ESA POLINSAR BIOMASS 2026

12th International Workshop on Science and Applications of SAR Polarimetry and Polarimetric Interferometry and
6th Biomass Science Workshop and 1st Cal/Val meeting

Ionospheric effects on BIOMASS interferometry

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BIOMASS InSAR

Ensuring **high quality interferometric data** is fundamental for a number of BIOMASS products:

- **AGBD**, since it leverages ground-cancelled products derived from multiple orbits
- **Forest Height**, since it leverages on InSAR and it's sensitive to coherence drops due to unpredicted sources
- **Forest Disturbance**, since it compares data across different dates
- **Digital Terrain Model**
- **Tomography**
- **Ice structure & Ice motion**
- Any other future potential products derived from multiple orbits

Due to the large sensitivity of P-Band to TEC, **Ionospheric phase advance** is by far the dominant source of degradation for InSAR data quality

$\Rightarrow$ **Ionospheric correction of InSAR data is a fundamental component of BIOMASS**

Effect	Variation w.r.t. TEC	L-Band (1275 MHz)	P-Band (435 MHz)
Phase advance	$\varphi = 4\pi\zeta\frac{TEC}{cf}$	13.3 rad/TECU	38.9 rad/TECU
Faraday Rotation	$\Omega = \frac{\zeta(e\vec{B}\cdot\hat{k})}{cm_e^2 f^2} TEC$	$6\cdot10^{-3}$ rad/TECU (@ $\vec{B}\cdot\hat{k}$ =$4\cdot10^{4}$ nT)	$5\cdot10^{-2}$ rad/TECU (@ $\vec{B}\cdot\hat{k}$ =$4\cdot10^{4}$ nT)

BIOMASS InSAR

Ionosphere impacts on BIOMASS InSAR in different ways

Very slow-varying TEC causes phase artefacts

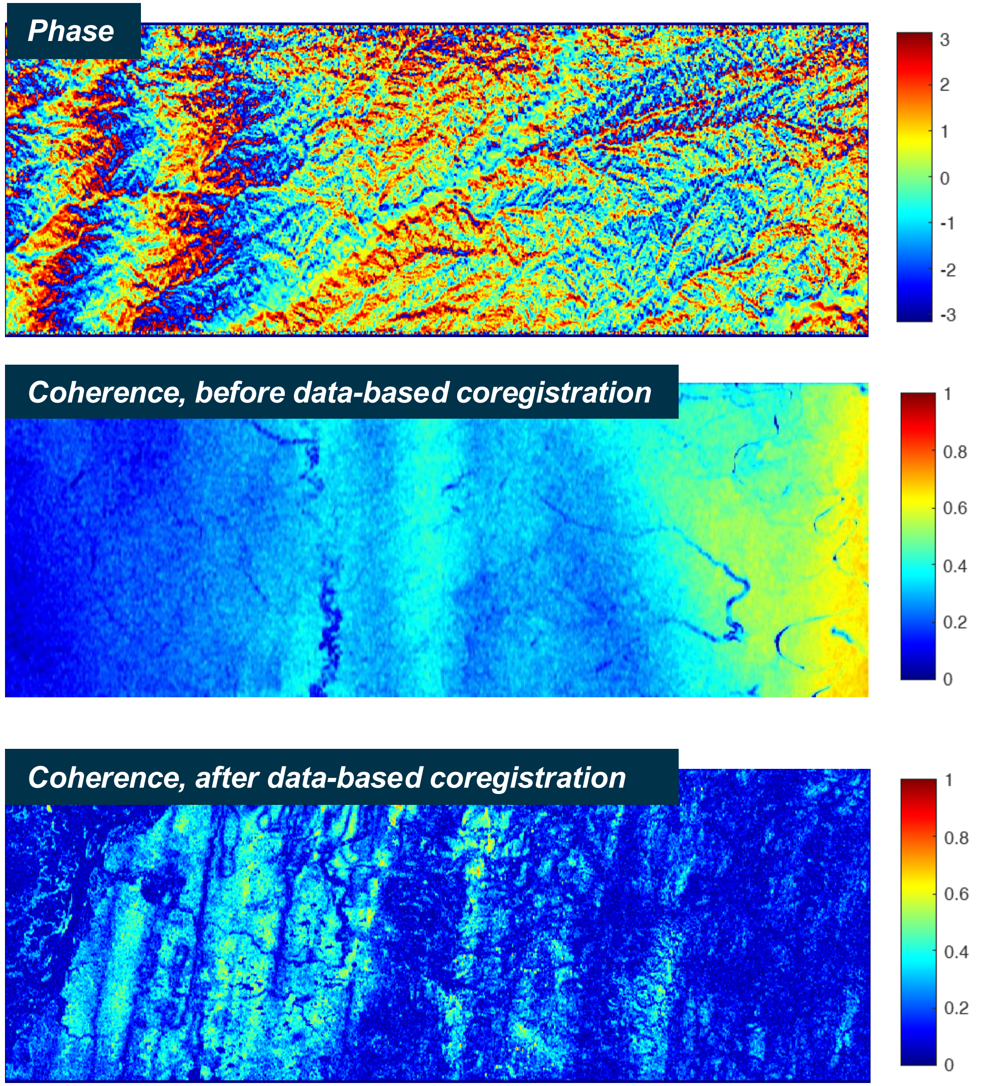
TEC causes range shifts

TEC gradients cause azimuth shifts

⇒ coherence losses that can be recovered by data-based coregistration

Random TEC variations **faster** than a synthetic aperture cause defocusing

⇒ coherence losses that **cannot** be recovered by data-based coregistration



Scopes of this work

This talk is focused on the latter case, i.e.: **coherence losses induced by different defocusing patterns in different passes**

Relevance:

⇒ This phenomenon is being observed often at Boreal and Antarctic latitudes, and sporadically also over Africa and Australia

Severity:

⇒ Major source of degradation for all products derived from InSAR

Uncharted territory:

⇒ No prior literature on this topic

- Data-based coregistration **cannot** restore focusing quality
- Split-spectrum **cannot** compensate for ionospheric phase residuals faster than a synthetic aperture
- Autofocus of single images, either based on polarimetry (FR), map-drift, contrast enhancement, **lacks** the sensitivity required by Interferometry

Methodology

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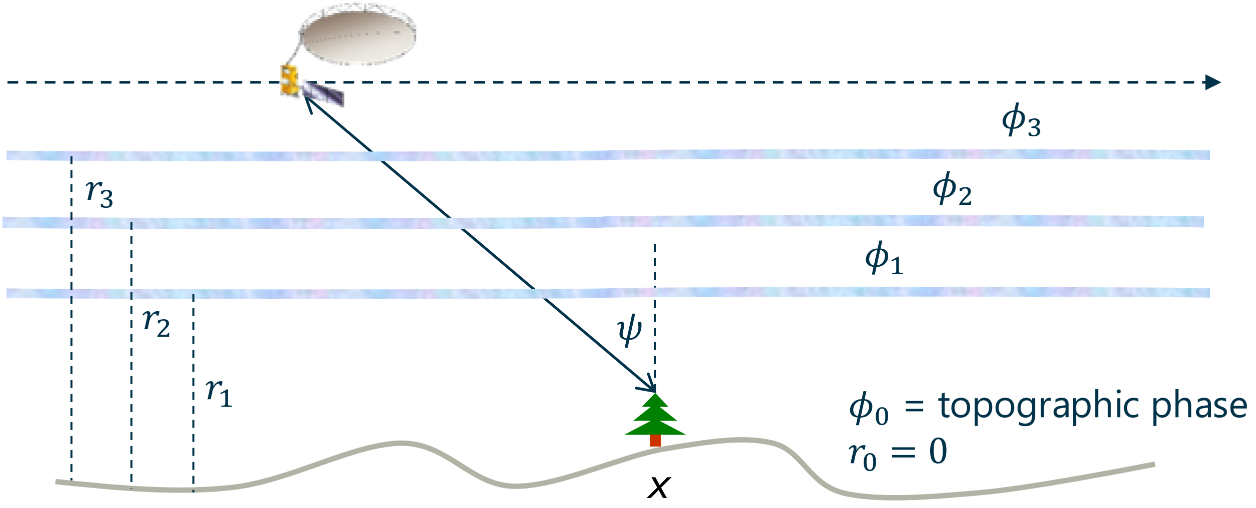
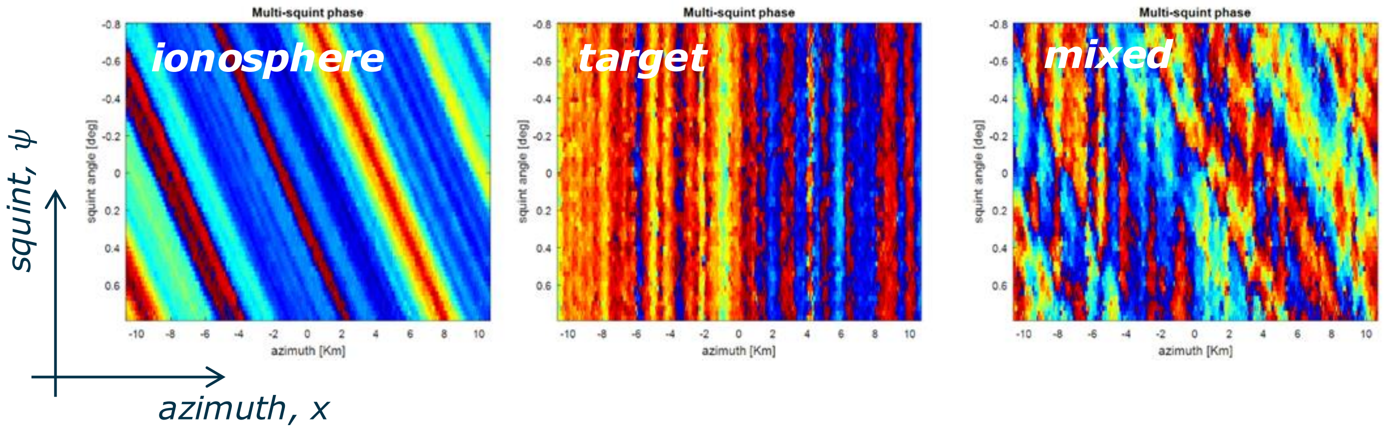
MS-InSAR is used as the main diagnosis tool

In the presence of multiple ionospheric layers at constant range r_k the MS-InSAR phase can be modeled as

$$\phi_{ms}(\psi, x) = \sum_{k=0}^{N_i} \phi_k(x - r_k\psi)$$

Each layer appears in the azimuth/squint plane as being associated with a characteristic **slope**, determined by the ionospheric range r_k





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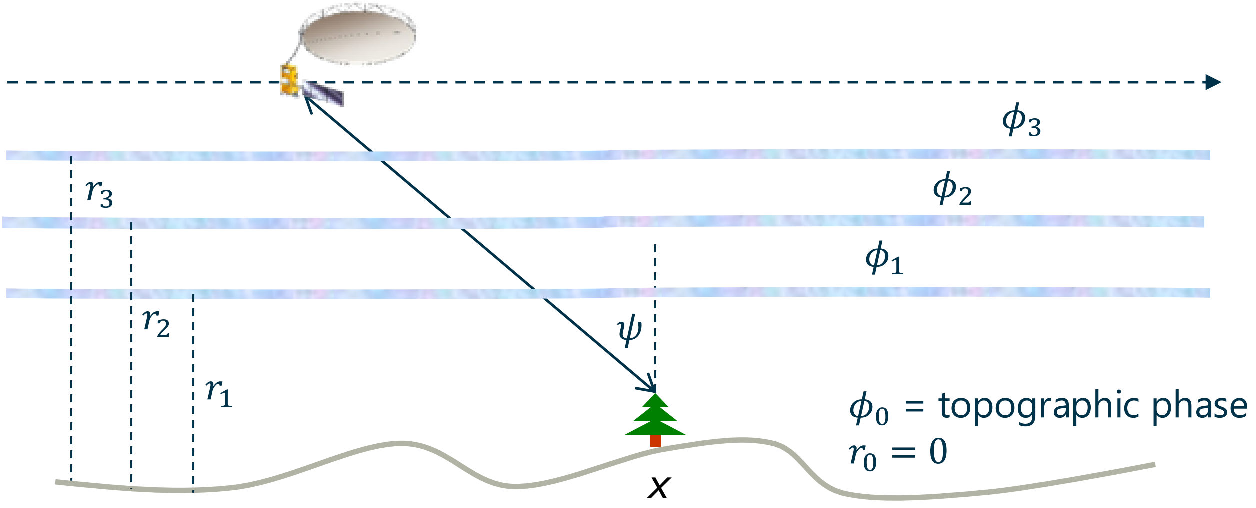
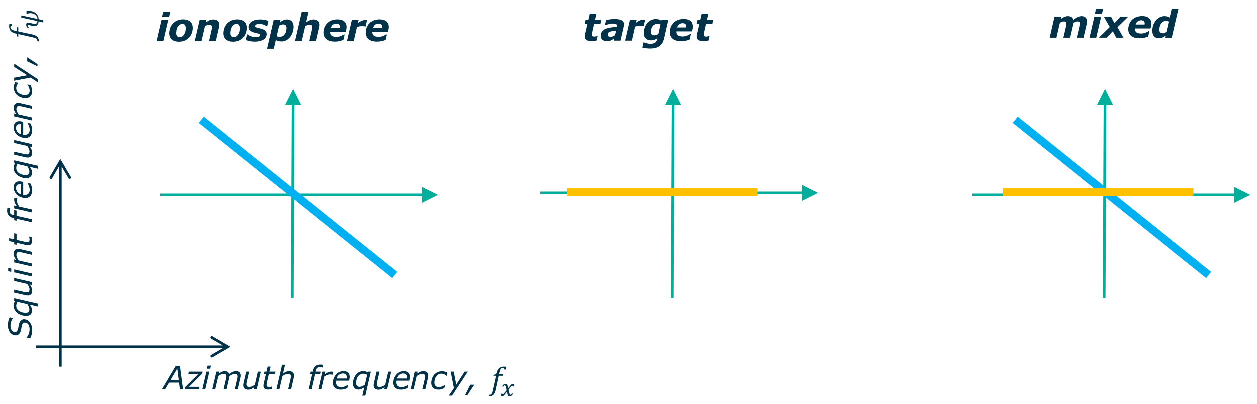


