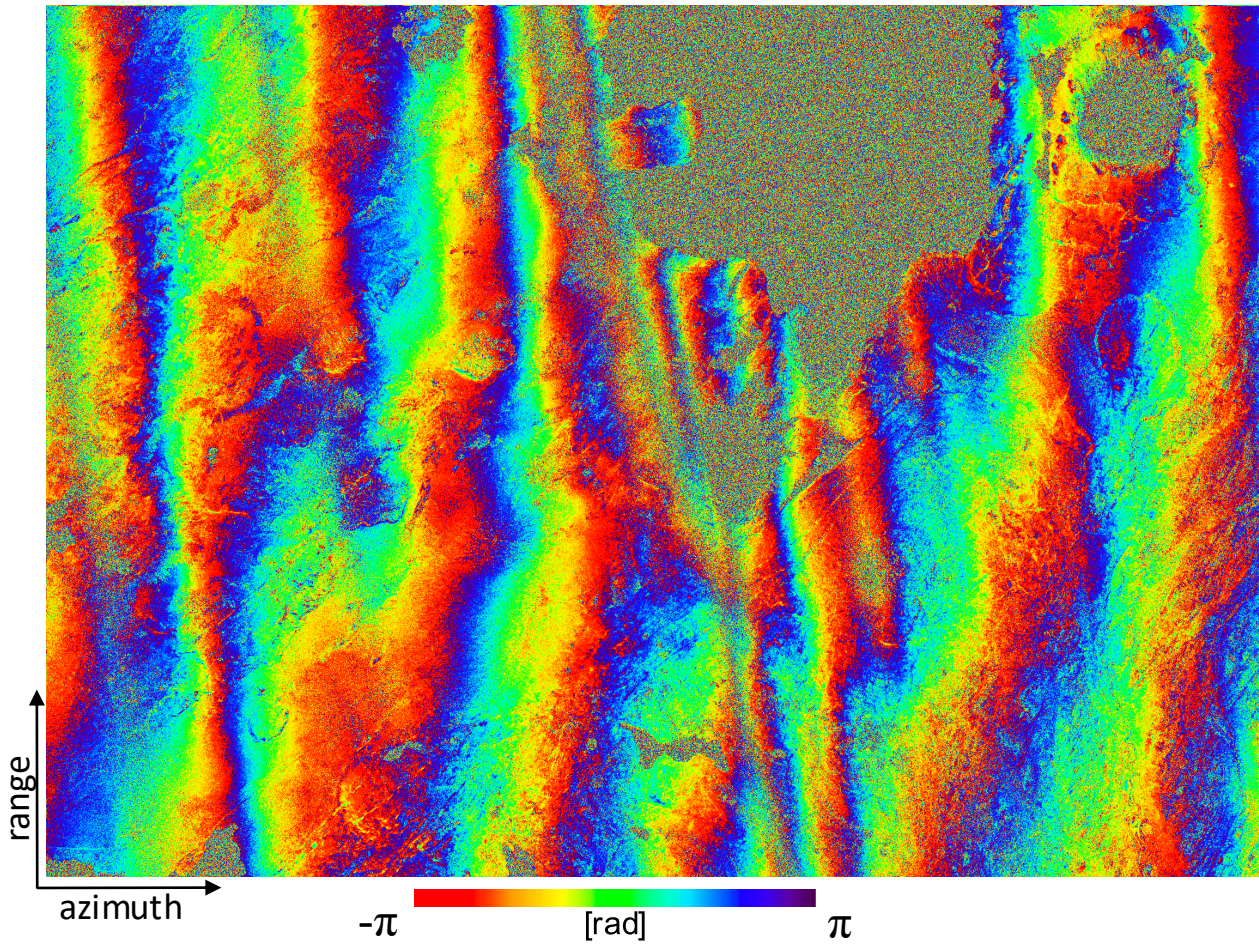


Ionospheric Azimuth contribution mitigation

Differential interferogram

Before

Interferometric coherence

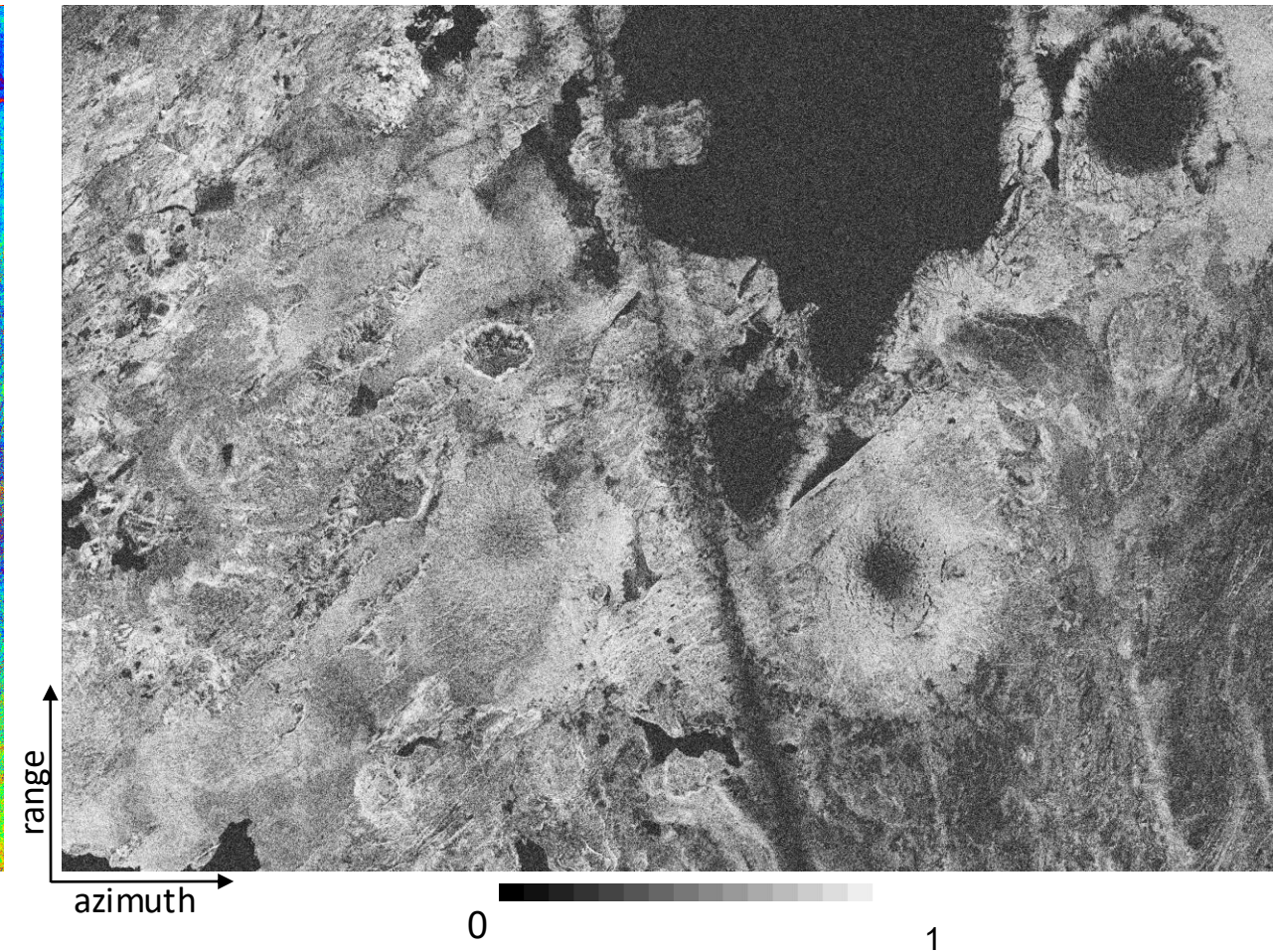
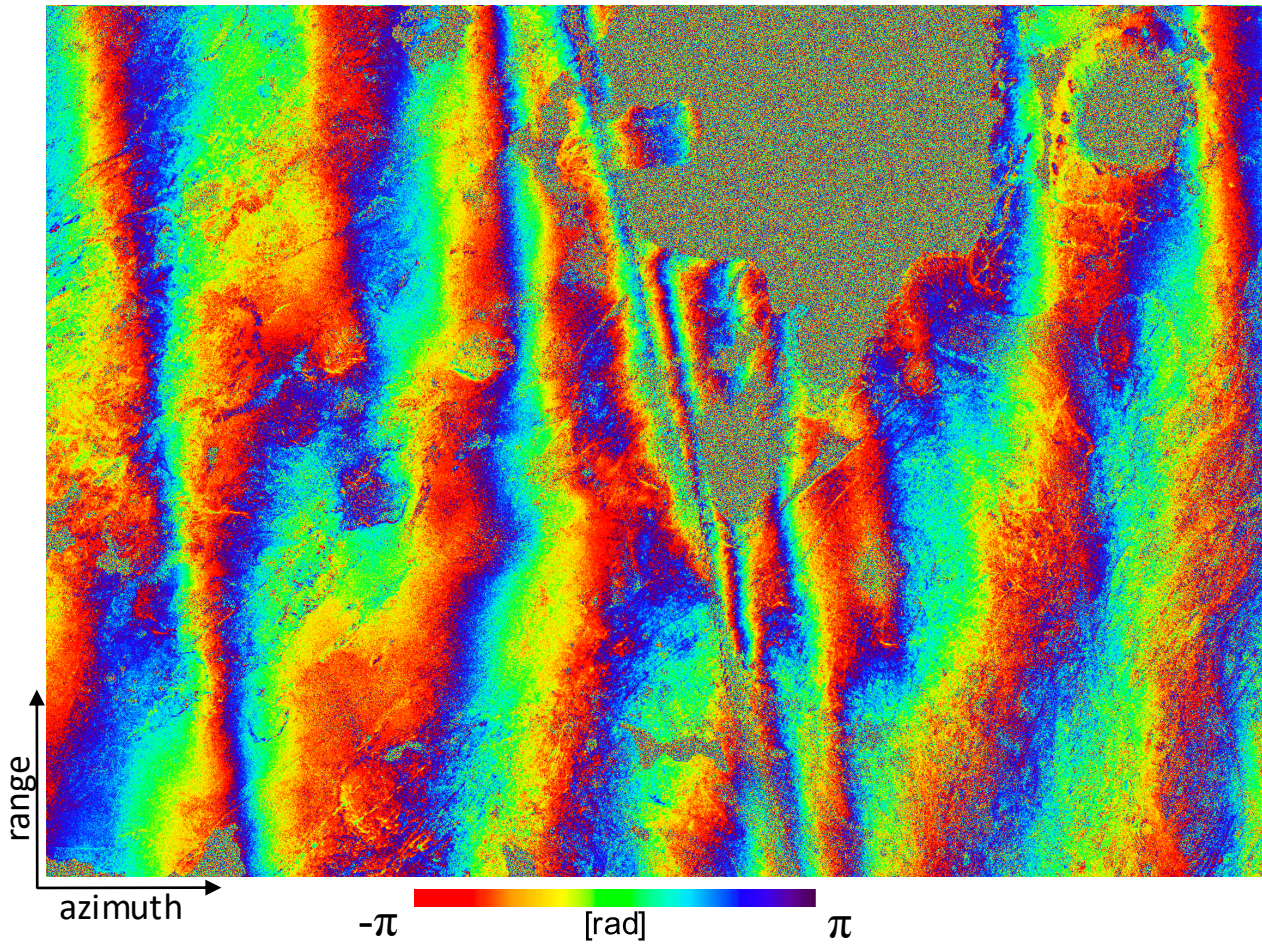


Ionospheric Azimuth contribution mitigation

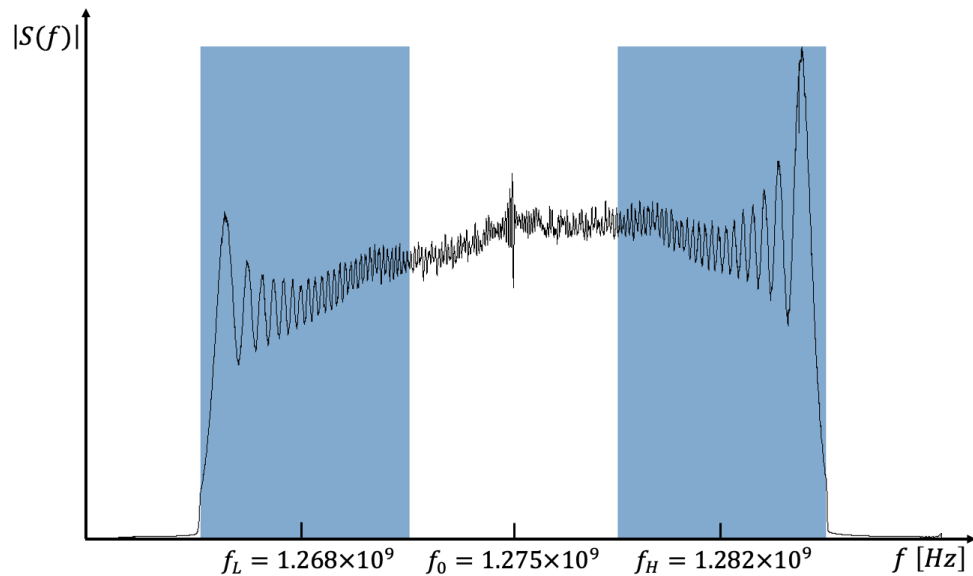
Differential interferogram after POT

After

Interferometric coherence after POT



Standard Range Split Spectrum Approach

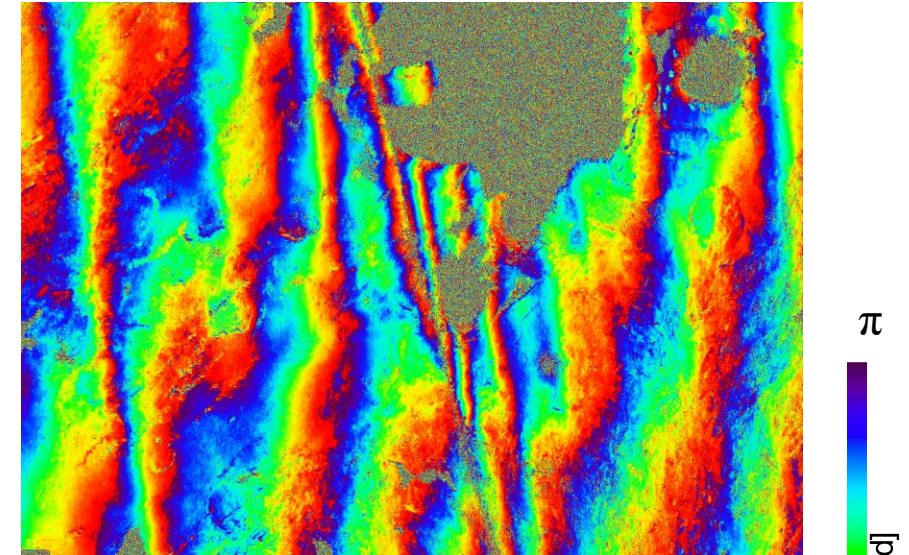


$$\Delta\phi = \Delta\phi_{non-disp} + \Delta\phi_{iono}$$

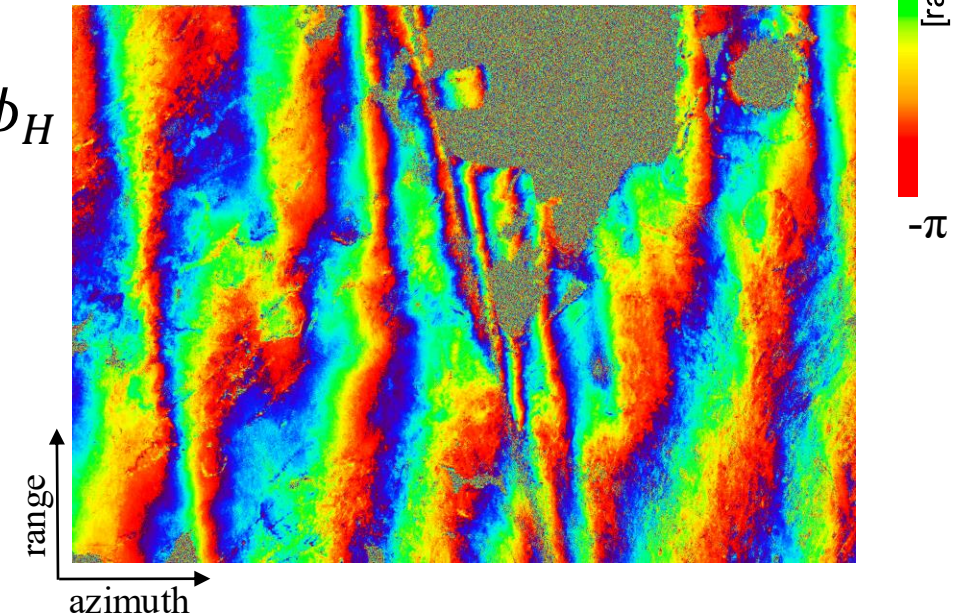
$$\Delta\phi_L = \Delta\phi_{non-disp} \frac{f_L}{f_0} + \Delta\phi_{iono} \frac{f_0}{f_L}$$

$$\Delta\phi_H = \Delta\phi_{non-disp} \frac{f_H}{f_0} + \Delta\phi_{iono} \frac{f_0}{f_H}$$

$\Delta\phi_L$



$\Delta\phi_H$



P. Rosen, S. Hensley and C. Chen, "Measurement and mitigation of the ionosphere in L-band interferometric SAR data," 2010

Criticalities of Standard Range Split Spectrum Approach

$$\Delta\hat{\phi}_{non-disp} = \frac{\lambda_H \lambda_L^2}{(\lambda_L^2 - \lambda_H^2) \lambda_0} \left(\Delta\phi_H - \frac{\lambda_H}{\lambda_L} \Delta\phi_L \right)$$

$$\Delta\hat{\phi}_{iono} = \underbrace{\frac{\lambda_0 \lambda_H}{\lambda_H^2 - \lambda_L^2}}_{\text{Ionospheric Extraction Factor}} \underbrace{\left(\Delta\phi_H - \frac{\lambda_L}{\lambda_H} \Delta\phi_L \right)}_{\text{Raw Ionospheric Term}}$$

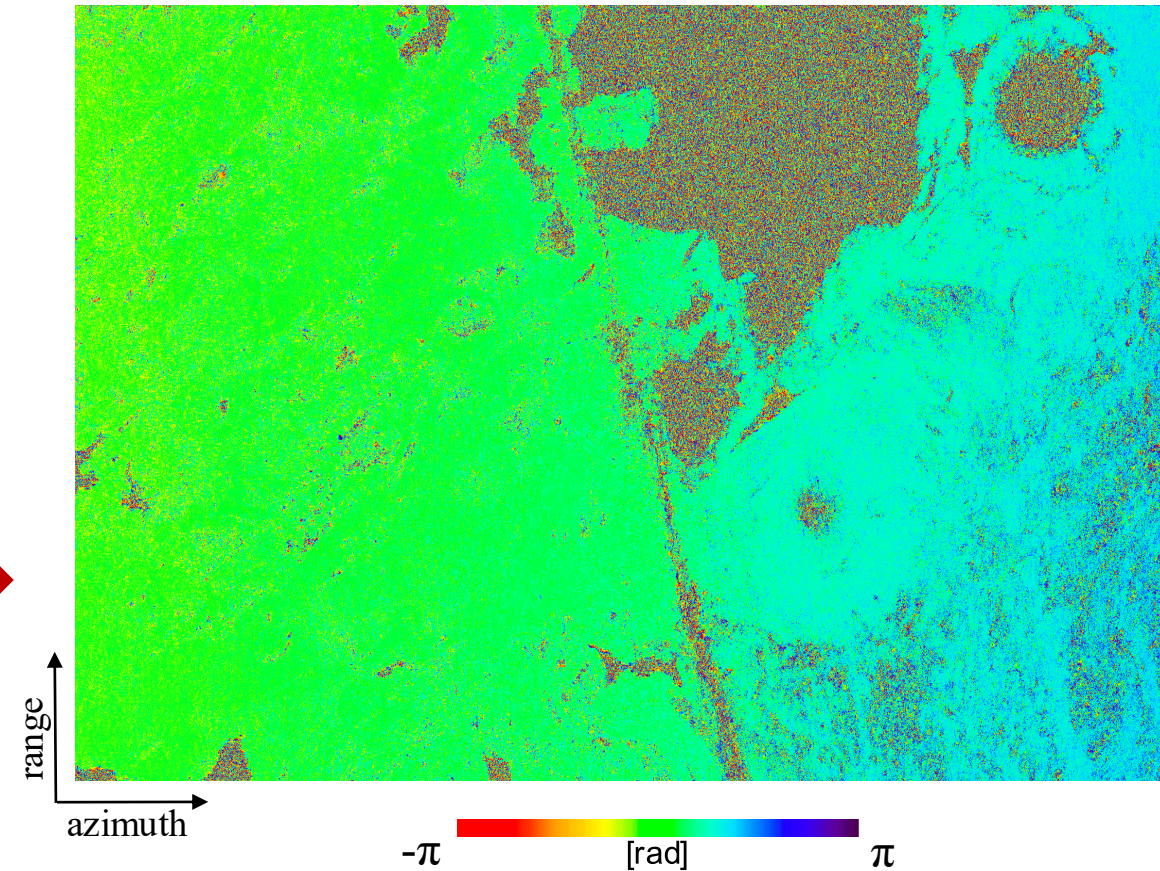
Ionospheric
Extraction
Factor

Raw Ionospheric
Term

$$\alpha = \frac{\lambda_0 \lambda_H}{\lambda_H^2 - \lambda_L^2} = -43.41$$

Raw Ionospheric Term

typically characterized by slow spatial variations



Criticalities of Standard Range Split Spectrum Approach

$$\Delta\hat{\phi}_{non-disp} = \frac{\lambda_H \lambda_L^2}{(\lambda_L^2 - \lambda_H^2) \lambda_0} \left(\Delta\phi_H - \frac{\lambda_H}{\lambda_L} \Delta\phi_L \right)$$

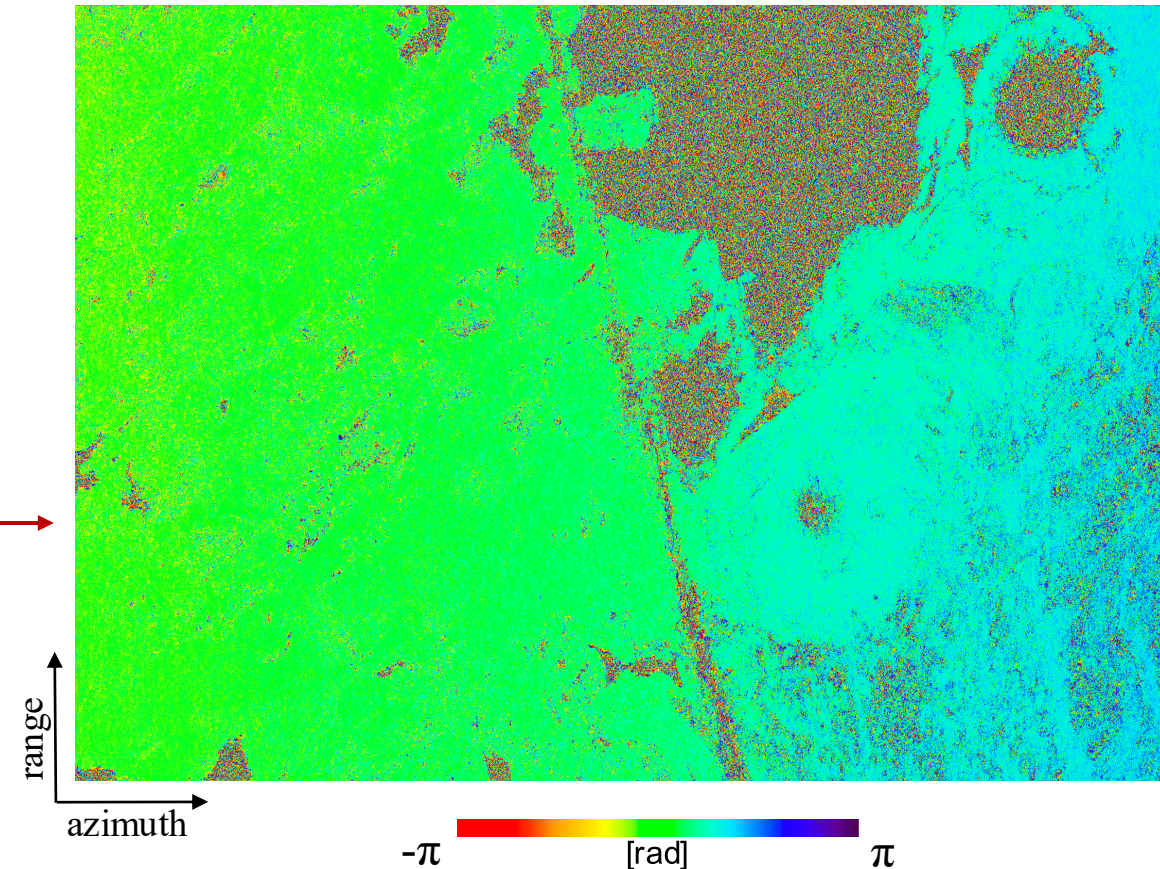
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multiplication

Raw Ionospheric Term

typically characterized by slow spatial variations



Criticalities of Standard Range Split Spectrum Approach

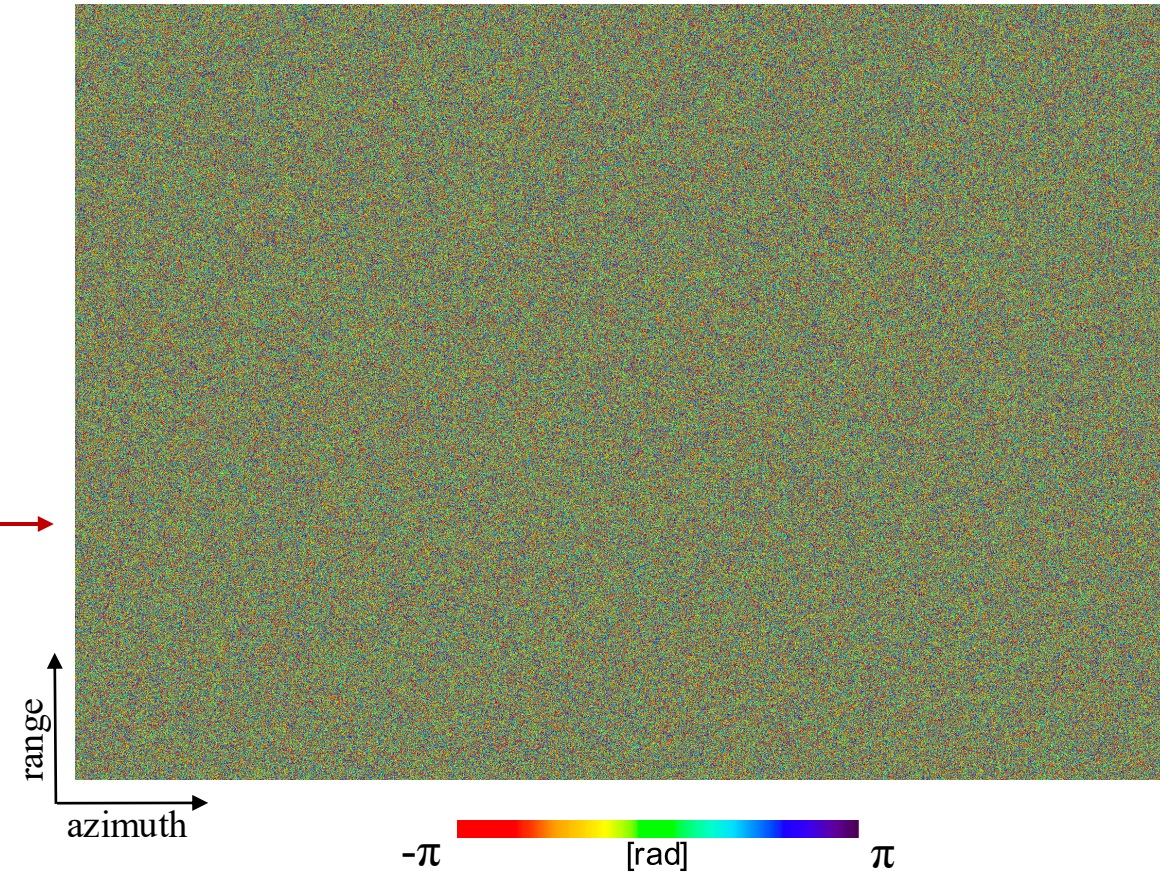
$$\Delta\hat{\phi}_{non-disp} = \frac{\lambda_H \lambda_L^2}{(\lambda_L^2 - \lambda_H^2) \lambda_0} \left(\Delta\phi_H - \frac{\lambda_H}{\lambda_L} \Delta\phi_L \right)$$

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$$\alpha = \frac{\lambda_0 \lambda_H}{\lambda_H^2 - \lambda_L^2} = -43.41$$

Ionospheric contribution

$$< \Delta\hat{\phi}_{iono} >$$



Criticalities of Standard Range Split Spectrum Approach

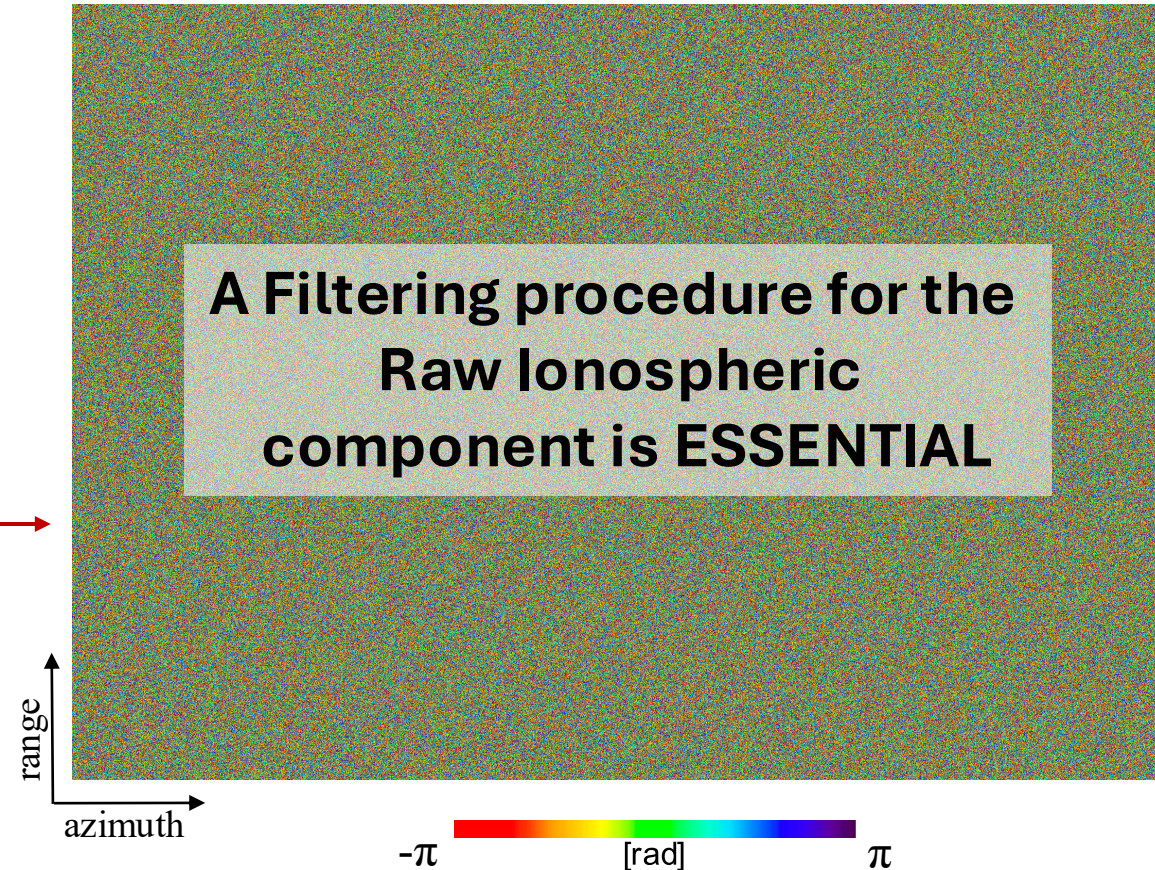
$$\Delta\hat{\phi}_{non-disp} = \frac{\lambda_H \lambda_L^2}{(\lambda_L^2 - \lambda_H^2) \lambda_0} \left(\Delta\phi_H - \frac{\lambda_H}{\lambda_L} \Delta\phi_L \right)$$

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$$\alpha = \frac{\lambda_0 \lambda_H}{\lambda_H^2 - \lambda_L^2} = -43.41$$