Each layer appears in the azimuth/squint plane as being associated with a characteristic **slope**, determined by the ionospheric range r_k

In the frequency domain, each layer appears as a line with a characteristic slope



Real data – Amazonia

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3-pass descending stack

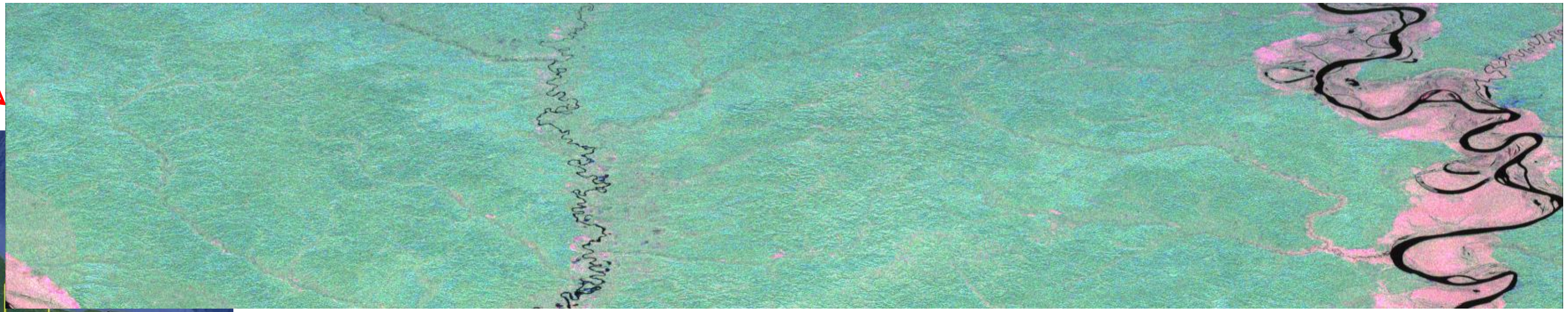
Hoa_12 = 600 m

Hoa_13 = 780 m

Hoa_23 = 2500 m

'BIO_S1_STA__1S_20250607T224654_20250607T224715_C_G___M___C___T____F157_01_DA3R7X'
'BIO_S1_STA__1S_20250610T224654_20250610T224714_C_G___M___C___T____F157_01_DA3R89'
'BIO_S1_SCS__1S_20250613T224654_20250613T224714_C_G___M___C___T____F157_01_DA7ELM '

Data amplitude



Real data – Amazonia

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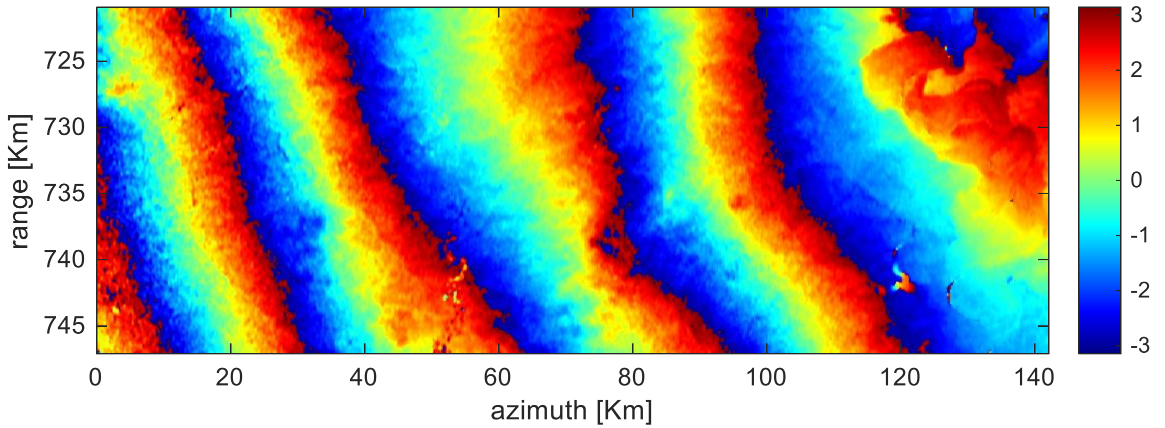
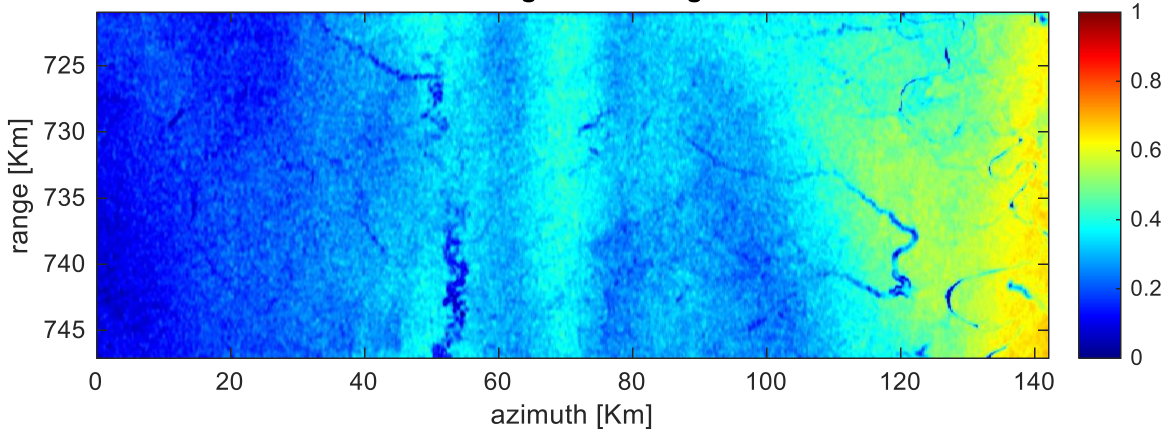
Geometrical coregistration and phase flattening

Phase [rad] - Original data

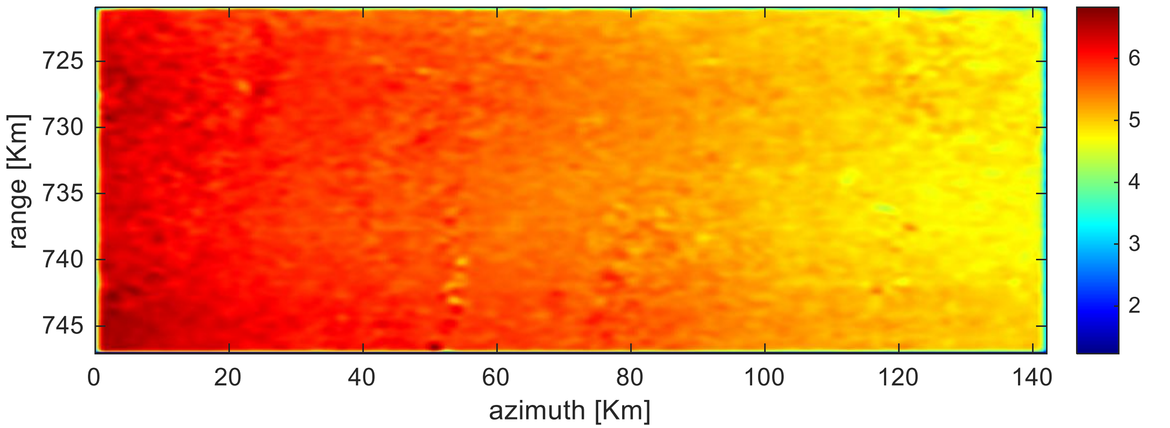


Coherence magnitude - Original data

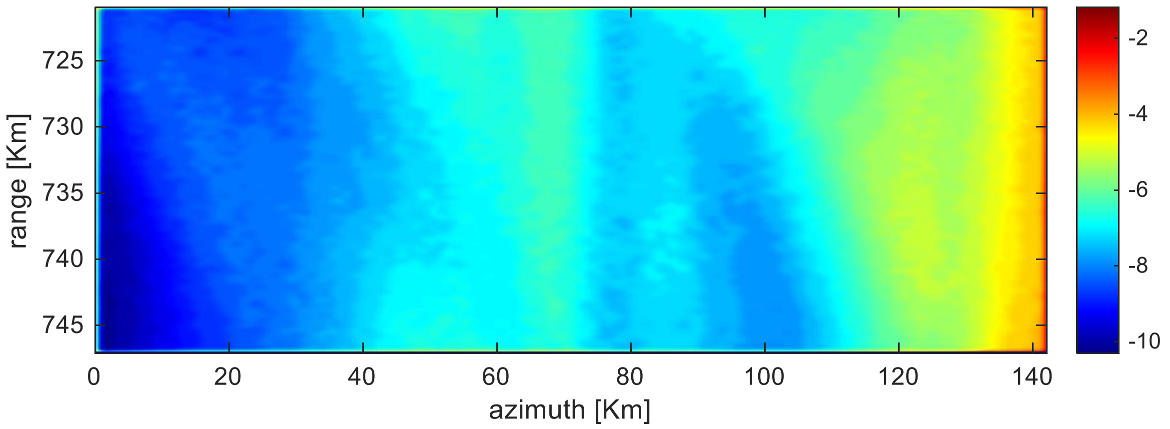


Estimated range and azimuth shifts

Range shift [m]



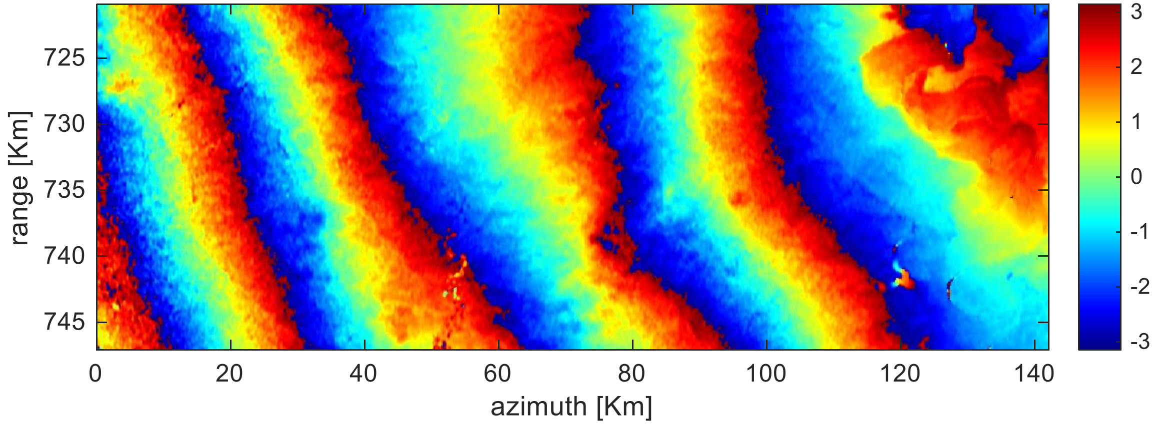
Azimuth shift [m]