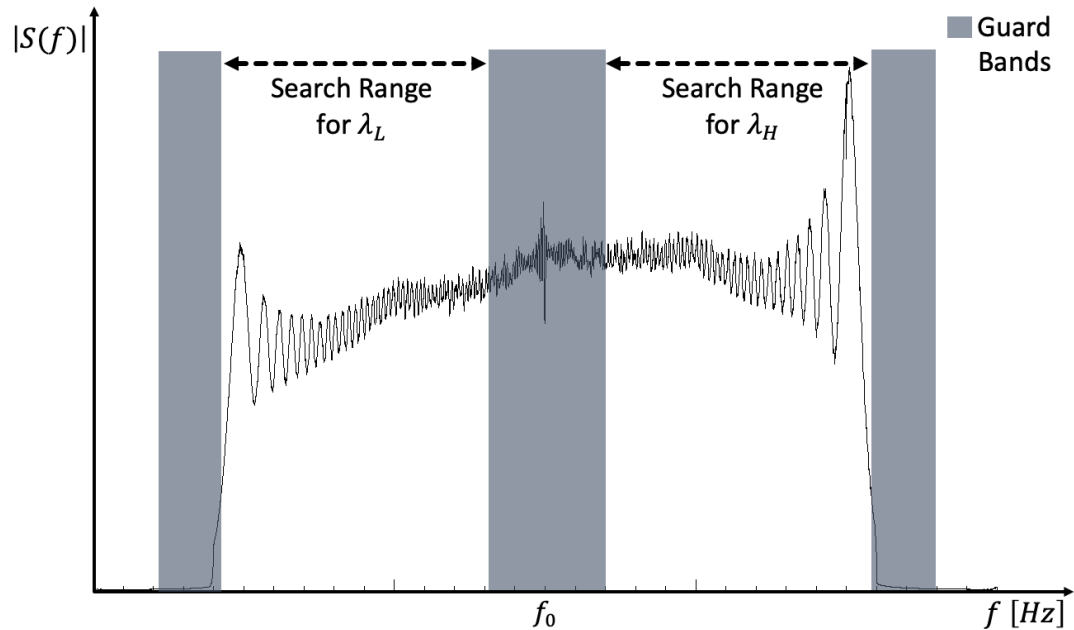
Ionospheric contribution

$$< \Delta\hat{\phi}_{iono} >$$



Proposed Enhanced Standard Range Split Spectrum Method

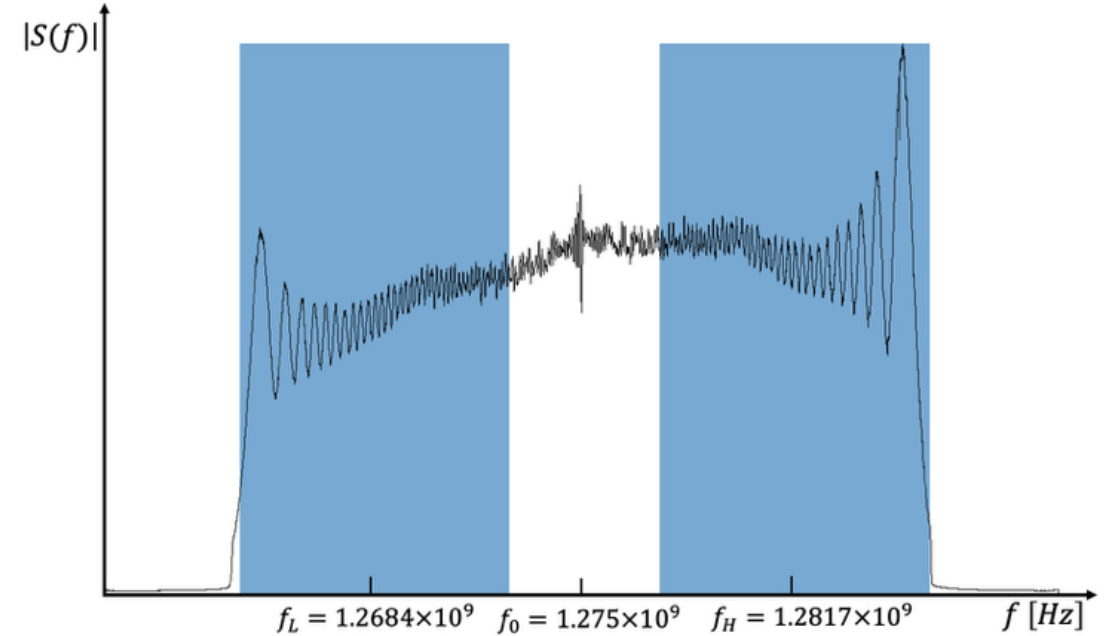
PRIME-RSS Algorithm



$$\lambda_{L,opt} = 23.633 \text{ cm} \quad (f_{L,opt} = 1.2684 \text{ GHz})$$

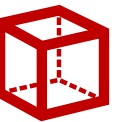
$$\lambda_{H,opt} = 23.390 \text{ cm} \quad (f_{H,opt} = 1.2817 \text{ GHz})$$

- Larger number of divisors
- Wider sub-band bandwidth



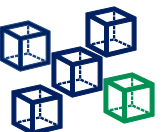
The corresponding extraction factor:

$$|\alpha_{opt}| = 48,000,083$$



This value can be factorized as:

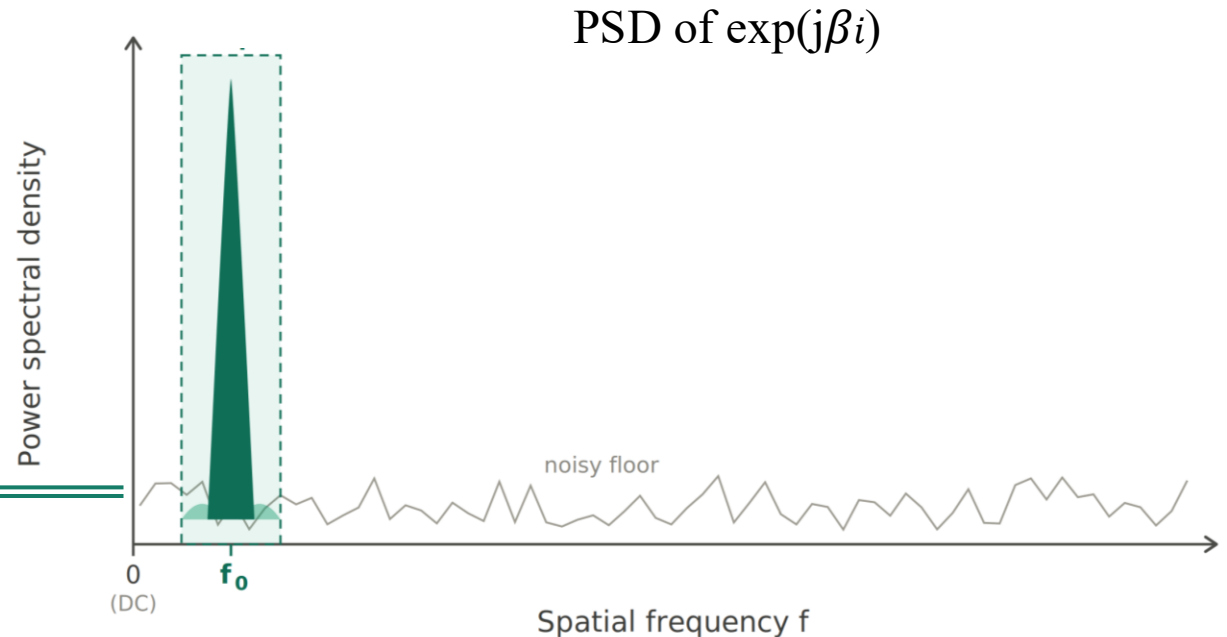
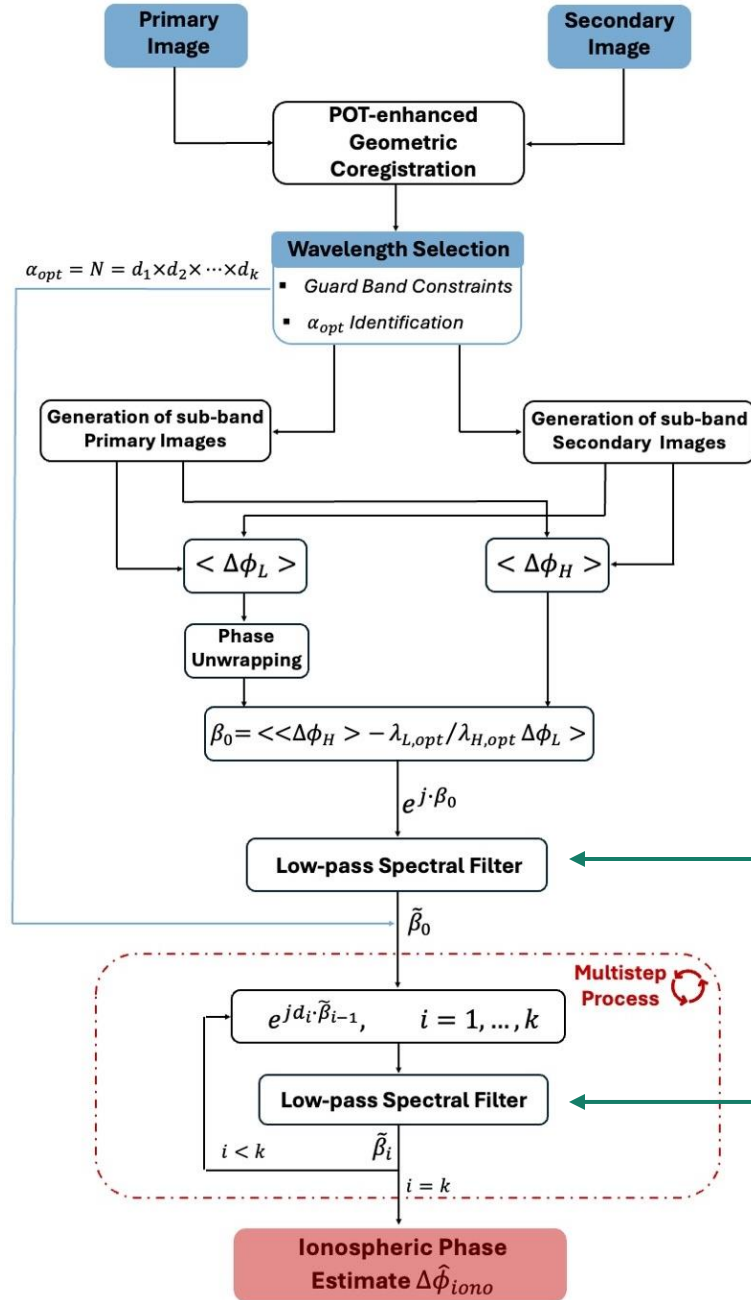
$$|\alpha_{opt}| \approx 2^4 \times 3$$



Proposed Enhanced Standard Range Split Spectrum Method

PRIME-RSS Algorithm

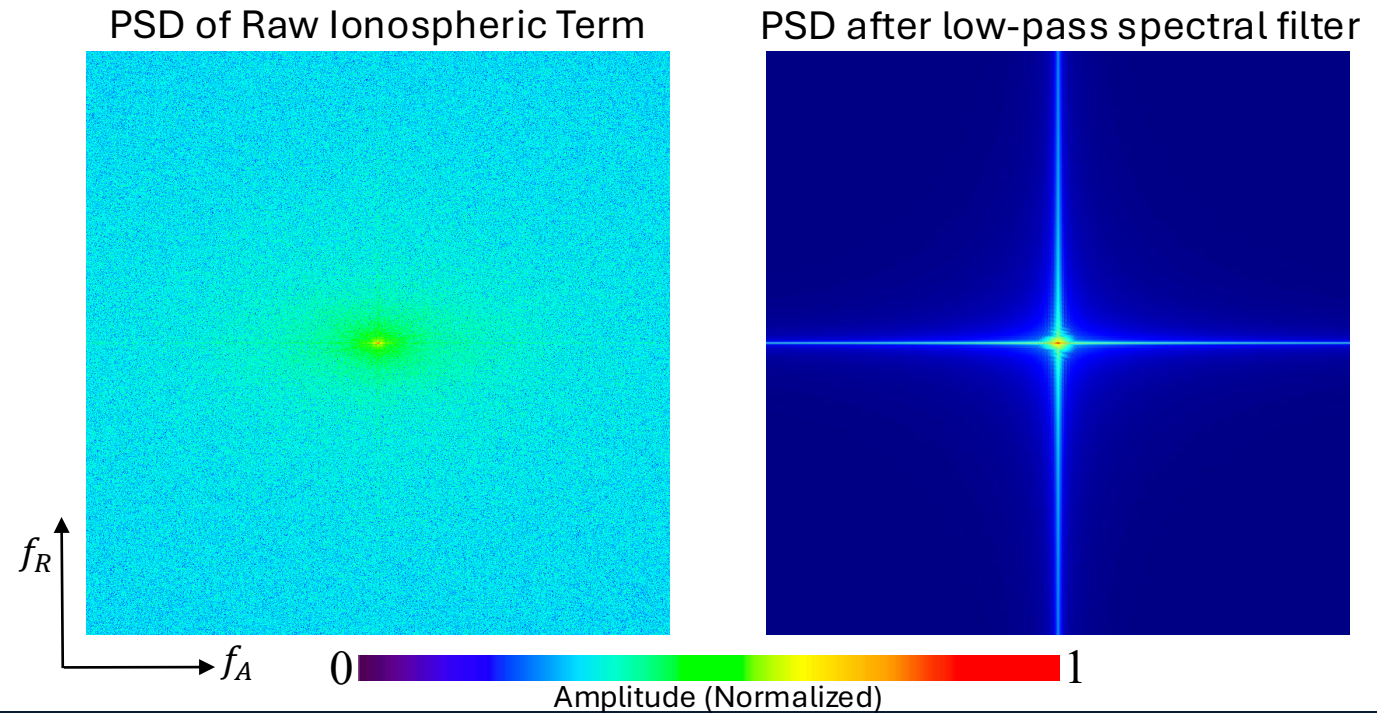
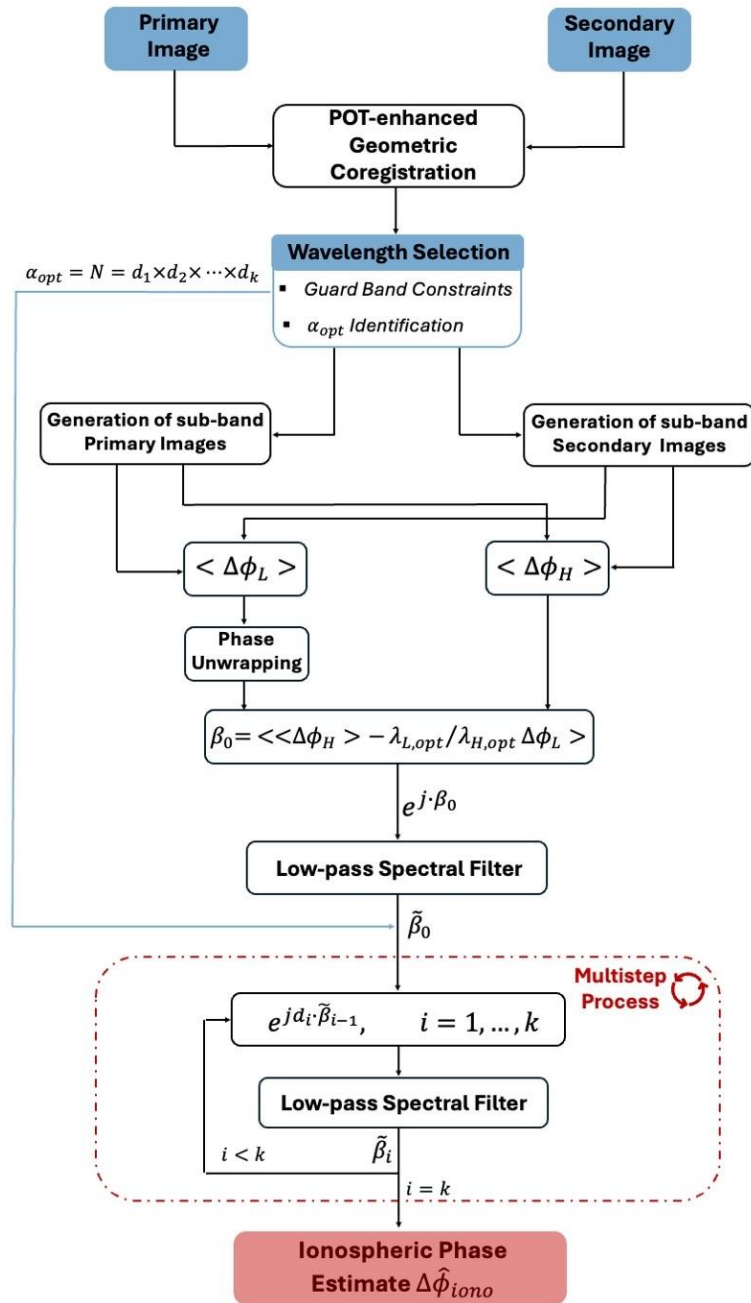
The wrapped phase of each iteration is embedded into a complex exponential $\exp(j\beta i)$ in order to emphasize, in the frequency domain, the ionospheric signal component, which typically has a “ramp-like” spatial evolution, before applying a spectral low-pass filter centred on the pick of PSD



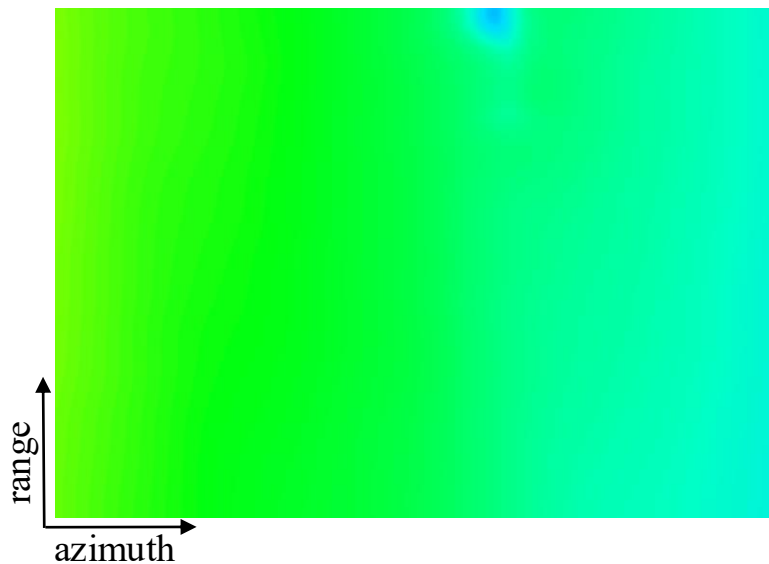
Proposed Enhanced Standard Range Split Spectrum Method

PRIME-RSS Algorithm

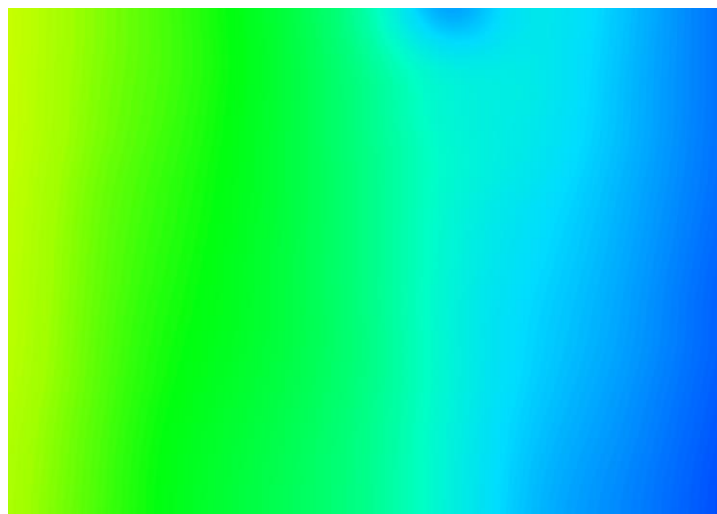
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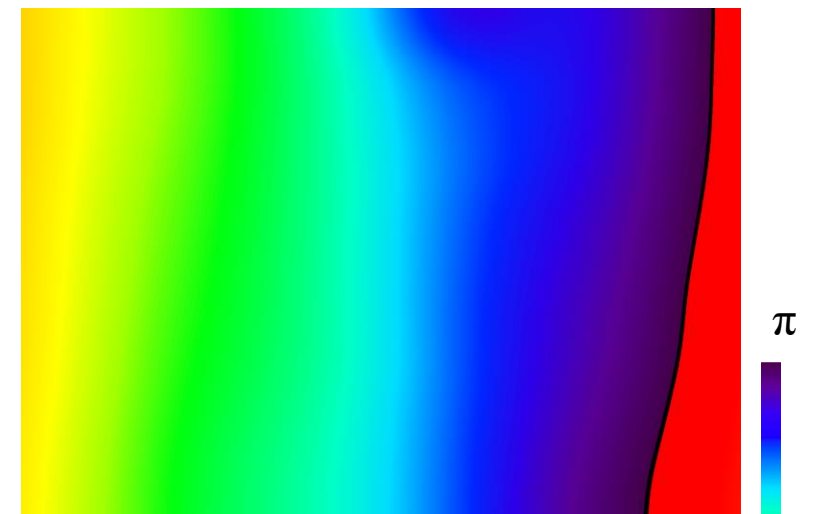
β_0 filtered



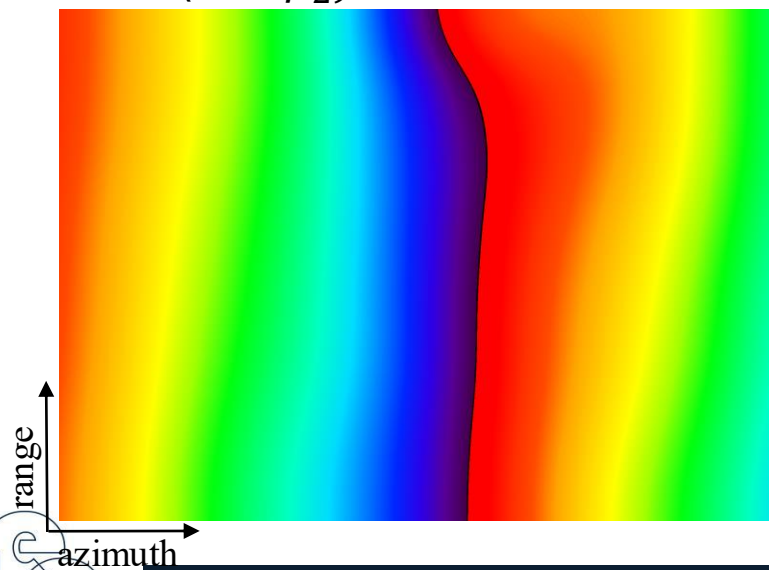
$(2 \times \tilde{\beta}_0)$ filtered



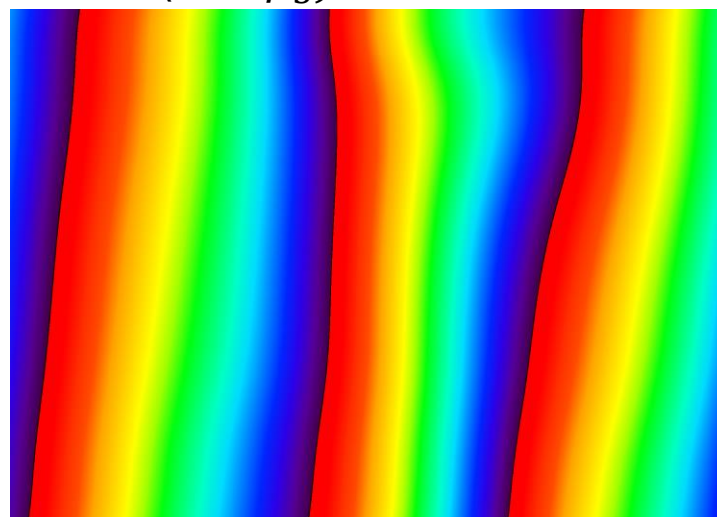
$(2 \times \tilde{\beta}_1)$ filtered



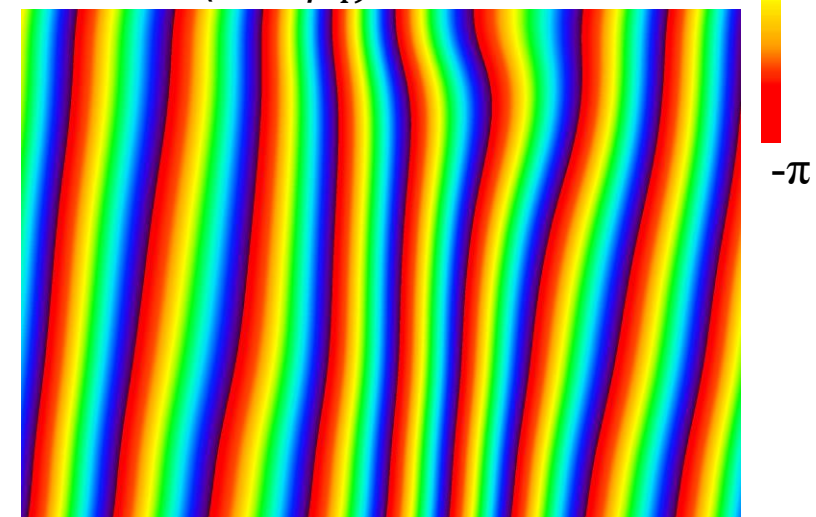
$(2 \times \tilde{\beta}_2)$ filtered



$(2 \times \tilde{\beta}_3)$ filtered



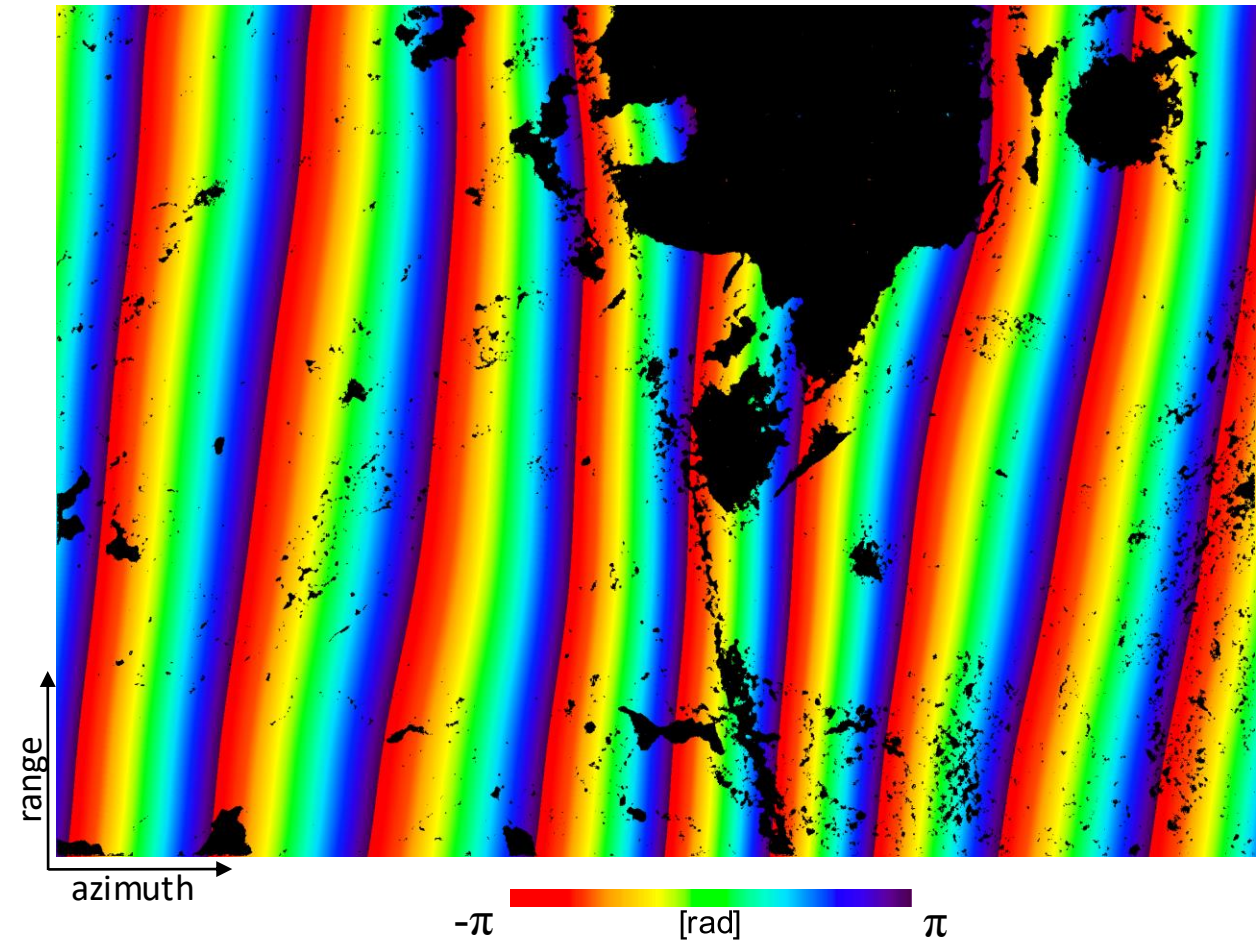
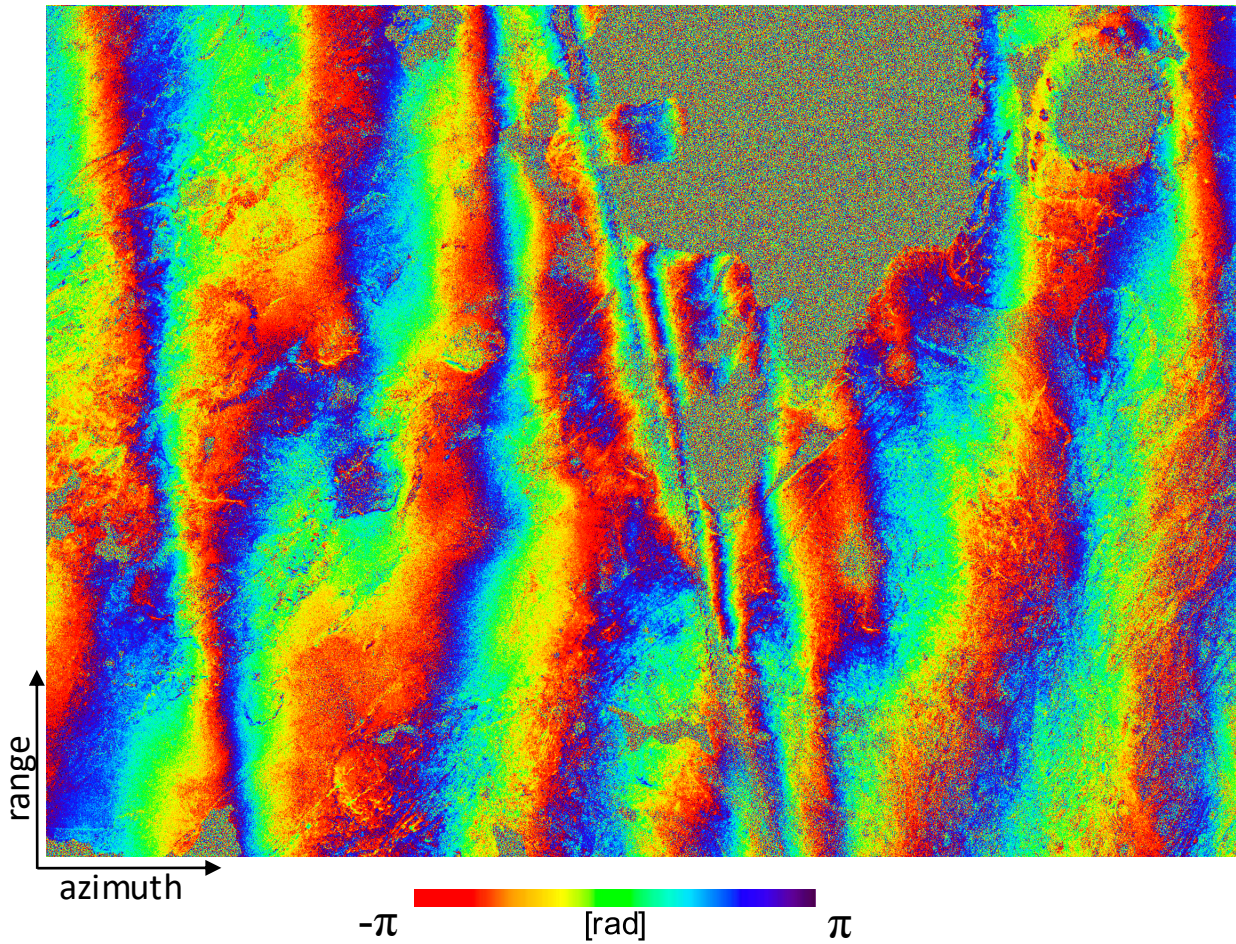
$(3 \times \tilde{\beta}_4)$ filtered