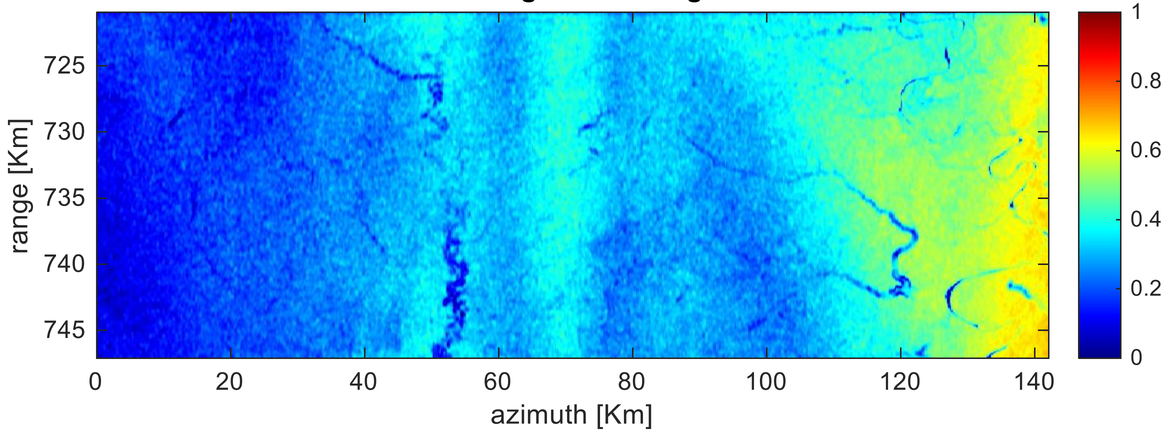
Real data – Amazonia

Geometrical coregistration and phase flattening

Phase [rad] - Original data

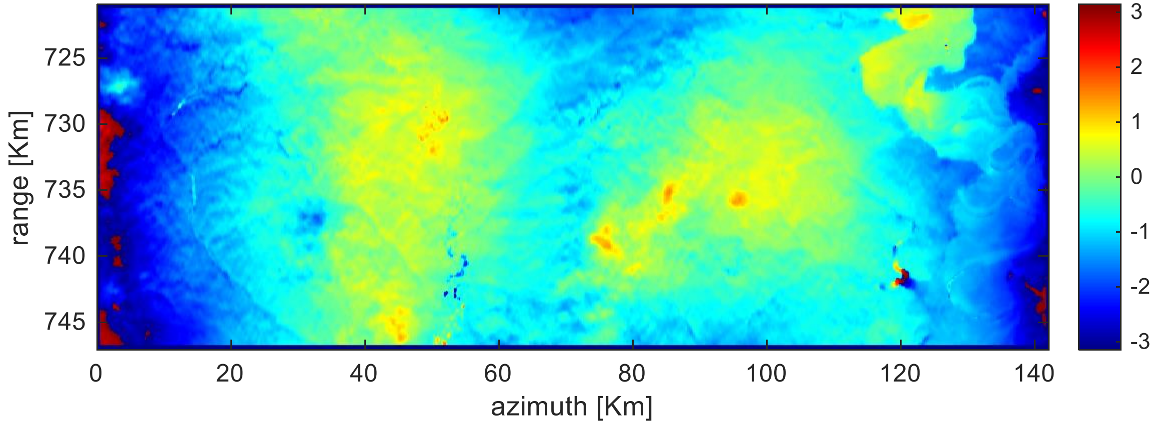


Coherence magnitude - Original data

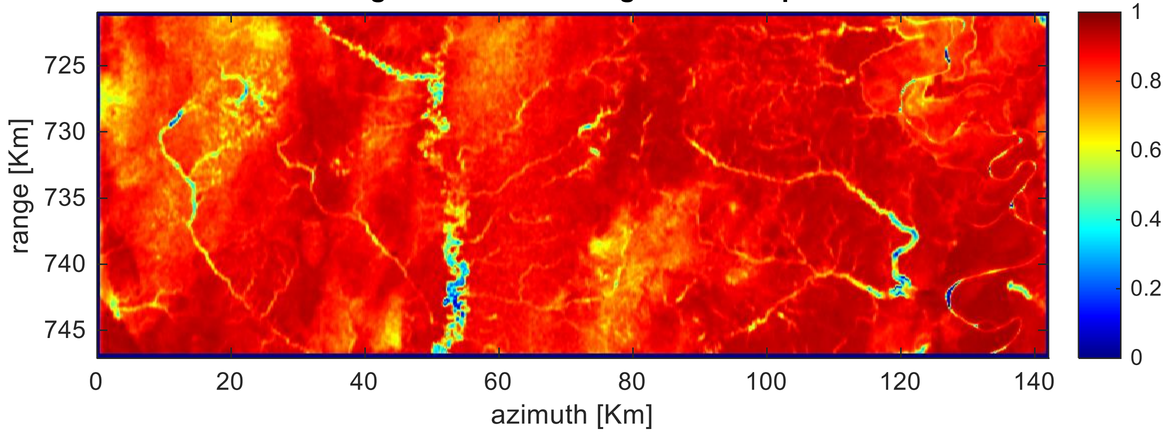


Data-based coregistration

Phase [rad] - Fine coregistration & plane removal



Coherence magnitude - Fine coregistration & plane removal

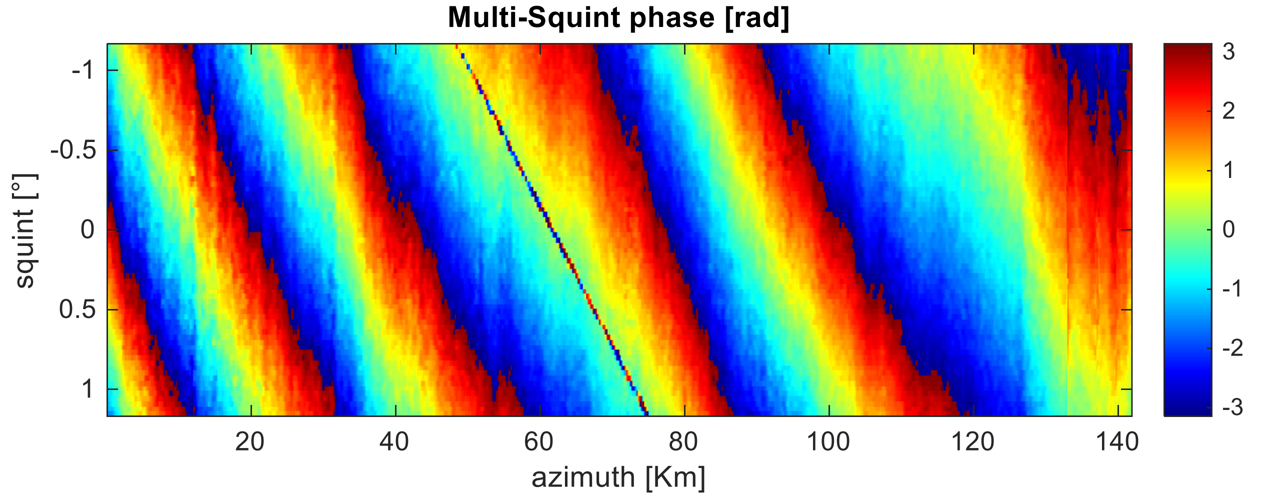


Coherence is very well restored by data-based coregistration

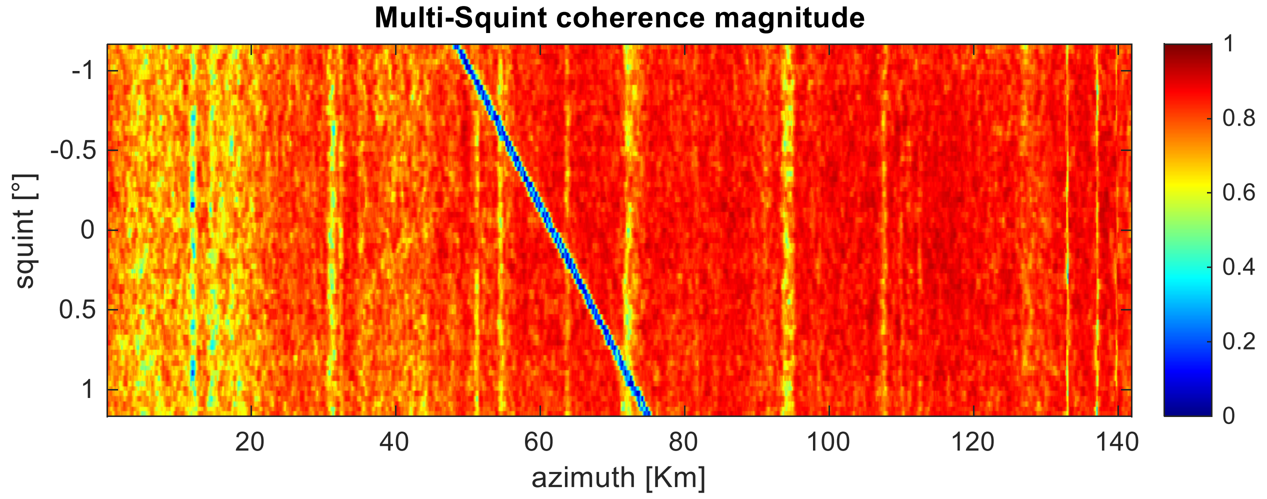
Real data – Amazonia

MS-InSAR:

- Subaperture res = 300 m
- 250 m range average
- 600 m azimuth average
- Run after range-only adaptive coregistration



- ☺ Coherence is rather high
- ☺ Phase shows typical ionospheric slope signature
- Consistent with an effective ionospheric range of 330 Km
- The diagonal line comes from an RFI



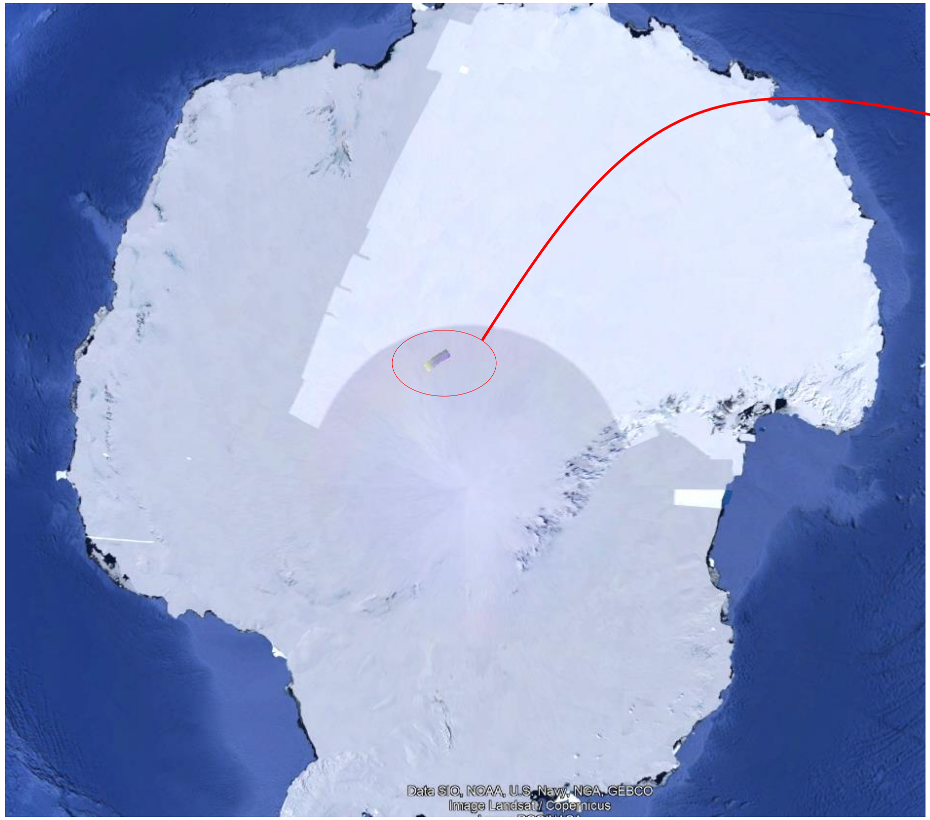
Real data – Antarctica

2-pass ascending stack

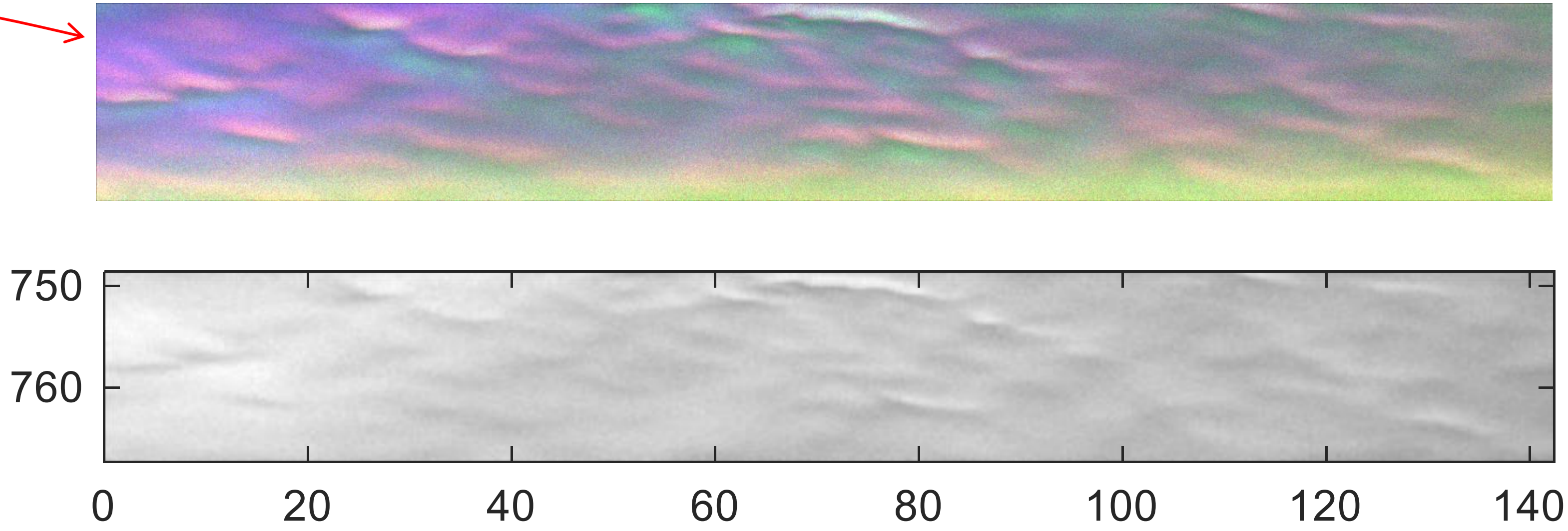
Hoa_12 = 1450 m

'BIO_S1_SCS__1S_20250607T082644_20250607T082705_C_G___M___C___T____F231_01_D9V1US'

'BIO_S1_SCS__1S_20250610T082644_20250610T082705_C_G___M___C___T____F231_01_DA0MTC'

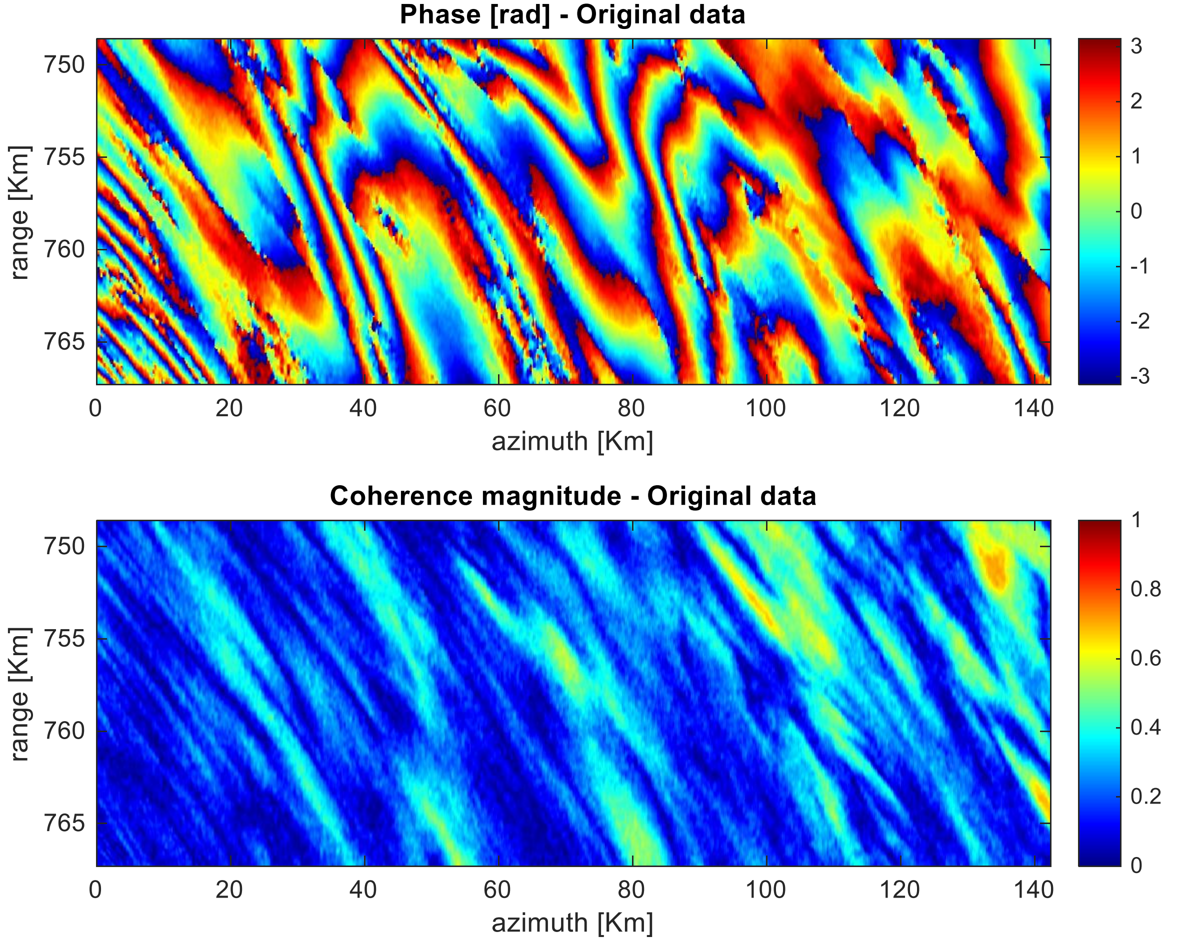


Data amplitude

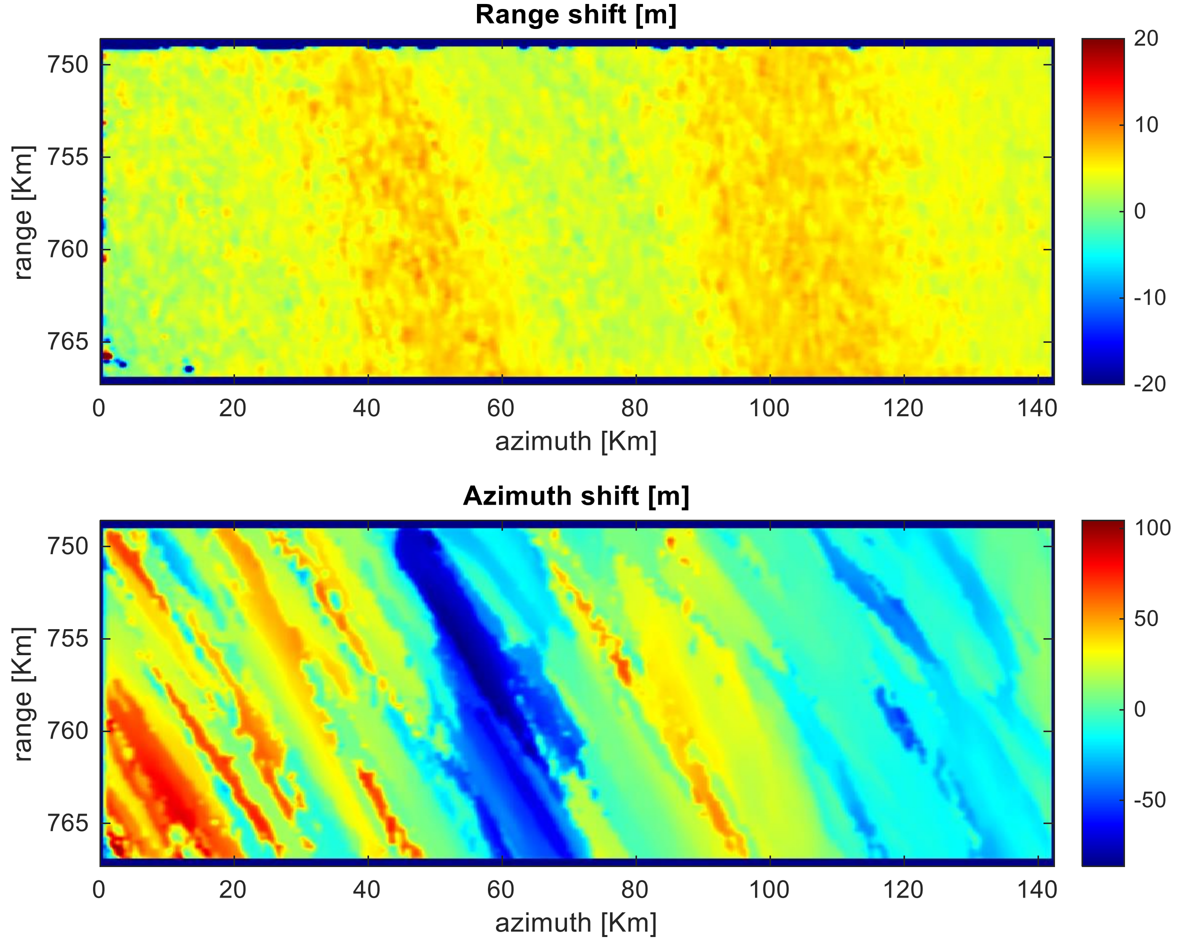


Real data – Antarctica

Geometrical coregistration and phase flattening

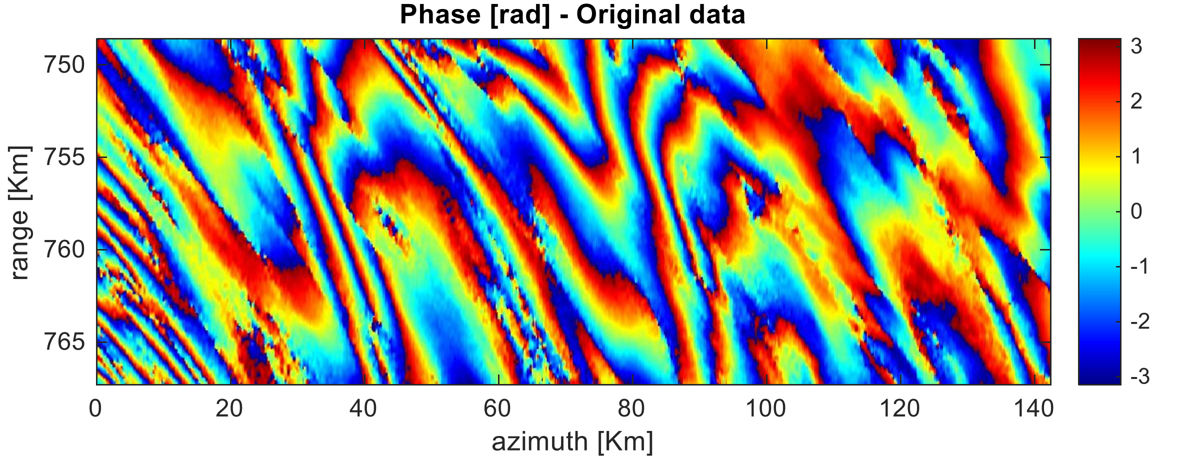


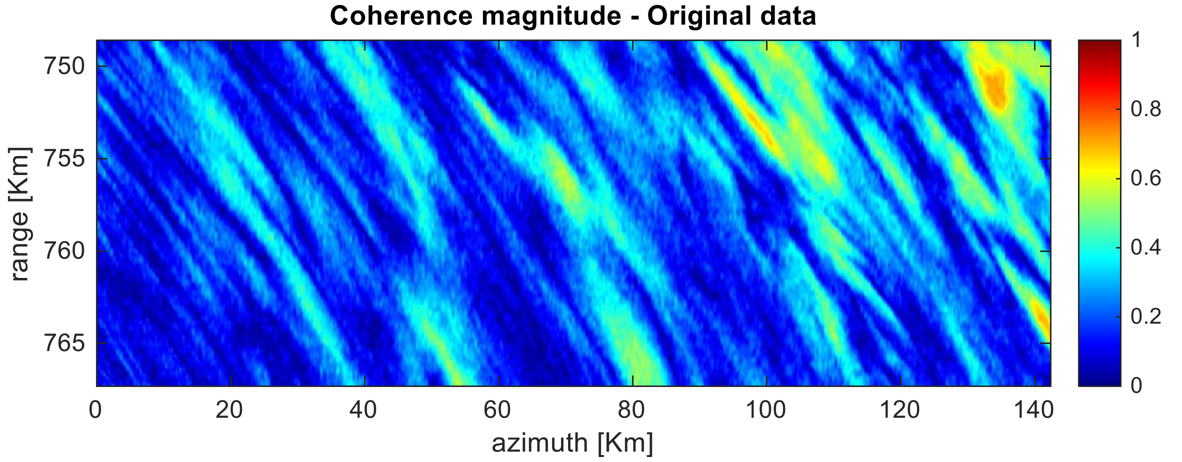
Estimated range and azimuth shifts



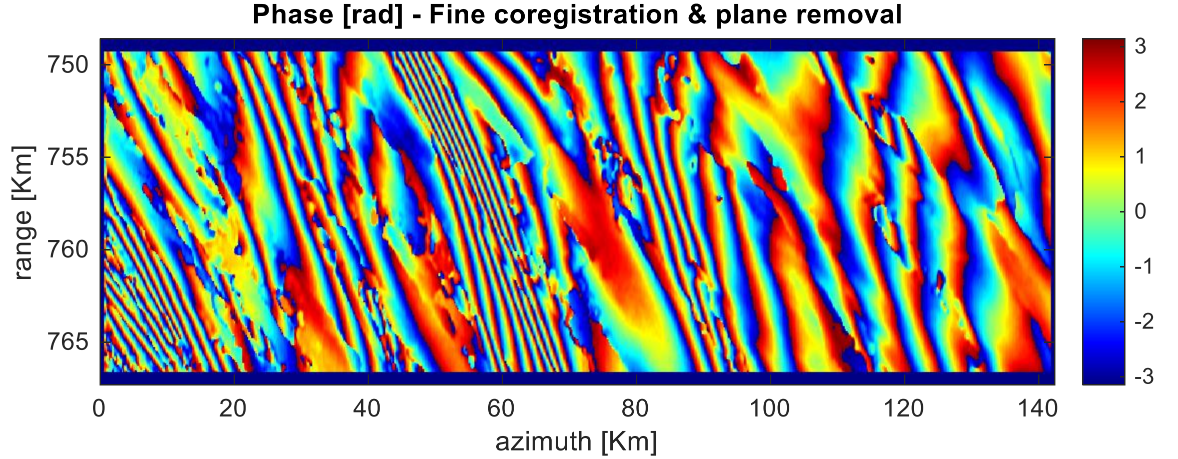
Real data – Antarctica

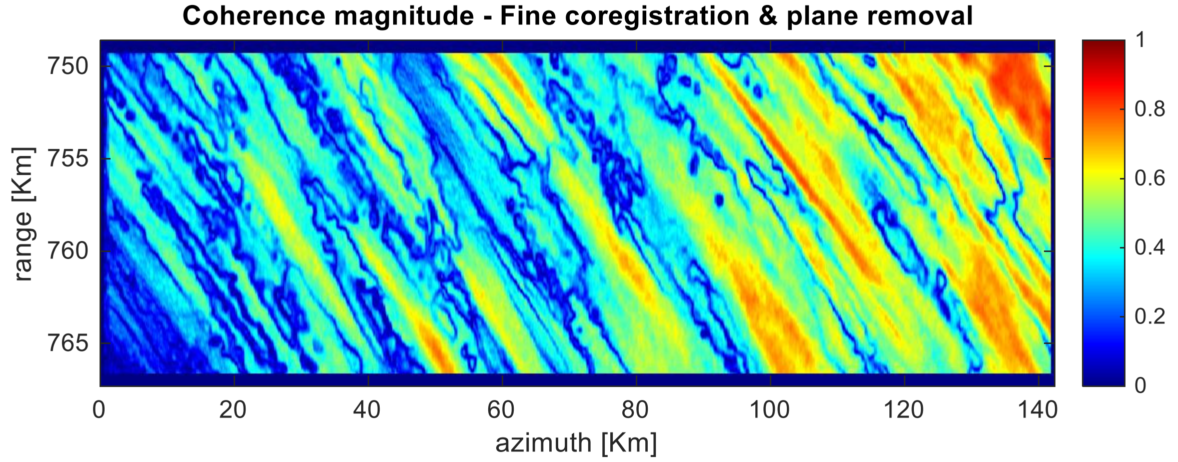
Geometrical coregistration and phase flattening





Data-based coregistration





Data-based coregistration leads nowhere here

Real data – Antarctica

MS-InSAR:

- Subaperture res = 300 m