π
[rad]
 $-\pi$

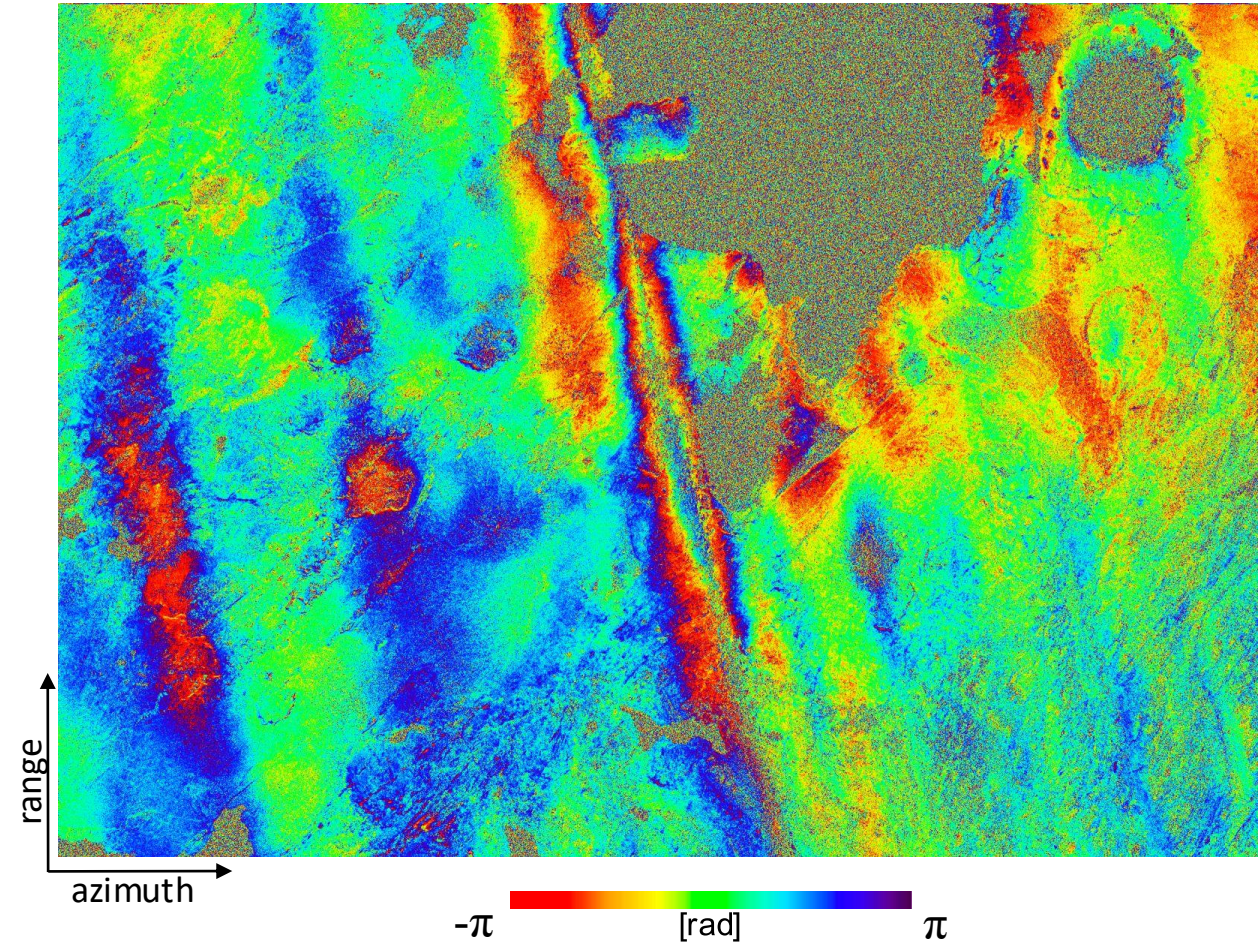
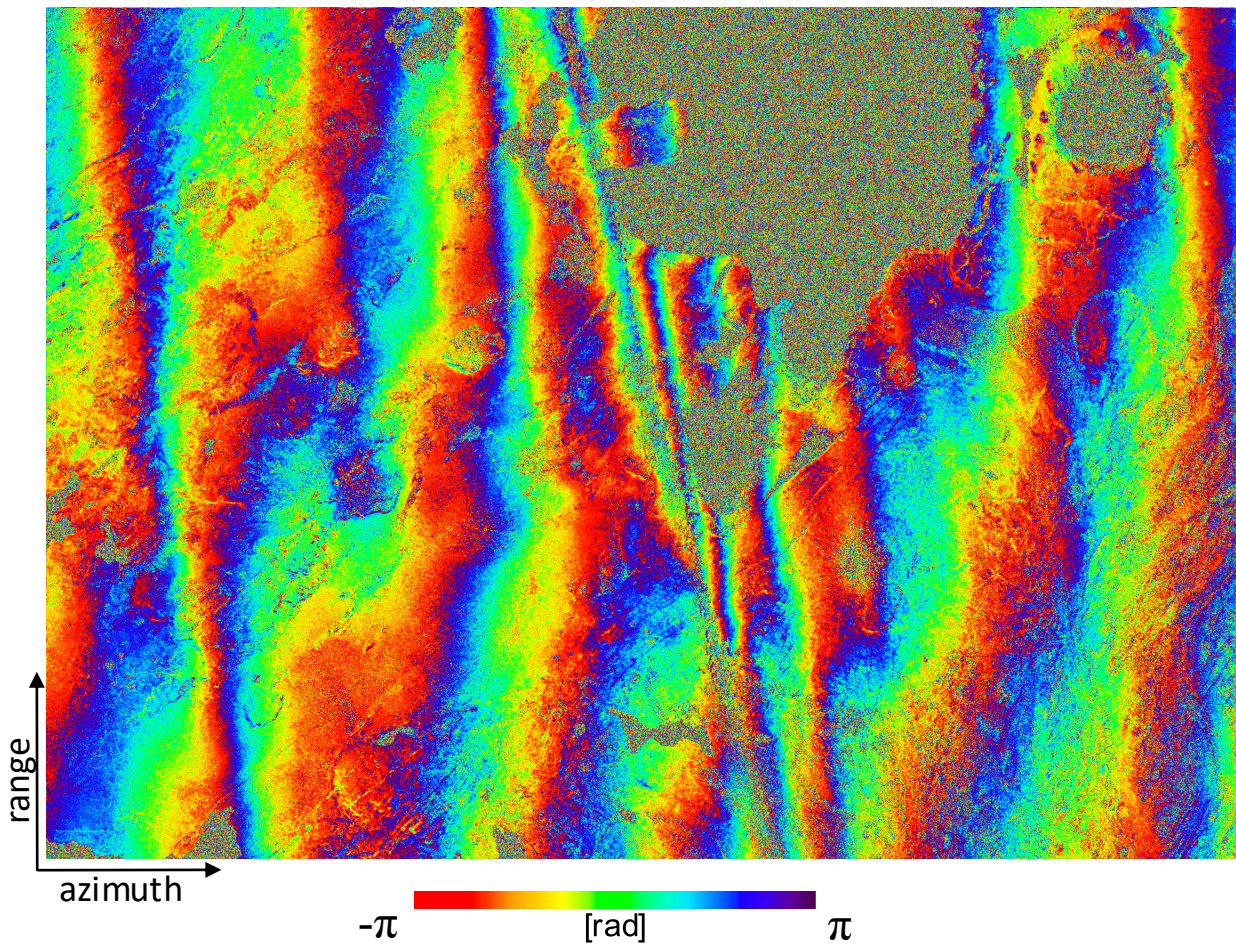
Results

PRIME-RSS Algorithm + Multi-step Noise Filter



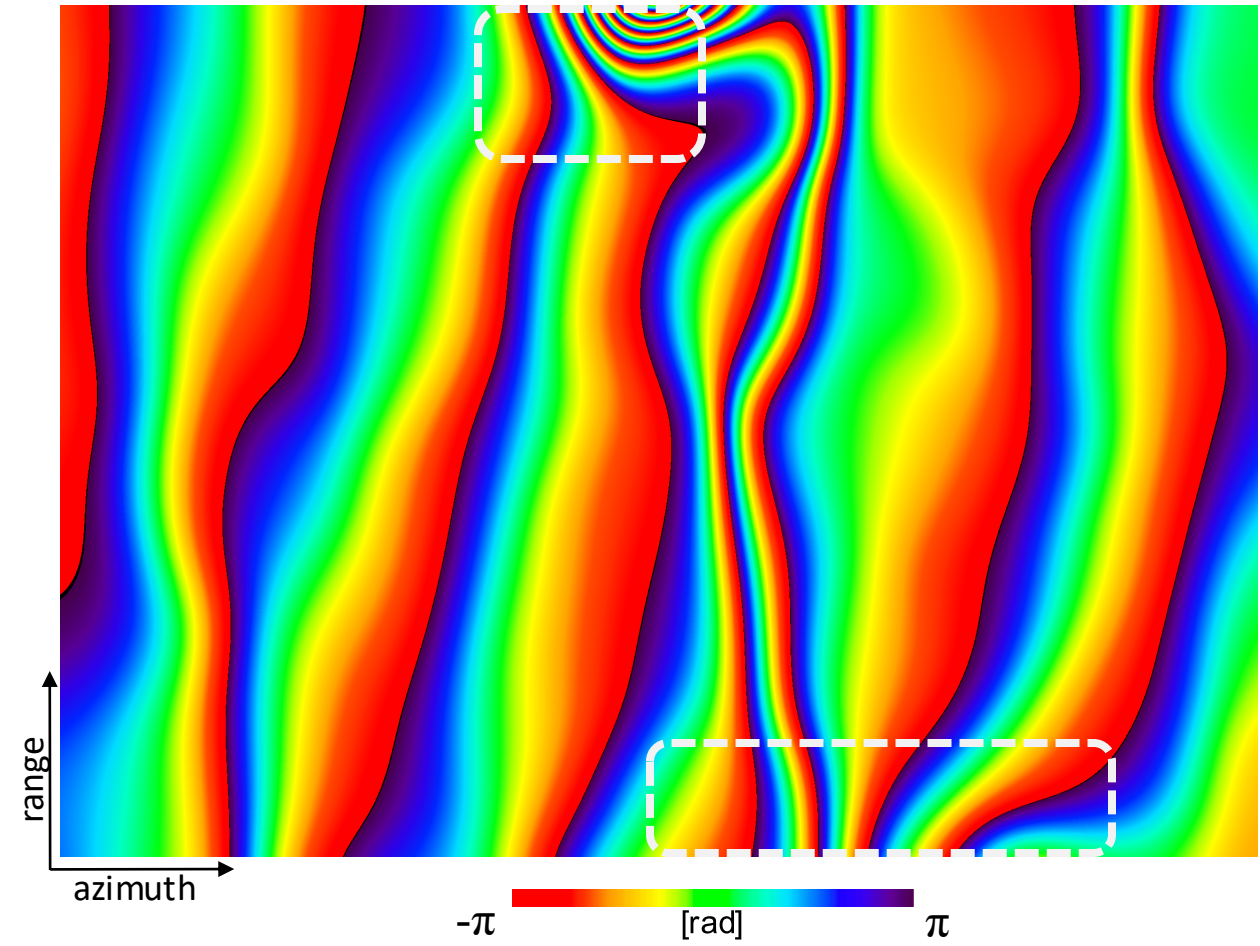
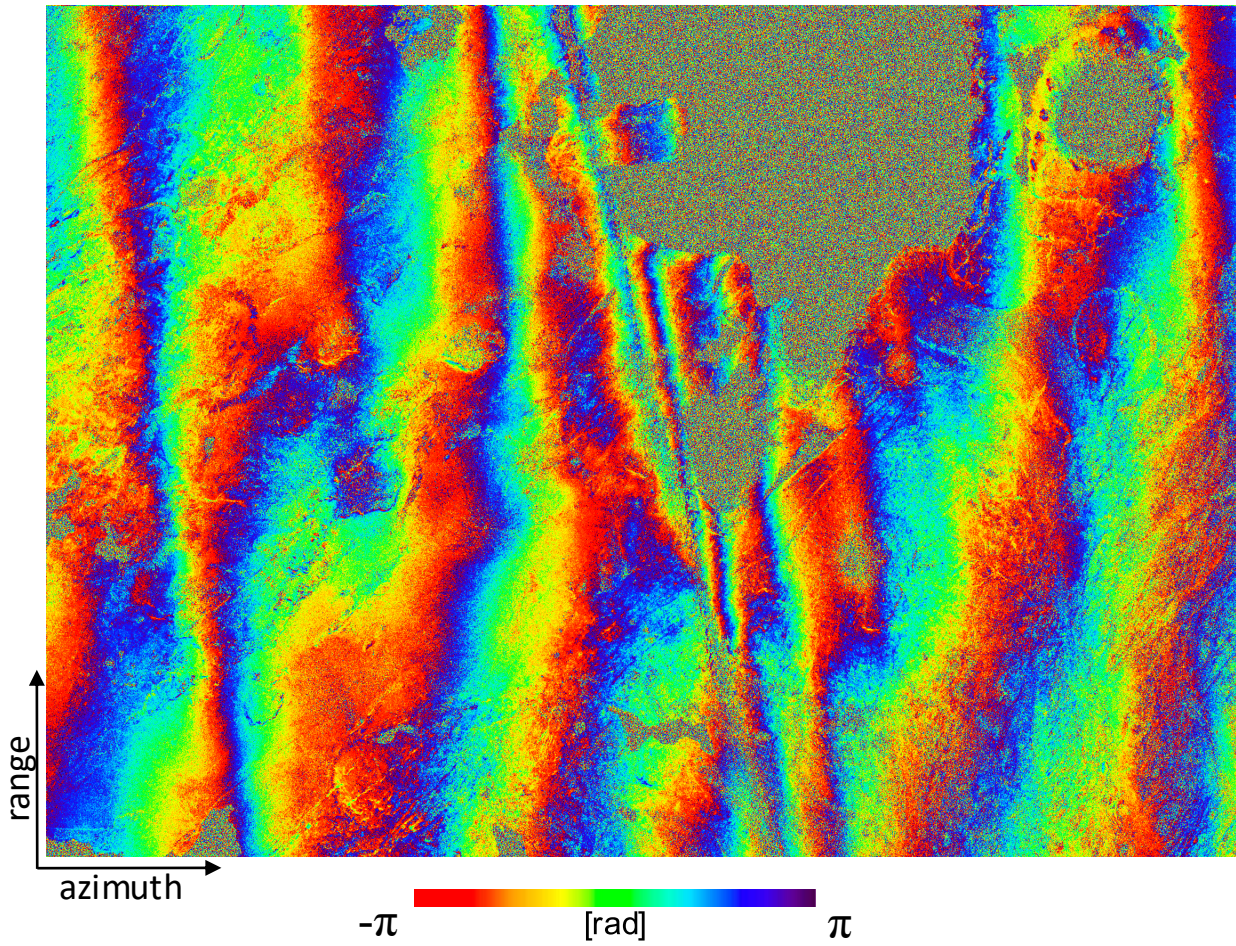
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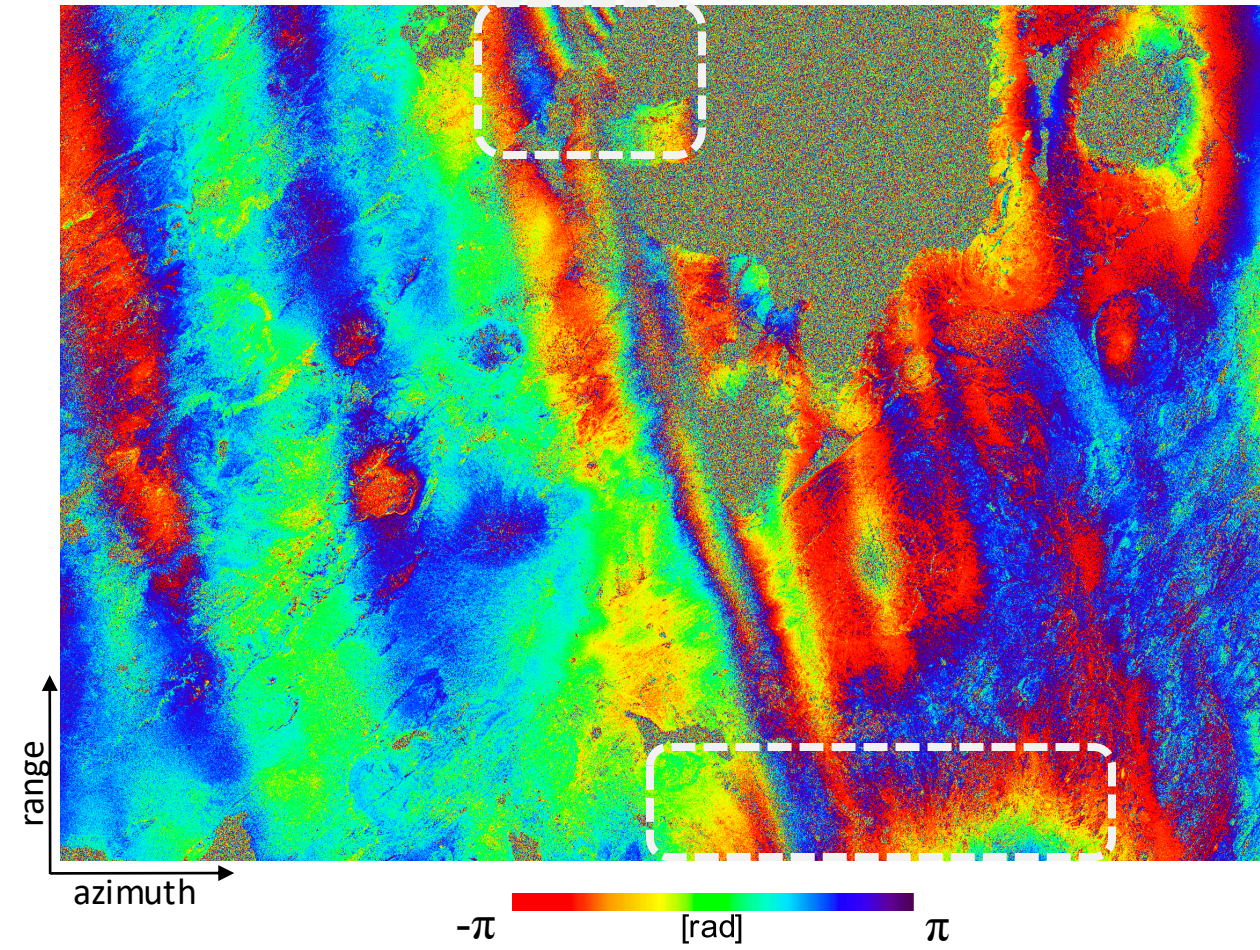
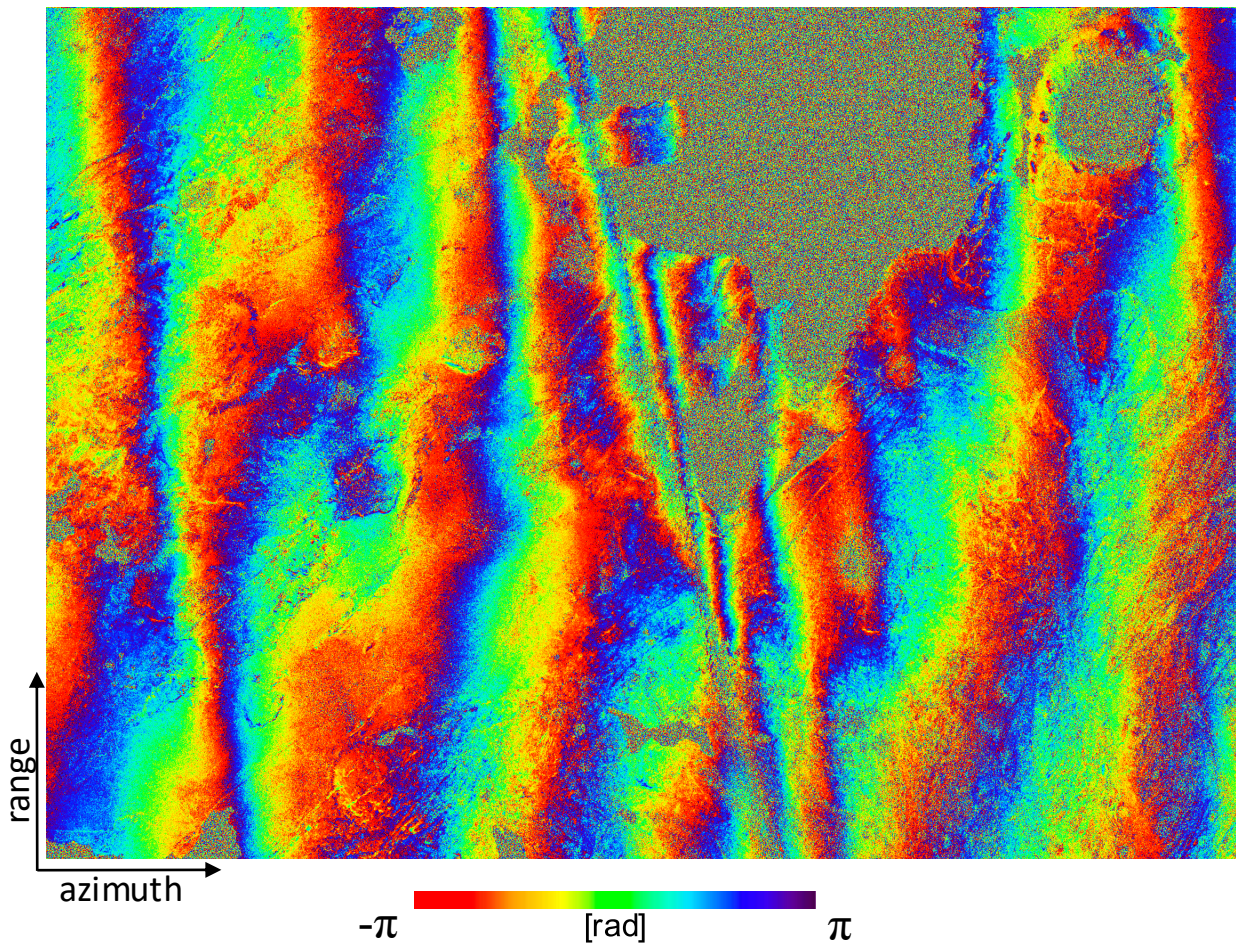
Results