- 250 m range average
- 600 m azimuth average
- Run after range-only adaptive coregistration

☺ Coherence is rather high

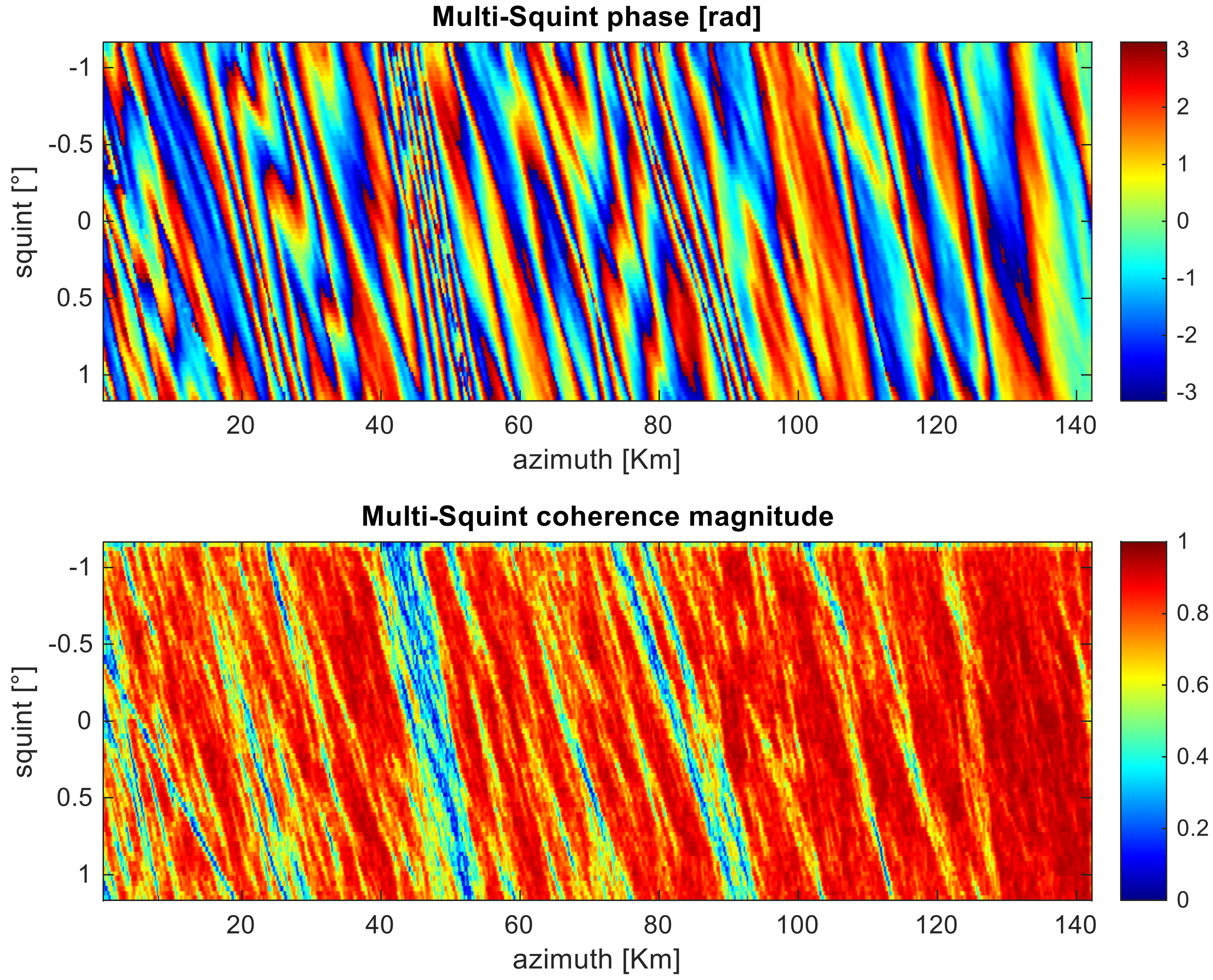
☺ No artefact detected

☺ Phase shows typical ionospheric slope signature

⇒ Instrument is OK

⇒ Ice here is very coherent

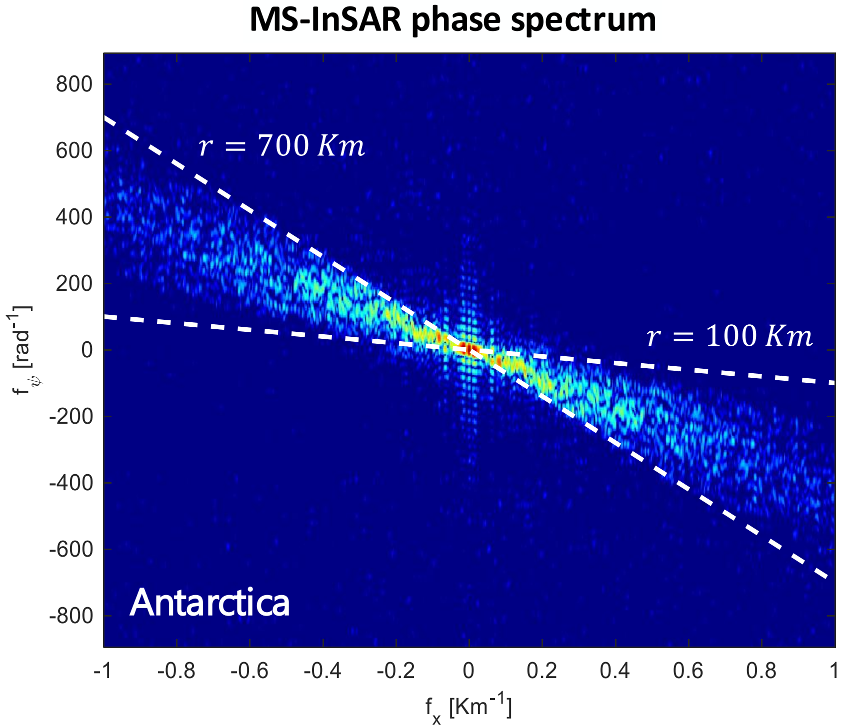
⇒ Coherence loss is due to ionosphere

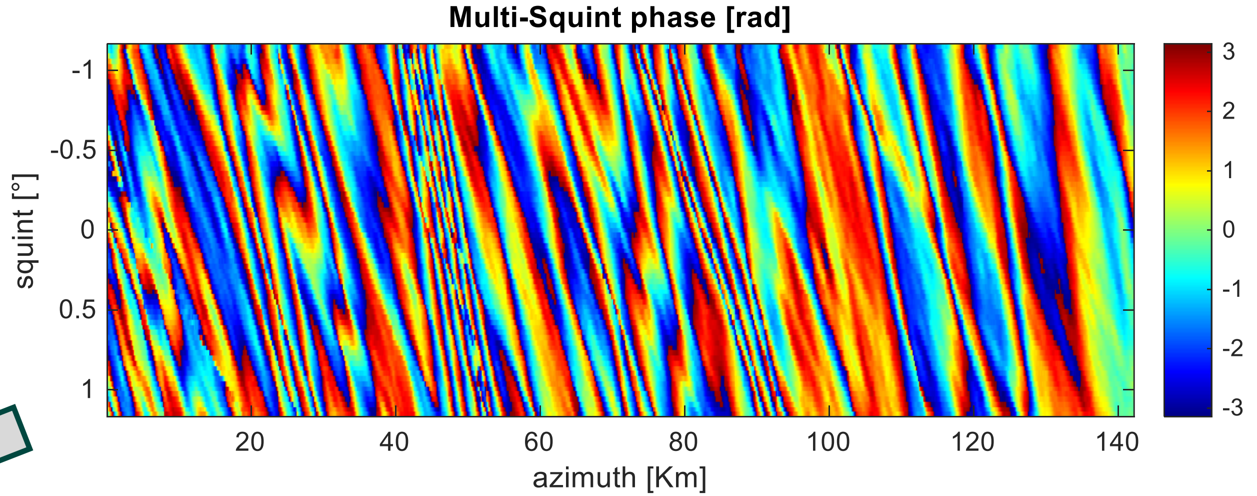


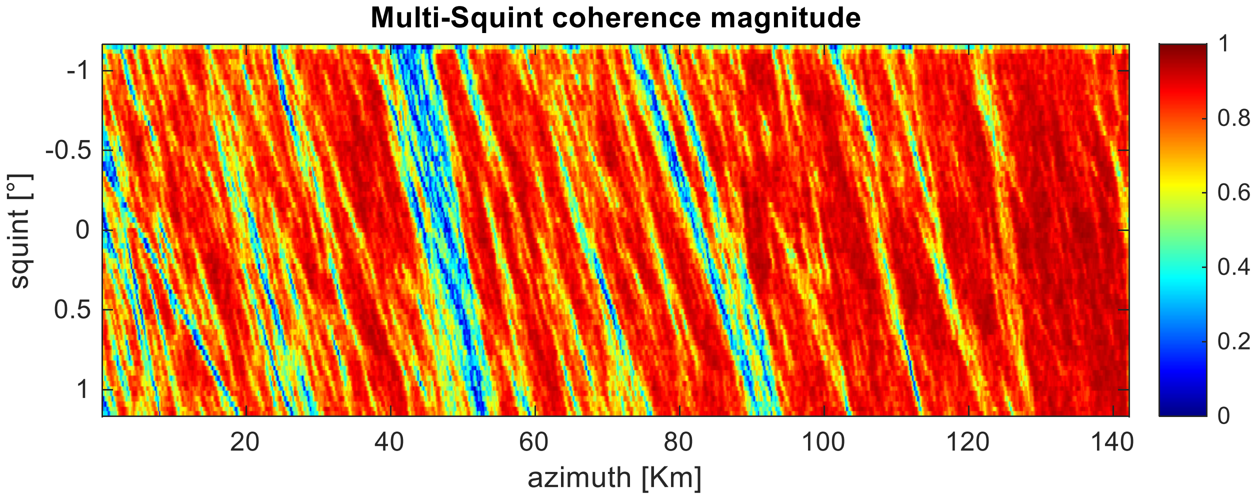
Real data – Antarctica

MS-InSAR:

The observed MS-InSAR phase shows here a complex structure characterized by different slopes, consistently with a vertical stratification with several layers between the ground and the satellite's orbit