ISCE solution

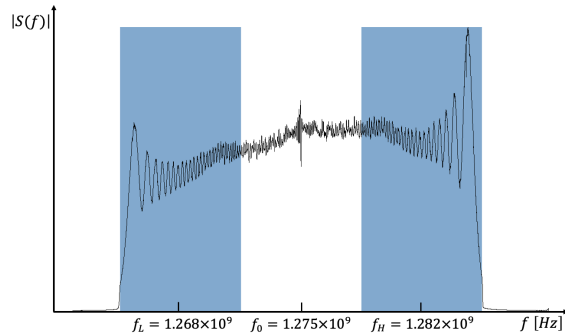


Results

ISCE solution



Alternative Range Split Spectrum Approach



$$\Delta\hat{\phi}_{iono} = x\Delta\phi + z(\Delta\phi_H - \Delta\phi_L)$$

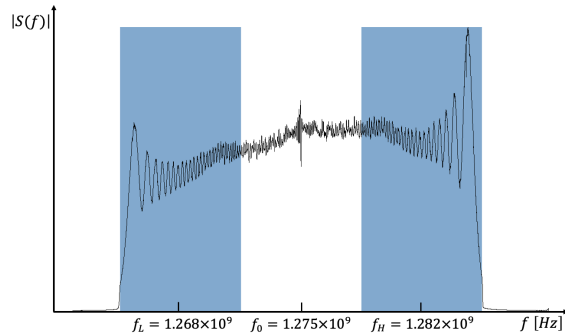
$$x = \frac{\lambda_0}{\lambda_H + \lambda_L} \approx 0.5, \quad z = \frac{\lambda_0}{2(\lambda_H - \lambda_L)}.$$

$$\langle 2\Delta\hat{\phi}_{iono} \rangle = \langle \Delta\phi \rangle + 2z(\Delta\phi_H - \Delta\phi_L)$$

unlike the standard RSS-based approach, it **does not require the phase unwrapping** of any interferogram but only of the two times ionospheric contribution

U. Wegmüller, C. Werner, O. Frey and C. Magnard, "Estimation and compensation of the ionospheric path delay phase in PALSAR-3 and NISAR-L interferograms.," 2024.

Alternative Range Split Spectrum Approach



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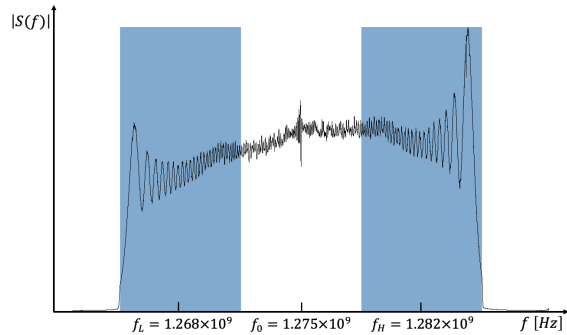
A filtering procedure has to be applied to this quantity **before multiplying for the amplification factor $2z$**



We apply the **PRIME-RSS** algorithm estimating $\lambda_{L,opt}$ and $\lambda_{H,opt}$, used for the definition of $\mathbf{z}_{opt}$

U. Wegmüller, C. Werner, O. Frey and C. Magnard, "Estimation and compensation of the ionospheric path delay phase in PALSAR-3 and NISAR-L interferograms.," 2024.

Alternative Range Split Spectrum Approach



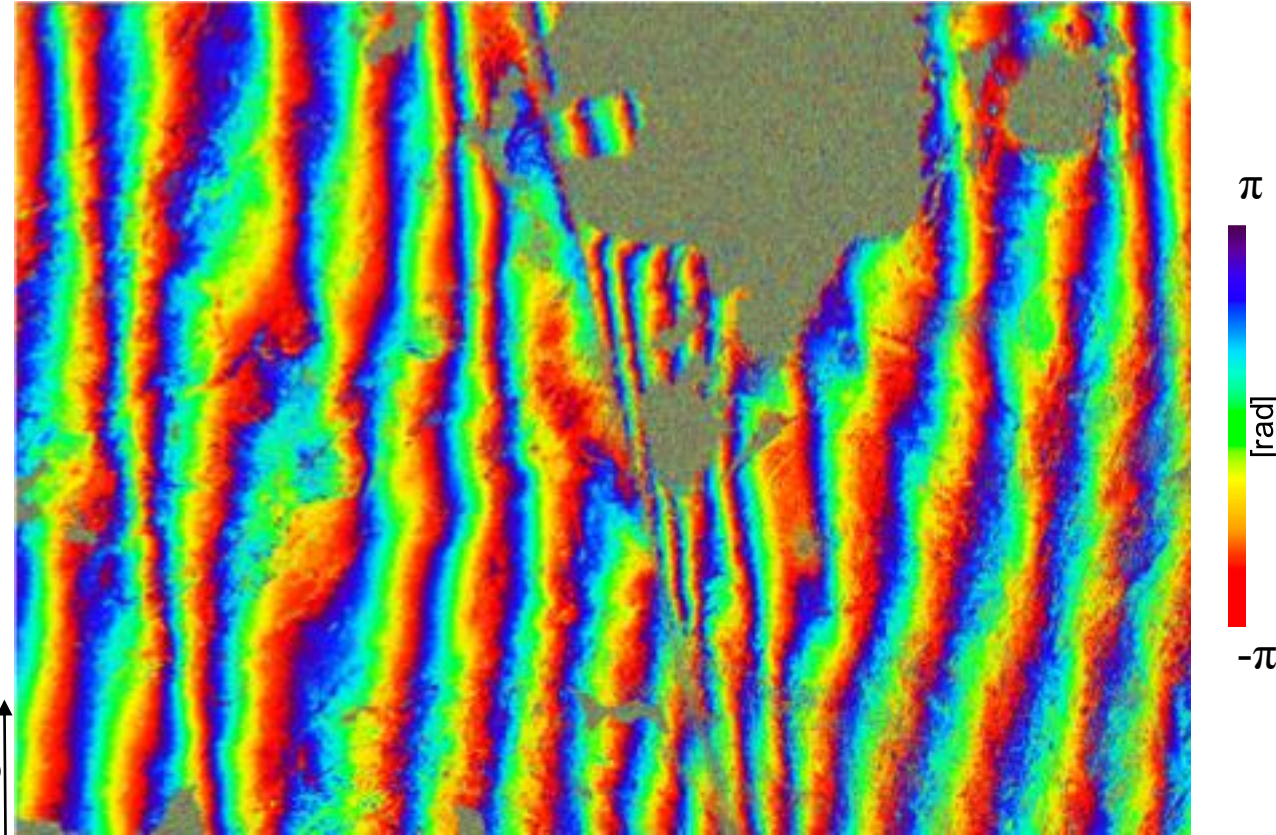
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$$\langle 2\Delta\hat{\phi}_{iono} \rangle = \langle \Delta\phi \rangle + 2z(\Delta\phi_H - \Delta\phi_L)$$

range
azimuth

$$\langle 2\Delta\hat{\phi}_{iono} \rangle$$

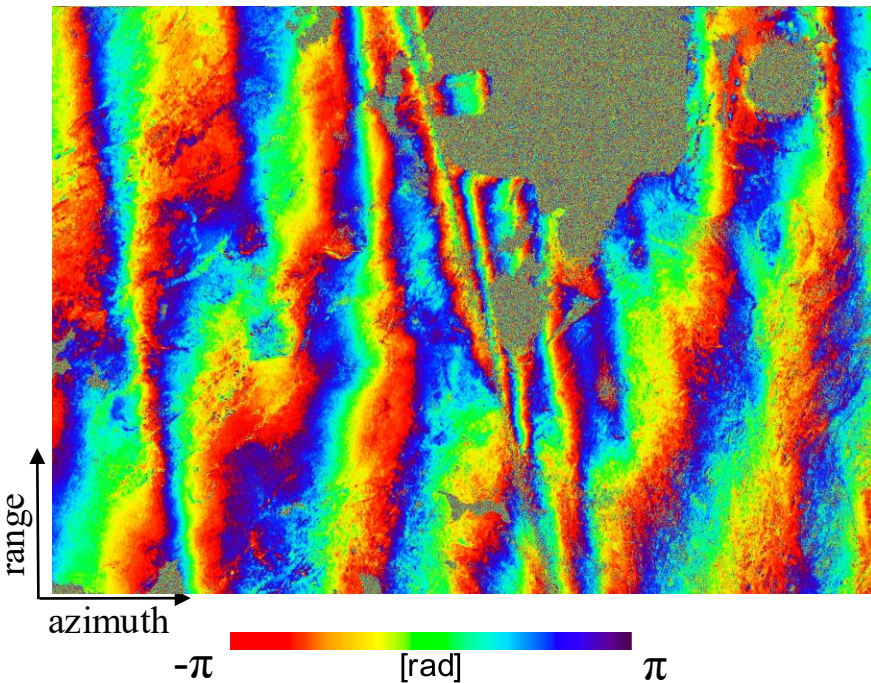


U. Wegmüller, C. Werner, O. Frey and C. Magnard, "Estimation and compensation of the ionospheric path delay phase in PALSAR-3 and NISAR-L interferograms.," 2024.

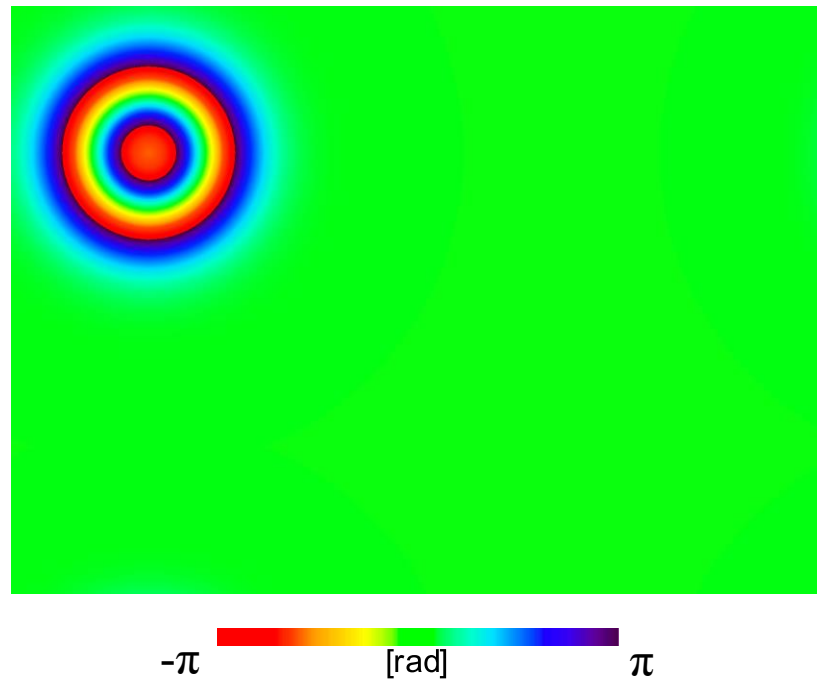
Alternative Range Split Spectrum Approach

Simulation of Real DInSAR context

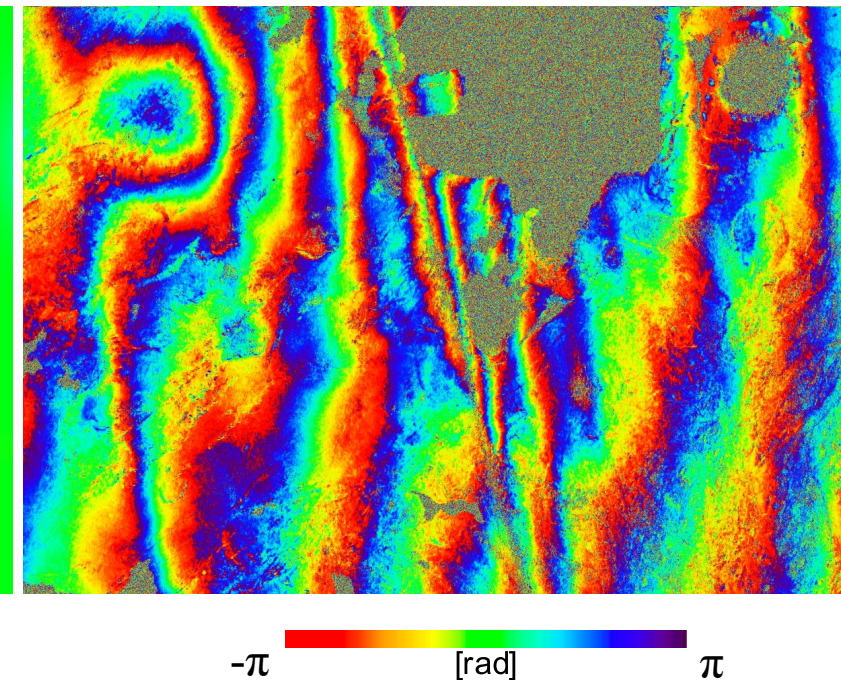
Original Differential Interferogram



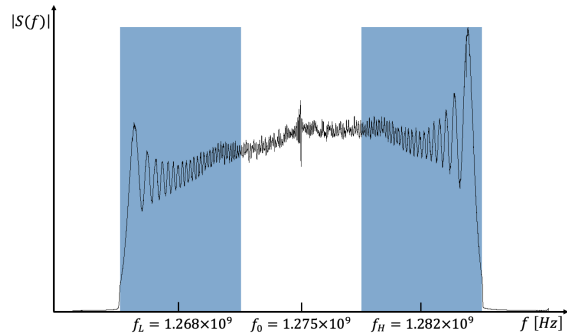
Simulated deformation pattern



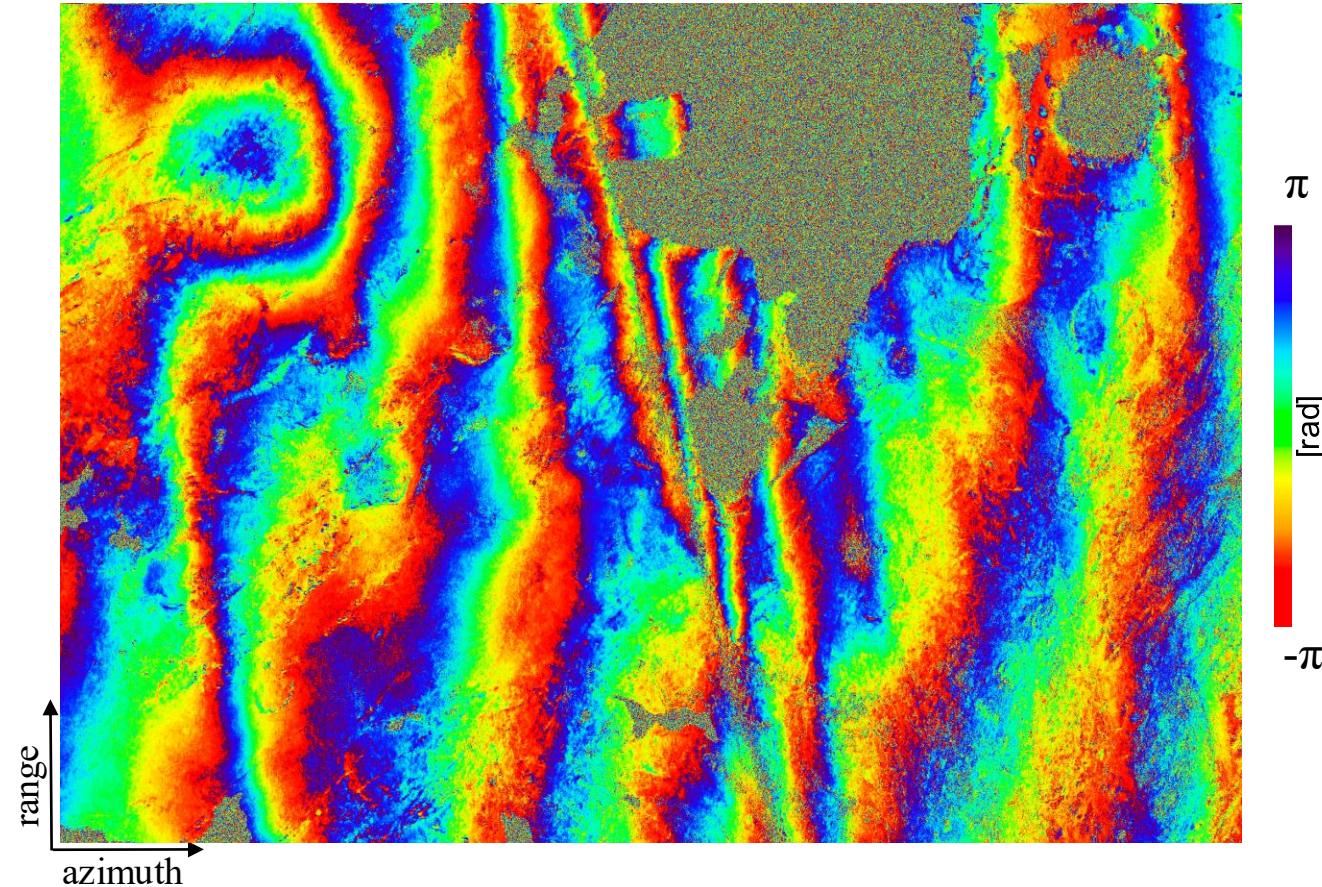
Differential Interferogram
+
Simulated ground deformation