Real data – Antarctica

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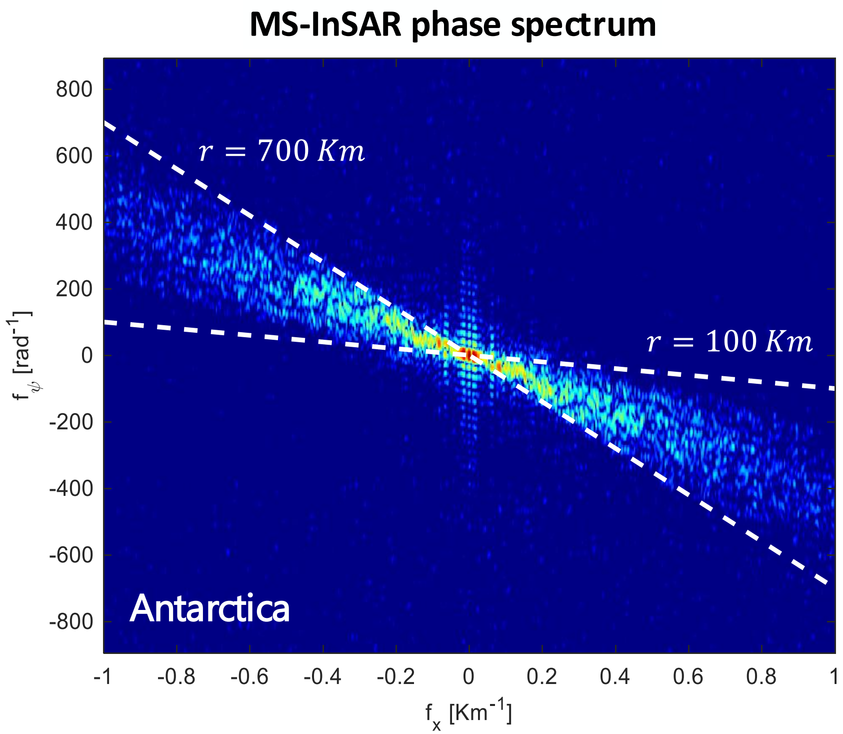
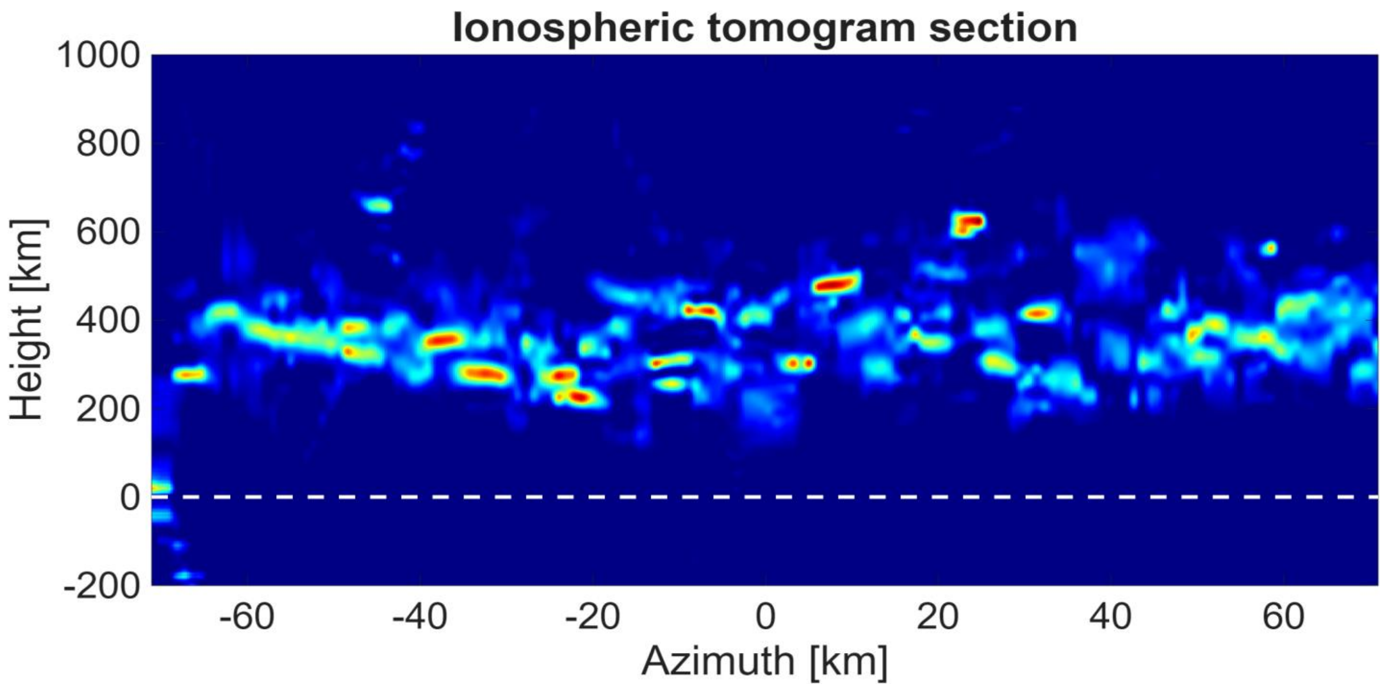
MS-InSAR:

The observed MS-InSAR phase shows here a complex structure characterized by different slopes, consistently with a vertical stratification with several layers between the ground and the satellite's orbit

This indicates the possibility to obtain a 3D representation of the ionospheric structure at an unprecedented resolution (in progress…)





Need for a new paradigm

Early InSAR results clearly called for the development of a new paradigm for estimating and correcting ionospheric propagation

Two key aspects:

- **Inversion**: new inversion algorithms required to estimate phase advances at multiple layers based on the observed MS-InSAR phase
- **Correction**: new correction algorithms required to restore decorrelation caused by multi-layer ionospheric propagation

In the development, we require the correction to be **transparent** ⇔ it does not have to involve any degradation w.r.t. adaptive coregistration

Multi-layer phase inversion

Ionospheric phase inversion is implemented as an iterative procedure that fits an arbitrary multi-layer model to minimize the residual w.r.t. the observed MS-InSAR phase

$$\phi_{ms}(r,x,\psi) = \sum_{k=0}^{N} \phi_k(r, x - r_k\psi) \Longrightarrow \hat{\phi}_k(r,x)$$

Observation

Model = target + N ionospheric layers

Estimate = Ionospheric phase at each layer & Target phase

The algorithm works directly on complex coherences, hence **no phase unwrapping** required

Conceptually similar to Phase Linking:

- The phase of one layer is estimated assuming that all the others are known and subtracted from the observation
- The procedure is iterated until the phase residual is conveniently small

Warning: solution is not unique!

Non-uniqueness of the solution

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BIOMASS's capability to resolve any two layers is easily understood in the Fourier domain, where layers appear as lines with thickness given by the inverse of the angular span $\Delta\psi$

$\Rightarrow$ The possibility to resolve any two layers is inherently a function of the spatial bandwidth of the ionospheric signal

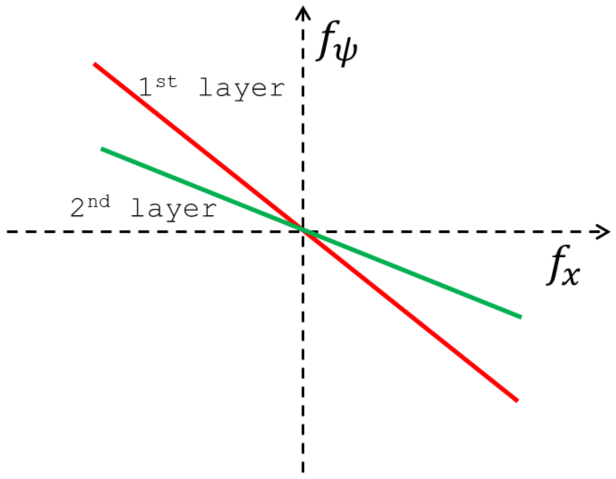
- High frequencies $\Leftrightarrow$ high sensitivity to layering
- Low frequencies $\Leftrightarrow$ poor sensitivity to layering

For the case of BIOMASS the available aperture in focused images is about 2.3°, which translates into a sensitivity to ionospheric range of approximately 50 Km for a decorrelation length of 1 Km

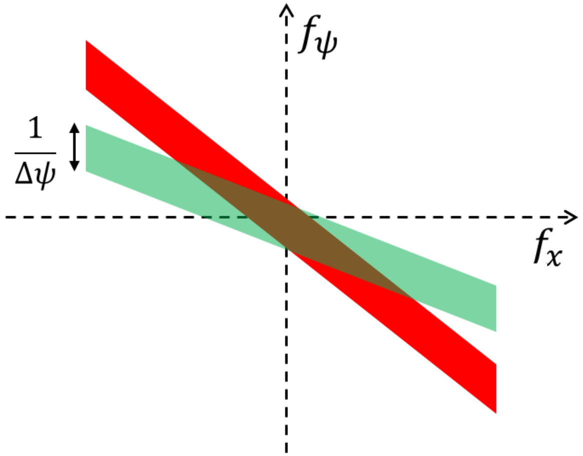
Note that the geophysical phase is equivalent to a layer at the surface level

$\Rightarrow$ **Intrinsic ambiguity** between slowly-varying components of the geophysical phase with lower ionospheric layers

MS-InSAR phase spectrum – ideal



MS-InSAR phase spectrum – accounting for resolution



Multi-layer correction

Multi-layer correction is implemented by **Sub-band refocusing**

Rationale: if sub-images are not sub-sampled, the full original image can always be obtained as:

$$I(r,x) = \sum_{k} I_{sub}(r,x,\psi_k)$$

- Sub-images were observed to preserve coherence @300 m resolution, implying that decorrelation at this scale is negligible

$\Rightarrow$ Coherence at full resolution can be restored by summing phase-corrected sub-images

$$I_{corr}(r,x) = \sum_{k} I_{sub}(r,x,\psi_k) \cdot e^{-j\hat{\phi}_{iono}(r,x,\psi_k)}$$