Alternative Range Split Spectrum Approach



**Differential Interferogram
+
simulated ground deformation**



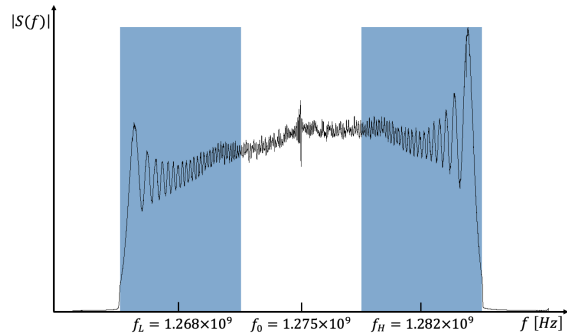
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Alternative Range Split Spectrum Approach



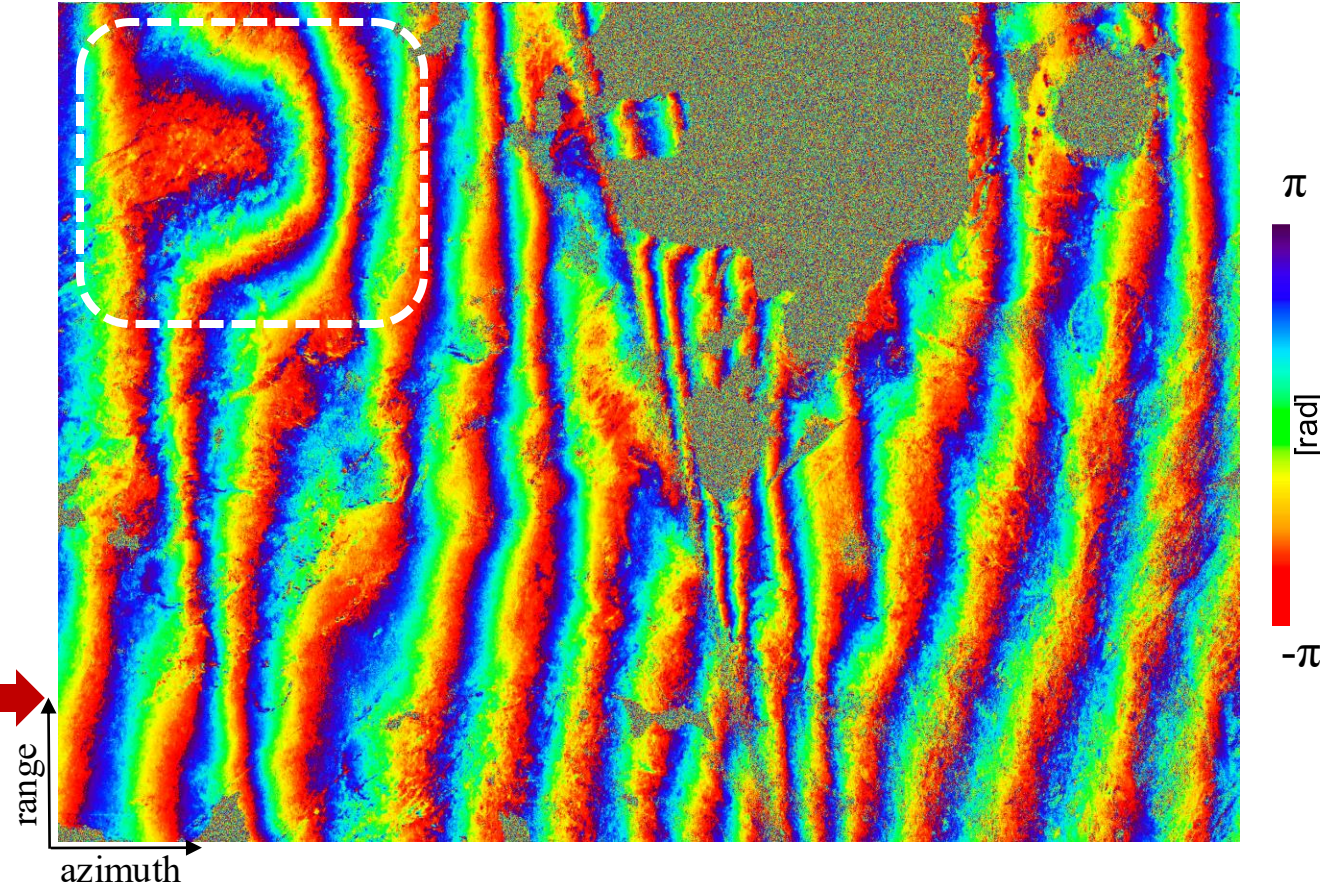
Ionosphere retrieval in real DInSAR context

$$\langle 2\Delta\hat{\phi}_{iono} \rangle$$

$$\Delta\hat{\phi}_{iono} = x\Delta\phi + z(\Delta\phi_H - \Delta\phi_L)$$

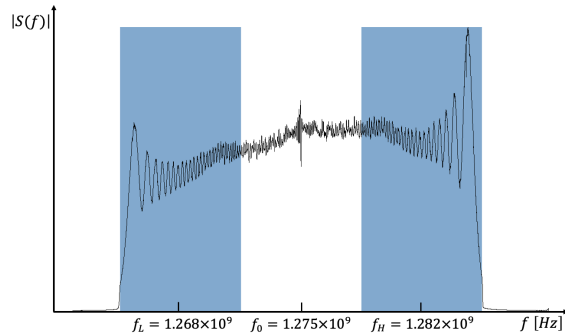
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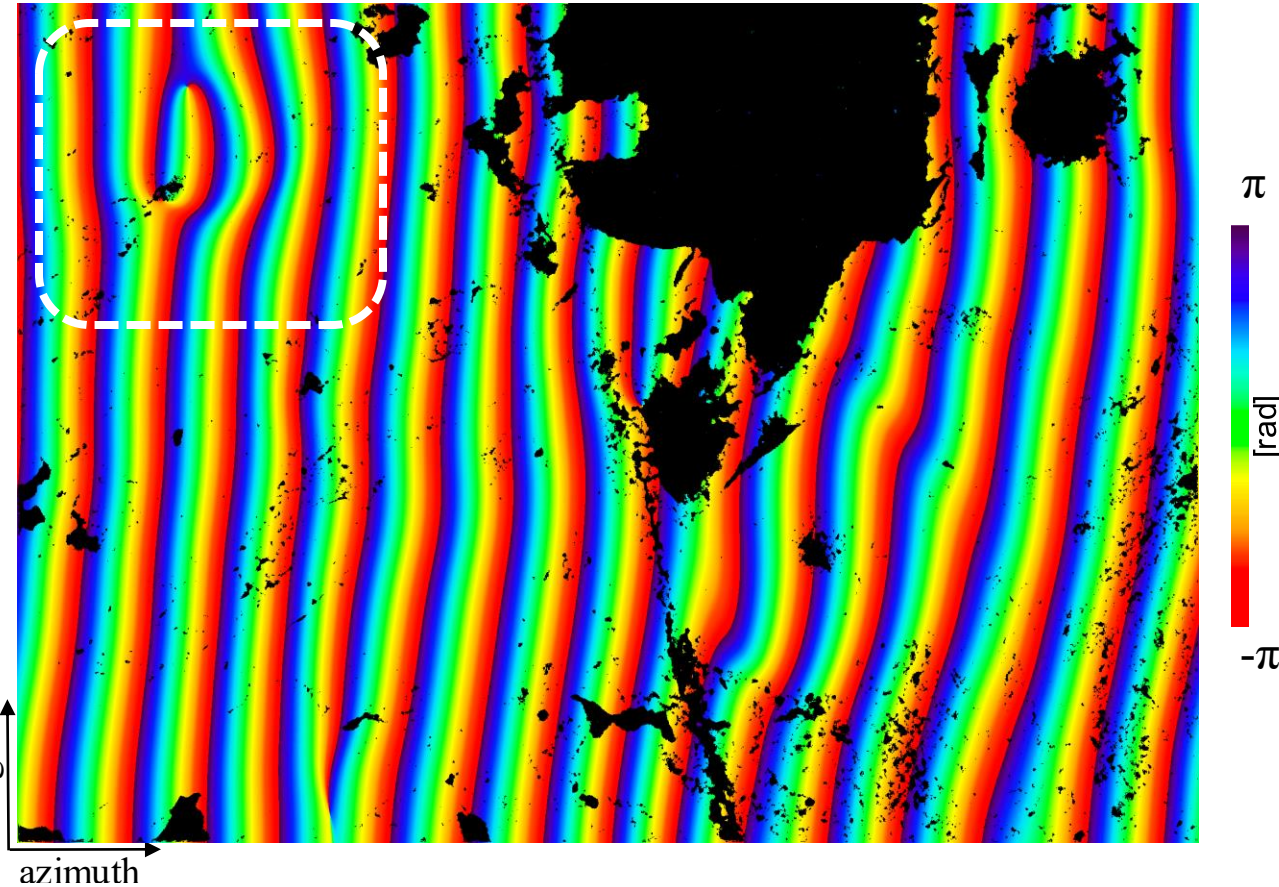
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Alternative Range Split Spectrum Approach



Ionosphere retrieval in real DInSAR context

Filtered $\langle 2\Delta\hat{\phi}_{iono} \rangle$



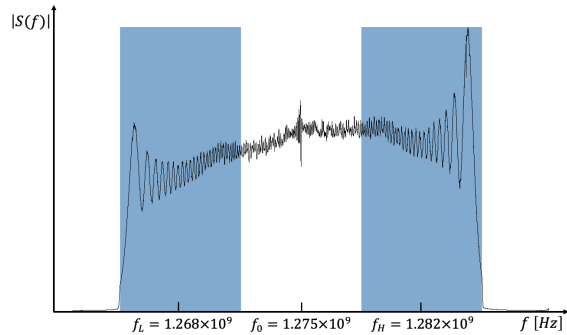
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$$\langle 2\Delta\hat{\phi}_{iono} \rangle = \langle \Delta\phi \rangle + 2z(\Delta\phi_H - \Delta\phi_L) \rightarrow$$

U. Wegmüller, C. Werner, O. Frey and C. Magnard, "Estimation and compensation of the ionospheric path delay phase in PALSAR-3 and NISAR-L interferograms.," 2024.

Alternative Range Split Spectrum Approach

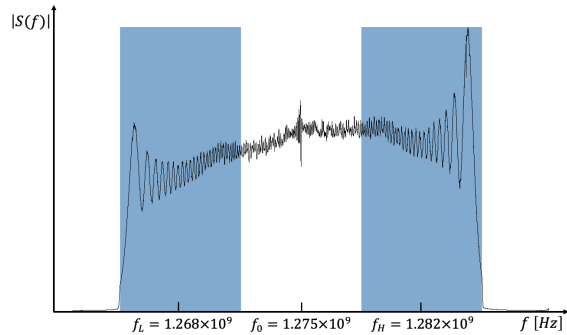


$$\Delta\hat{\phi}_{iono} = x\Delta\phi + z(\Delta\phi_H - \Delta\phi_L)$$

$$x = \frac{\lambda_0}{\lambda_H + \lambda_L} \approx 0.5, \quad z = \frac{\lambda_0}{2(\lambda_H - \lambda_L)} .$$

$$\Delta\hat{\phi}_{iono} = z \left(\frac{x}{z} \Delta\phi + (\Delta\phi_H - \Delta\phi_L) \right)$$

Alternative Range Split Spectrum Approach

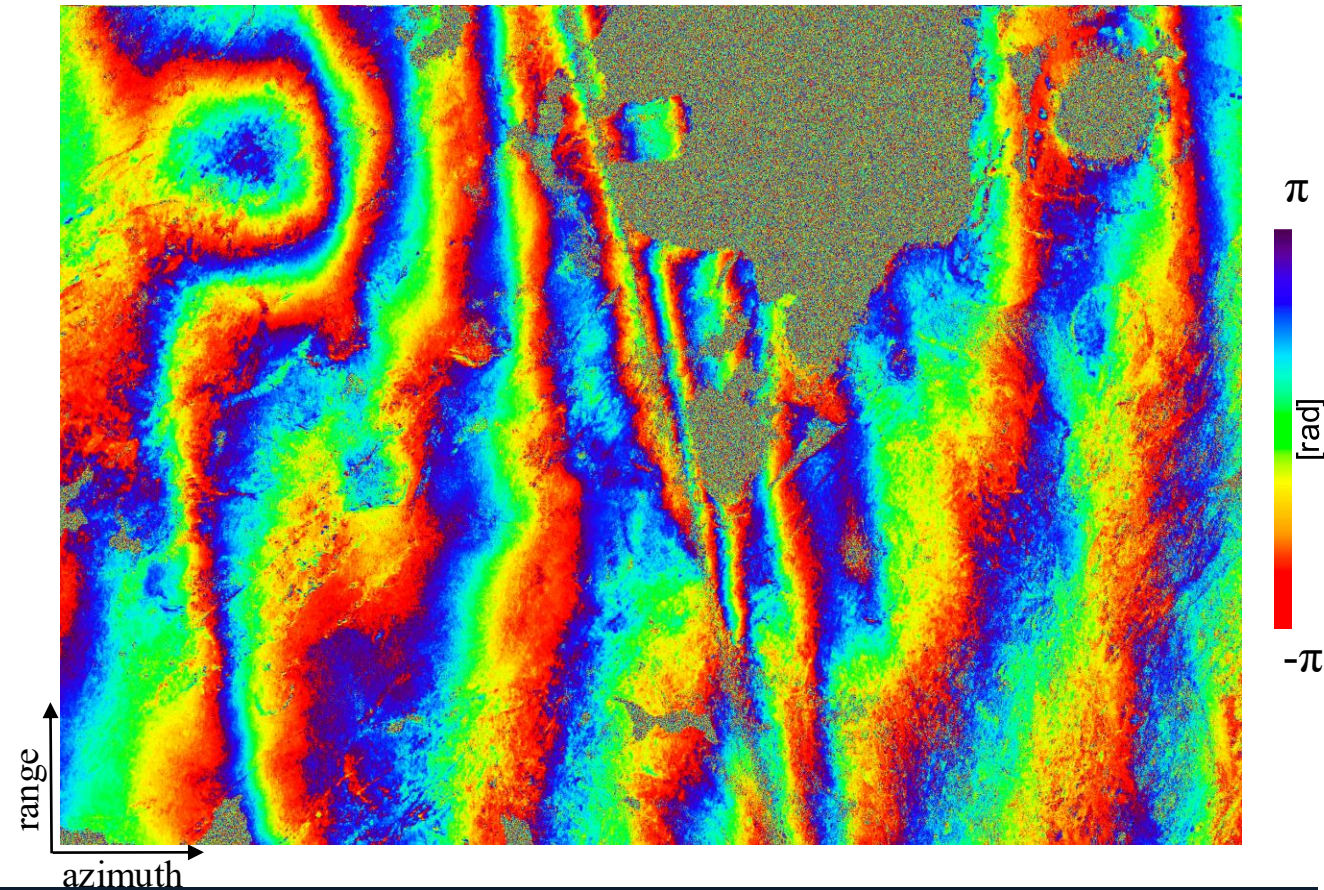


**Differential Interferogram
+
simulated ground deformation**

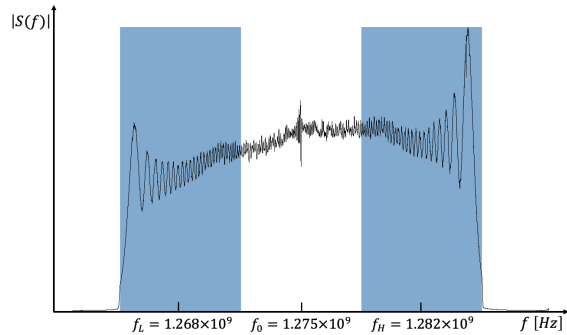
$$\Delta \hat{\phi}_{iono} = x \Delta \phi + z (\Delta \phi_H - \Delta \phi_L)$$

$$x = \frac{\lambda_0}{\lambda_H + \lambda_L} \approx 0.5, \quad z = \frac{\lambda_0}{2(\lambda_H - \lambda_L)}.$$

$$\Delta \hat{\phi}_{iono} = z \left(\frac{x}{z} \Delta \phi + (\Delta \phi_H - \Delta \phi_L) \right)$$



Alternative Range Split Spectrum Approach



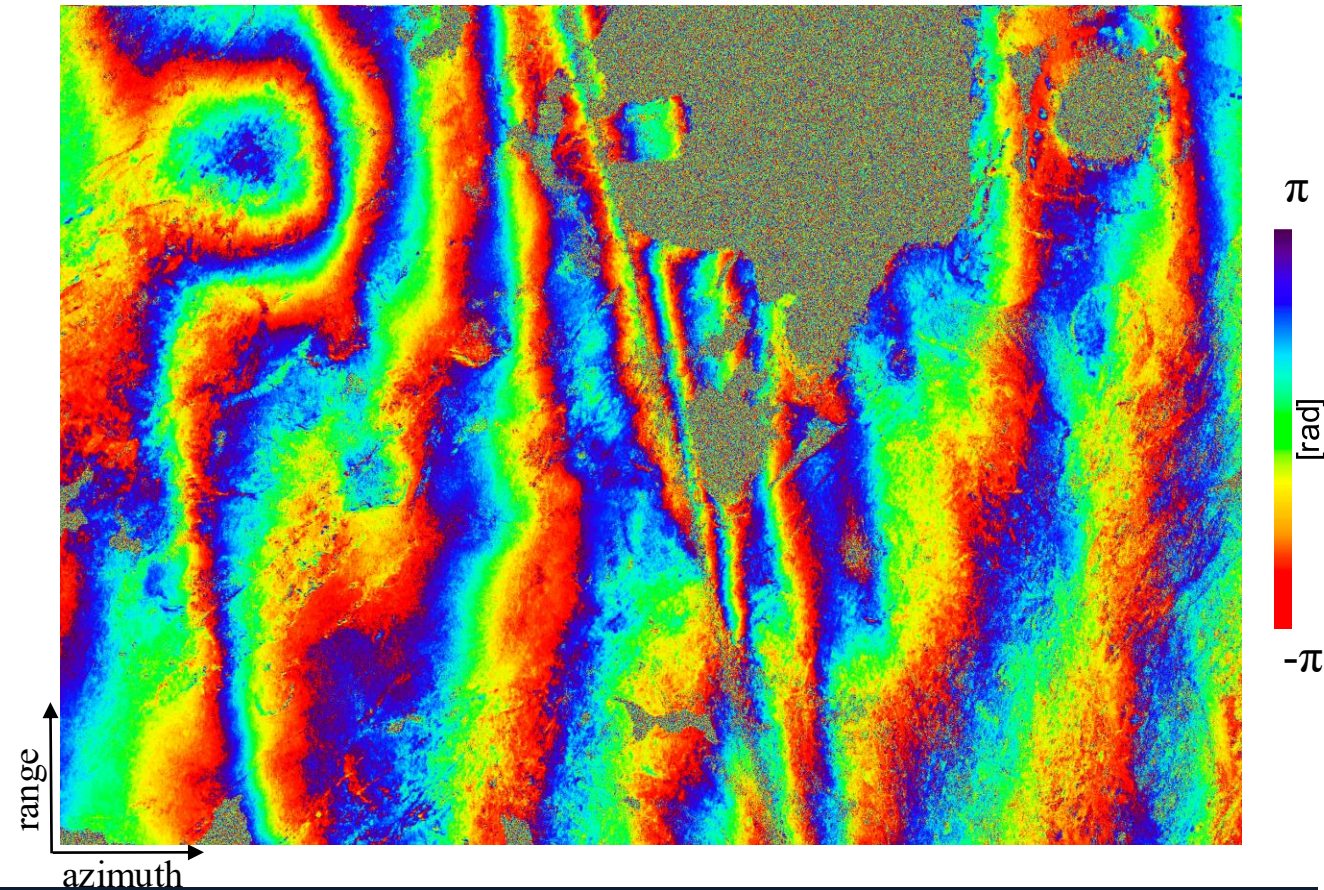
Differential Interferogram
+
simulated ground deformation

$$\Delta \hat{\phi}_{iono} = x \Delta \phi + z (\Delta \phi_H - \Delta \phi_L)$$

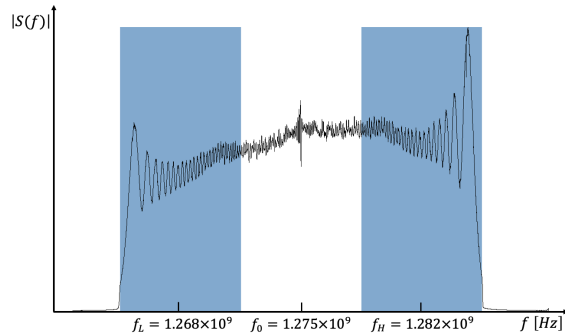
$$x = \frac{\lambda_0}{\lambda_H + \lambda_L} \approx 0.5, \quad z = \frac{\lambda_0}{2(\lambda_H - \lambda_L)}.$$

$$\Delta \hat{\phi}_{iono} = z \left(\frac{x}{z} \Delta \phi + (\Delta \phi_H - \Delta \phi_L) \right)$$

Unwrapped Phase



Alternative Range Split Spectrum Approach



$$\Delta\hat{\phi}_{iono} = x\Delta\phi + z(\Delta\phi_H - \Delta\phi_L)$$

$$x = \frac{\lambda_0}{\lambda_H + \lambda_L} \approx 0.5, \quad z = \frac{\lambda_0}{2(\lambda_H - \lambda_L)}.$$

$$\Delta\hat{\phi}_{iono} = z \left(\frac{x}{z} \Delta\phi + (\Delta\phi_H - \Delta\phi_L) \right)$$

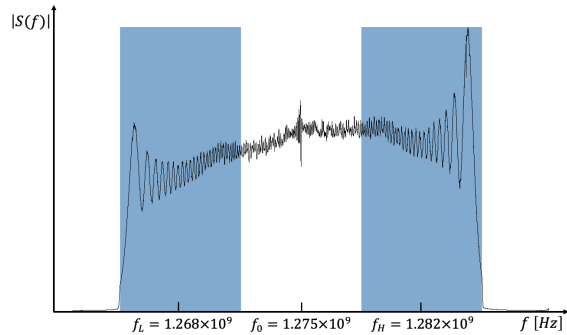
Amplification factor

A filtering procedure has to be applied to this quantity **before multiplying for the amplification factor z**

We apply the **PRIME-RSS** algorithm estimating $\lambda_{L,opt}$ and $\lambda_{H,opt}$, used for the definition of z_{opt}

$$z = -43.704 \quad \rightarrow \quad z_{opt} = -48$$

Alternative Range Split Spectrum Approach



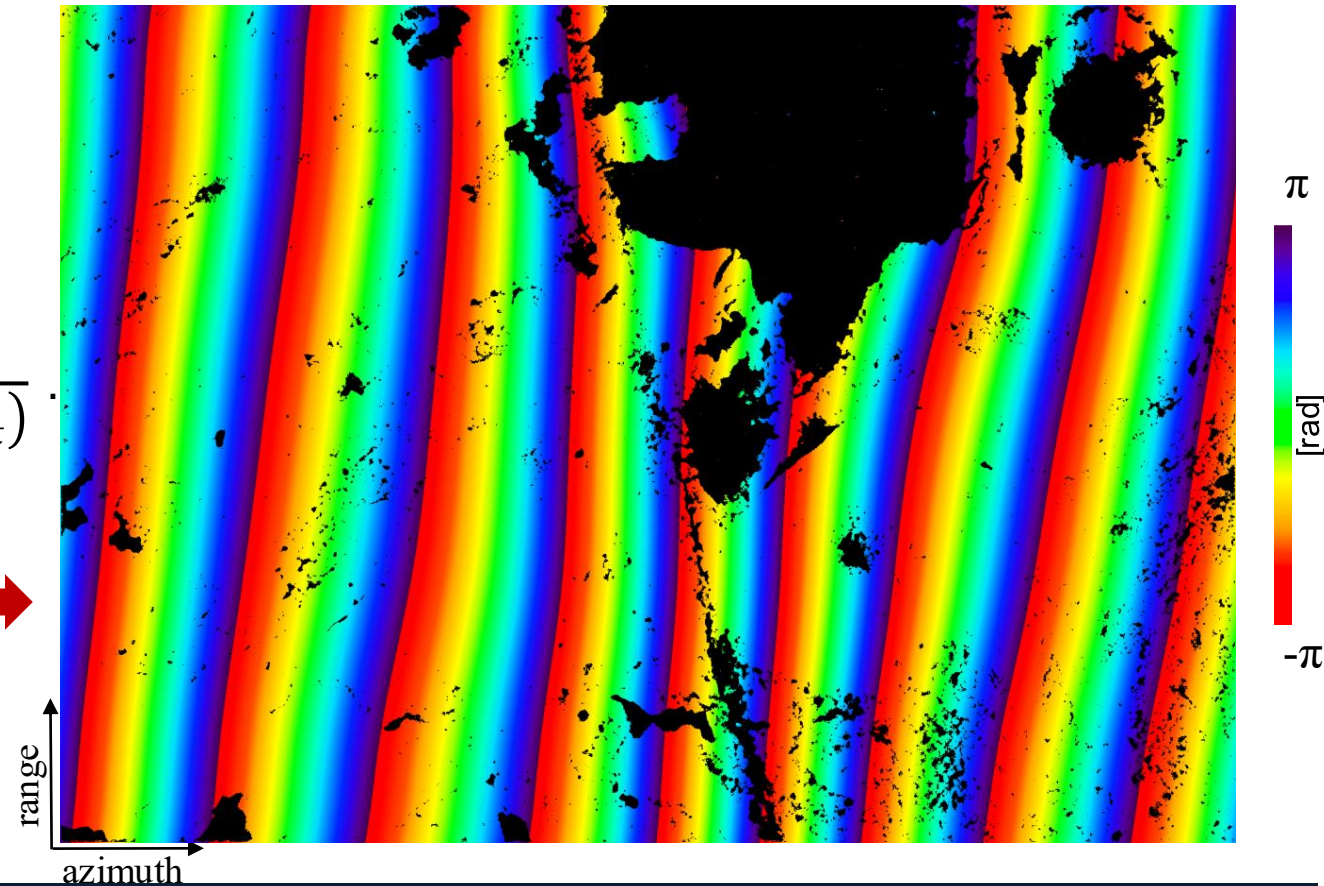
Ionosphere retrieval in real DInSAR context

$$\langle \Delta \hat{\phi}_{iono} \rangle$$

$$\Delta \hat{\phi}_{iono} = x \Delta \phi + z (\Delta \phi_H - \Delta \phi_L)$$

$$x_{opt} = \frac{\lambda_0}{\lambda_{H,opt} + \lambda_{L,opt}} \approx 0.5, \quad z_{opt} = \frac{\lambda_0}{2(\lambda_{H,opt} - \lambda_{L,opt})}$$

$$\Delta \hat{\phi}_{iono} = z_{opt} \left(\frac{x_{opt}}{z_{opt}} \Delta \phi + (\Delta \phi_H - \Delta \phi_L) \right)$$

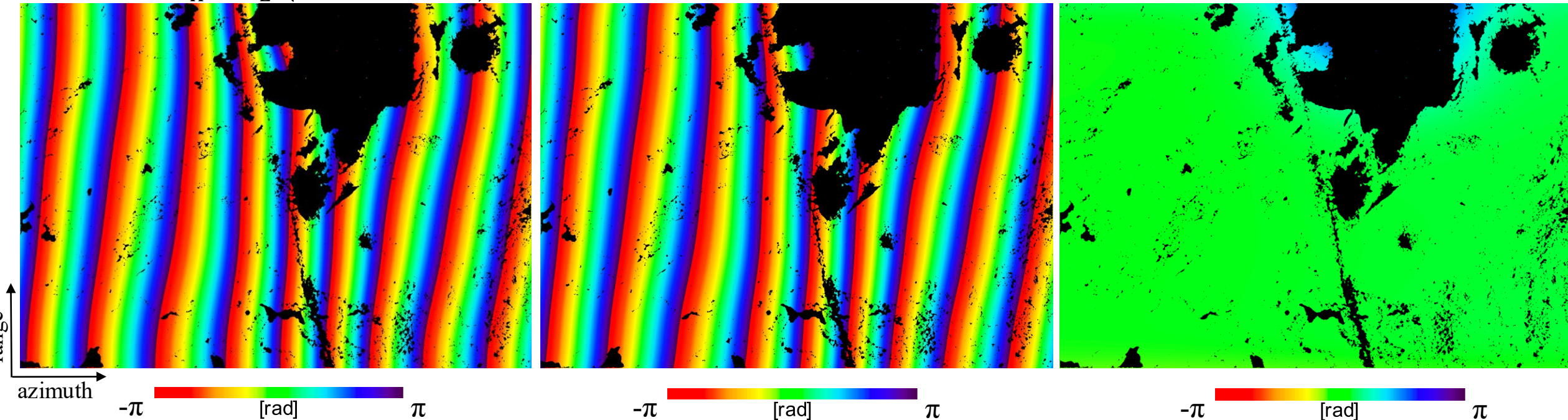


Comparative analysis of the PRIME-RSS algorithm for alternative RSS formulation

$$\Delta\hat{\phi}_{iono} = \frac{\lambda_0\lambda_H}{\lambda_H^2 - \lambda_L^2} \left(\Delta\phi_H - \frac{\lambda_L}{\lambda_H} \Delta\phi_L \right)$$

$$\Delta\hat{\phi}_{iono} = z \left(\frac{x}{z} \Delta\phi + (\Delta\phi_H - \Delta\phi_L) \right)$$

Difference



Independently from the RSS formulation, PRIME-RSS algorithm reaches a **Consensus** for the Ionospheric Phase Estimation in DInSAR Applications

Final Remarks

- PRIME-RSS is easy to implement both in prime factors identification and in spectral filtering procedure (to make the spectral filter very effective the exploitation of a complex exponential on the ionospheric phase is needed).
- PRIME-RSS reaches the same performance even if an alternative RSS-based formulation is used.
- PRIME-RSS does not directly address to the PhU problem but the use of spatio-temporal PhU algorithms in multitemporal DInSAR analysis can contribute to obtain a more robust phase unwrapping results.
- More details will be available in this paper just submitted:

PRIME-factorized Multistep Range Split-Spectrum (PRIME-RSS) Algorithm for Ionospheric Phase Estimation in DInSAR Exploitation

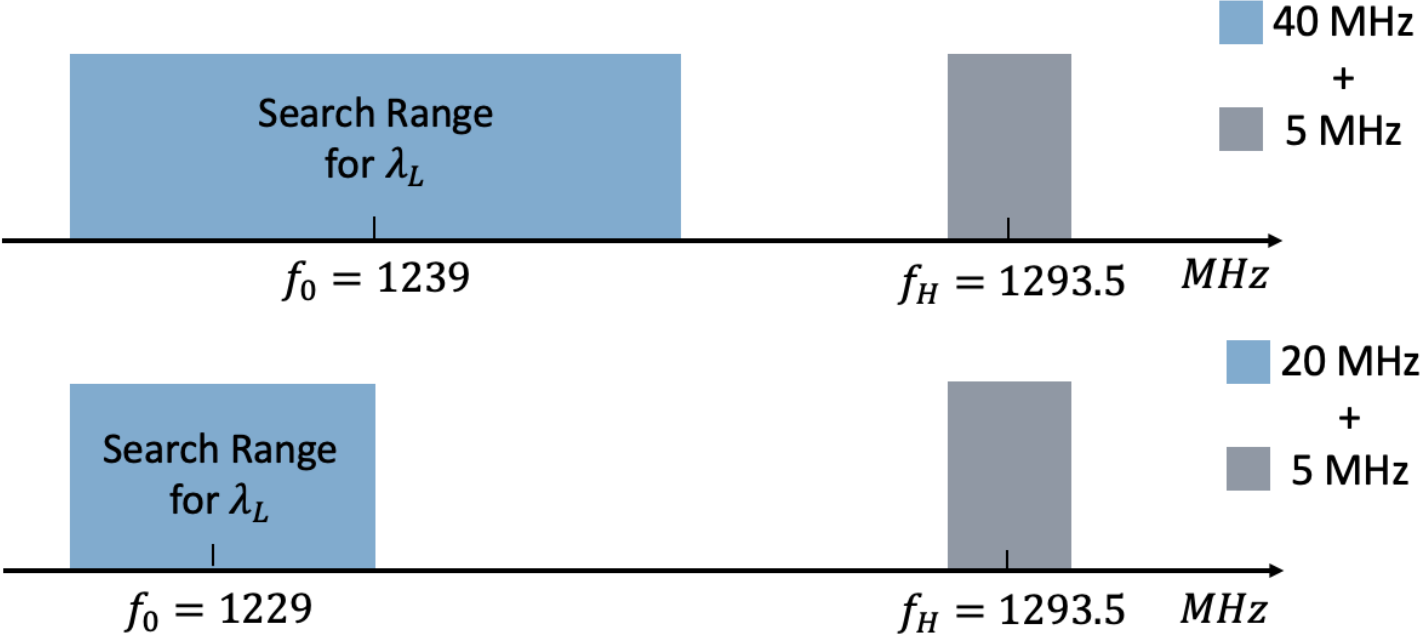
Marianna Franzese, Claudio De Luca, Antonio De Maio,
Giorgio Gomba, Yenni Lorena Belen Roa, and Riccardo Lanari

Thank you for your attention.



istituto per il rilevamento
elettromagnetico dell'ambiente
 Consiglio Nazionale delle Ricerche

PRIME-RSS optimization for the NISAR dual-frequency modes



$$\Delta\hat{\phi}_{iono} = \frac{\lambda_0\lambda_H}{\lambda_H^2 - \lambda_L^2} \left(\Delta\phi_H - \frac{\lambda_L}{\lambda_H} \Delta\phi_L \right)$$

	α	$\lambda_{L,opt}$ [cm]	α_{opt}
40 + 5 MHz	-11.611	24.164	-12
20 + 5 MHz	-9.770	24.552	-9