With $\hat{\phi}_{iono}$ the **estimated** ionospheric phase

Results – Amazonia, short baseline

3-pass descending stack

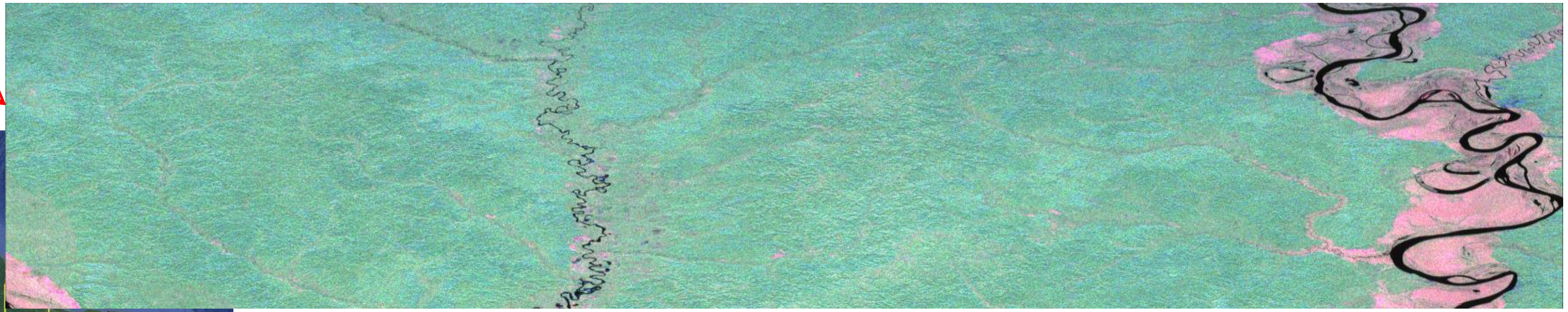
Hoa_12 = 600 m

Hoa_13 = 780 m

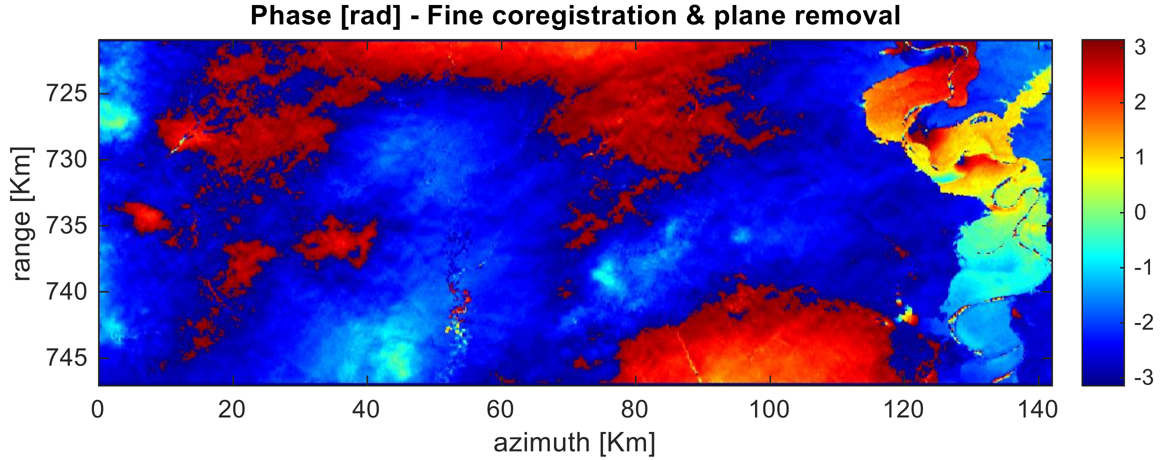
Hoa_23 = 2500 m

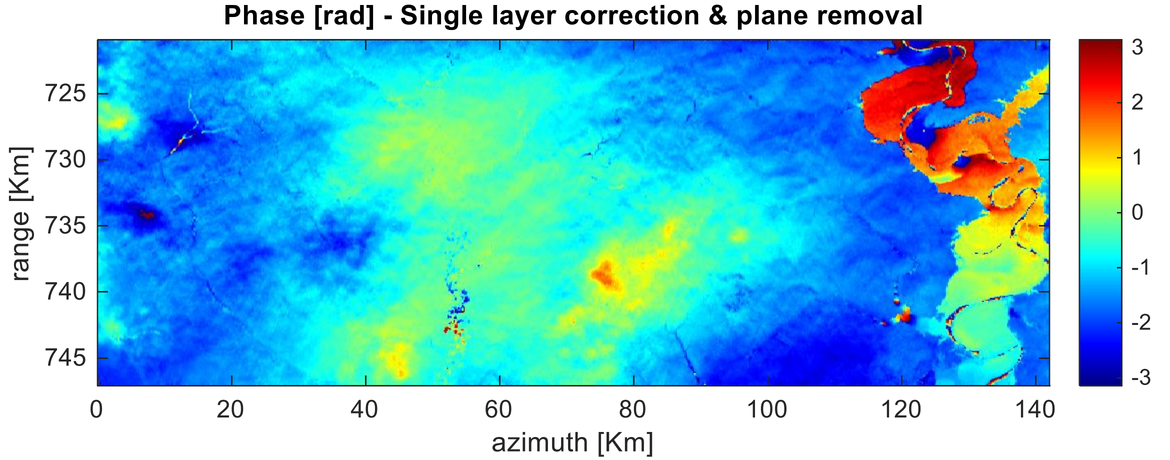
'BIO_S1_STA__1S_20250607T224654_20250607T224715_C_G___M___C___T____F157_01_DA3R7X'
'BIO_S1_STA__1S_20250610T224654_20250610T224714_C_G___M___C___T____F157_01_DA3R89'
'BIO_S1_SCS__1S_20250613T224654_20250613T224714_C_G___M___C___T____F157_01_DA7ELM '

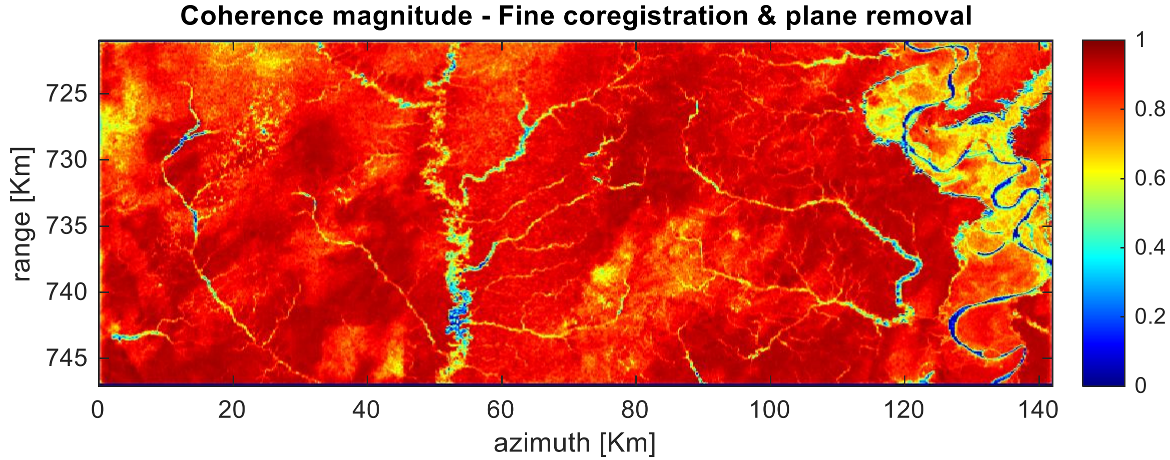
Data amplitude

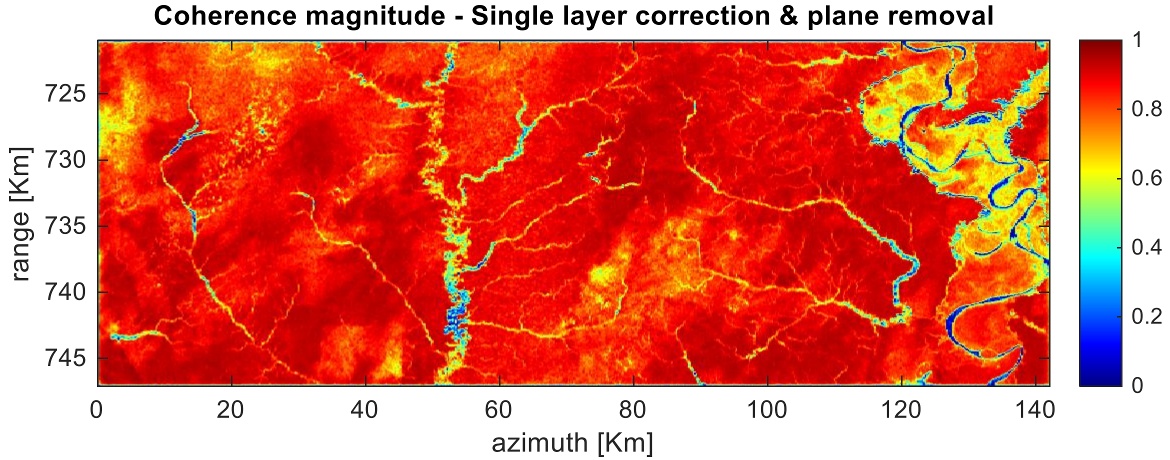


Results – Amazonia, short baseline









Results – Amazonia, long baseline

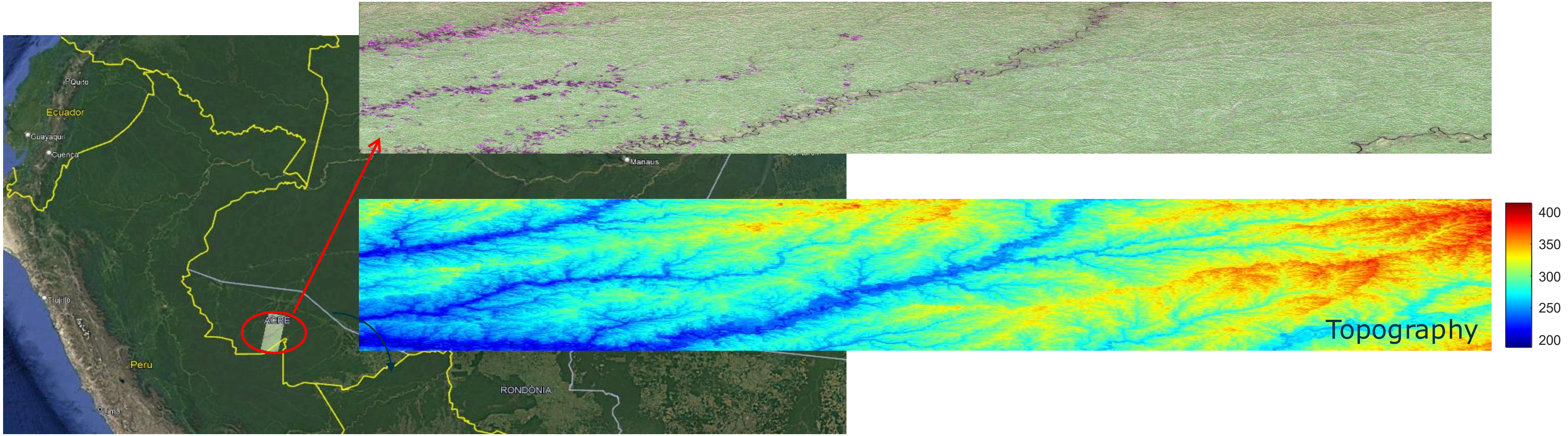
7-pass descending stack

Topographic scene

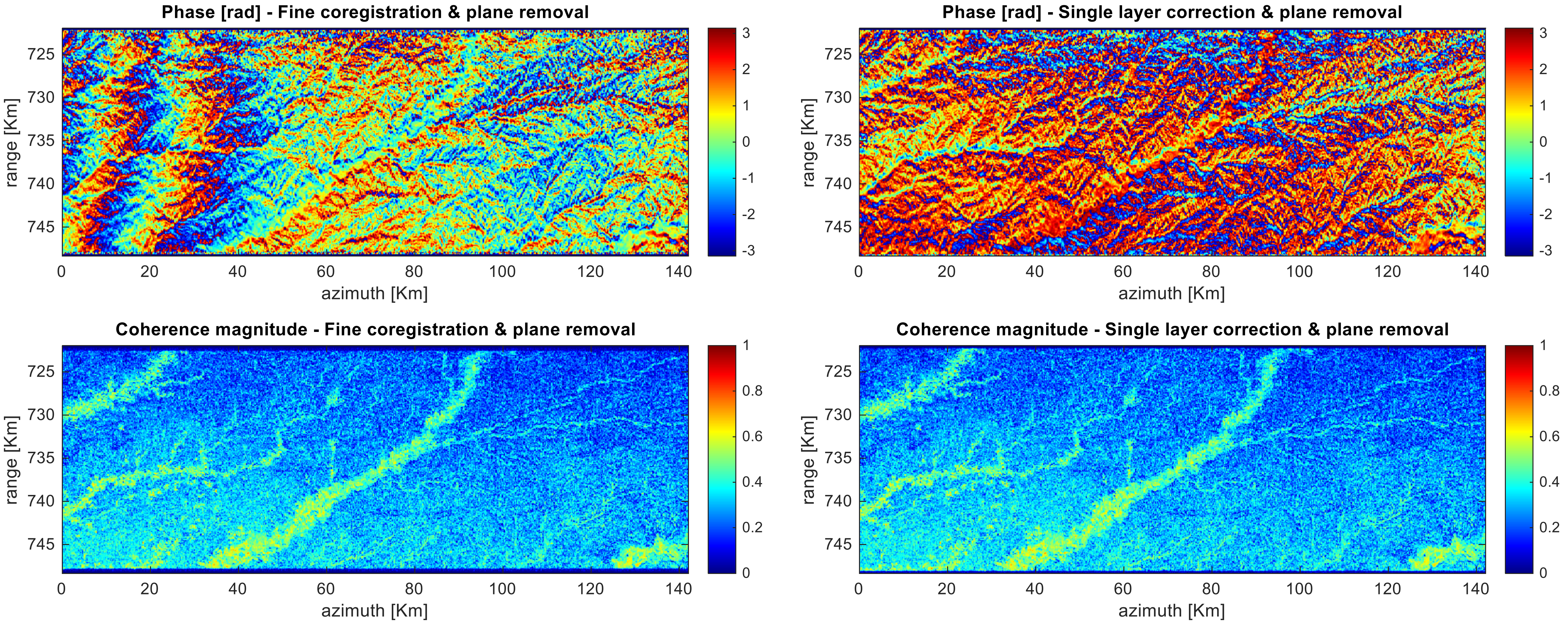
Hoa_57 = 70 m (minimum value for this stack)

'BIO_S1_SCS__1S_20250604T224847_20250604T224908_C_G___M___C___T____F163_01_D9SH21'
'BIO_S1_SCS__1S_20250607T224848_20250607T224909_C_G___M___C___T____F163_01_D9WHL4'
'BIO_S1_SCS__1S_20250610T224848_20250610T224908_C_G___M___C___T____F163_01_DA1X2X'
'BIO_S1_SCS__1S_20250613T224848_20250613T224908_C_G___M___C___T____F163_01_DA7ER4'
'BIO_S1_SCS__1S_20250616T224846_20250616T224907_C_G___M___C___T____F163_01_DACYK7'
'BIO_S1_SCS__1S_20250619T224848_20250619T224909_C_G___M___C___T____F163_01_DAII5M'
'BIO_S1_SCS__1S_20250622T224850_20250622T224911_C_G___M___C___T____F163_01_DAO1TC"

Data amplitude



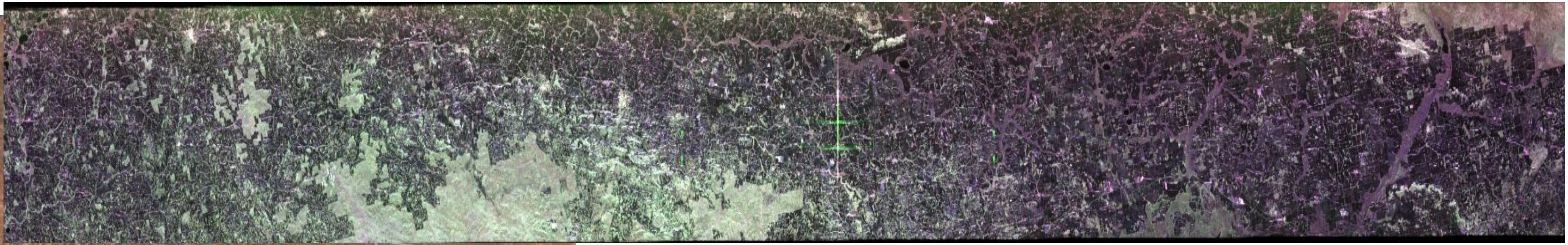
Results – Amazonia, long baseline

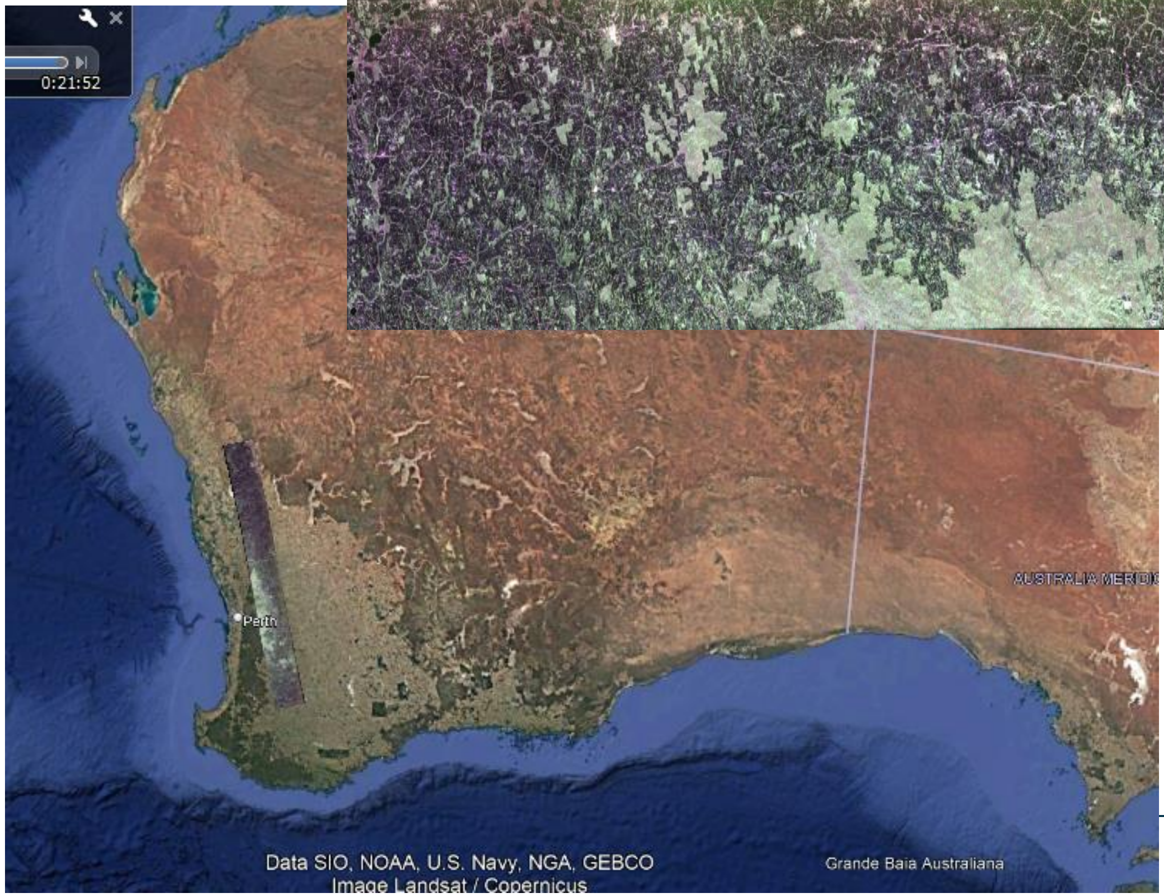


Results – Australia, BCT

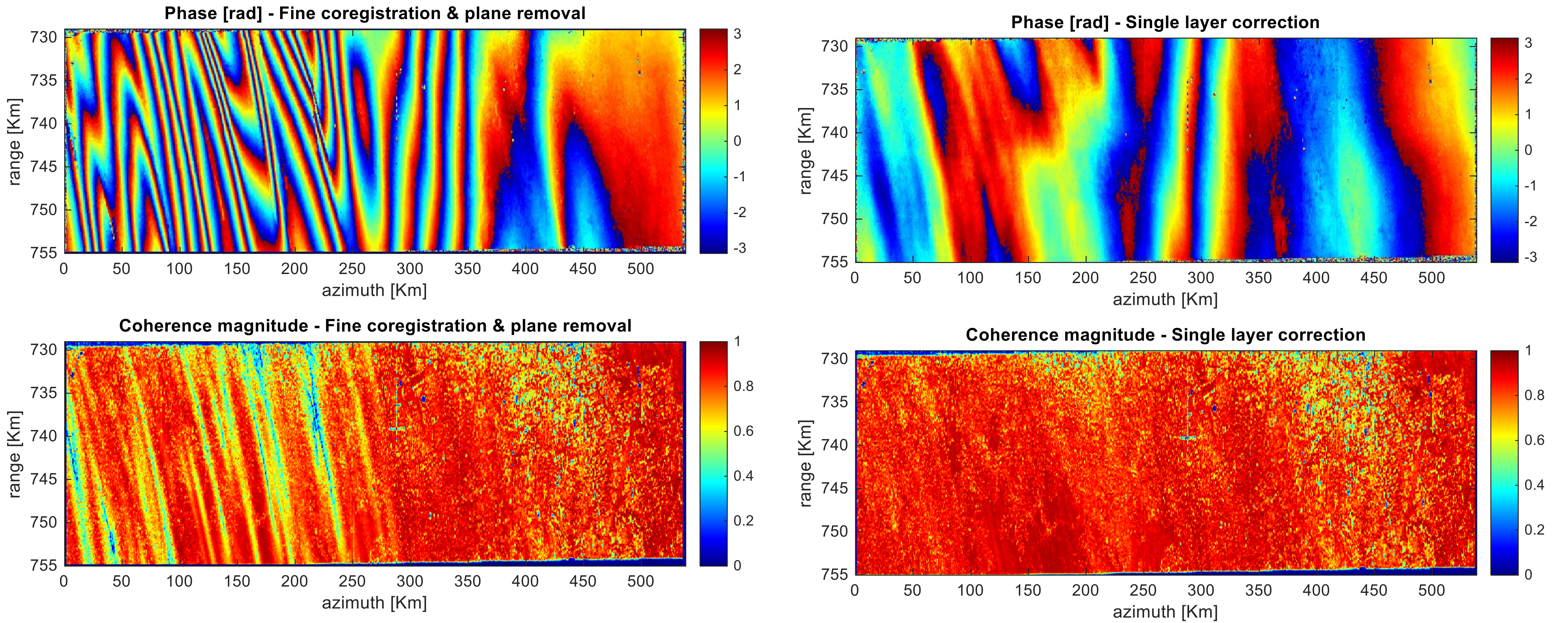
3-pass descending stack over the BCT

'BIO_S1_SCS__1S_20250530T222113_20250530T222232_C_G___M___C___T____F001_01_DCP166'
'BIO_S1_SCS__1S_20250602T222113_20250602T222231_C_G___M___C___T____F001_01_DCP1V4'
'BIO_S1_SCS__1S_20250611T222053_20250611T222232_C_G___M___C___T____F001_01_DCPCFO'





Results – Australia, BCT



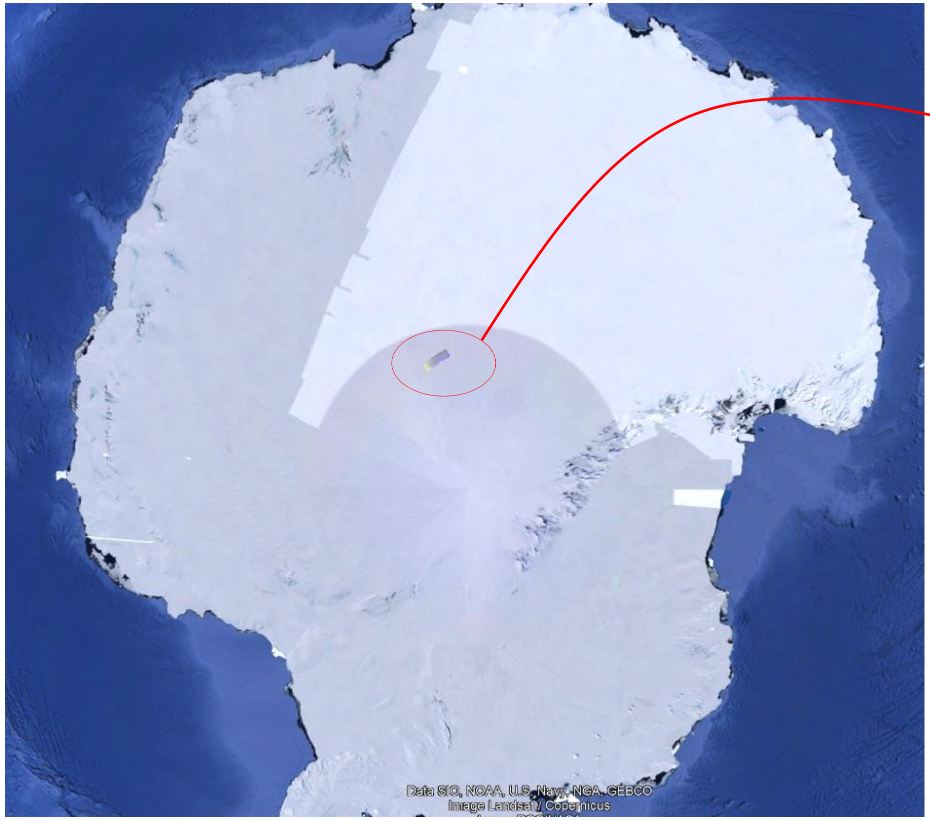
Results – Inner Antarctica

2-pass ascending stack

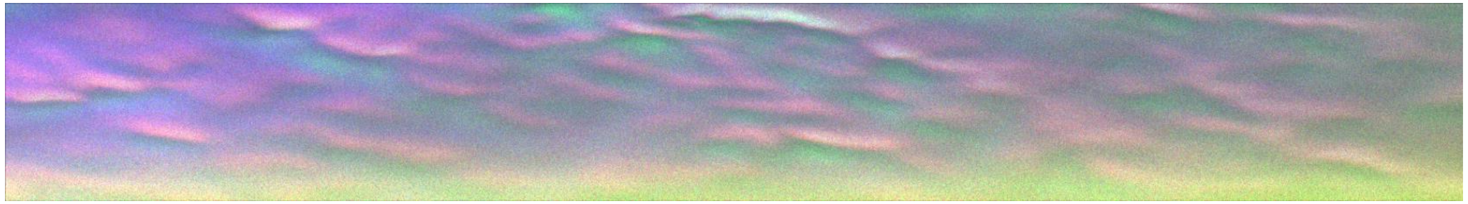
'BIO_S1_SCS__1S_20250607T082644_20250607T082705_C_G___M___C___T____F231_01_D9V1US'

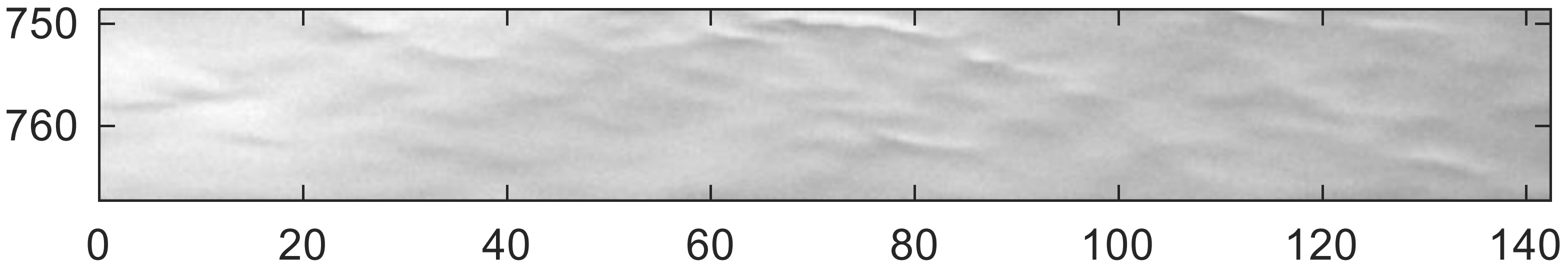
'BIO_S1_SCS__1S_20250610T082644_20250610T082705_C_G___M___C___T____F231_01_DA0MTC'

Hoa_12 = 1450 m



Data amplitude

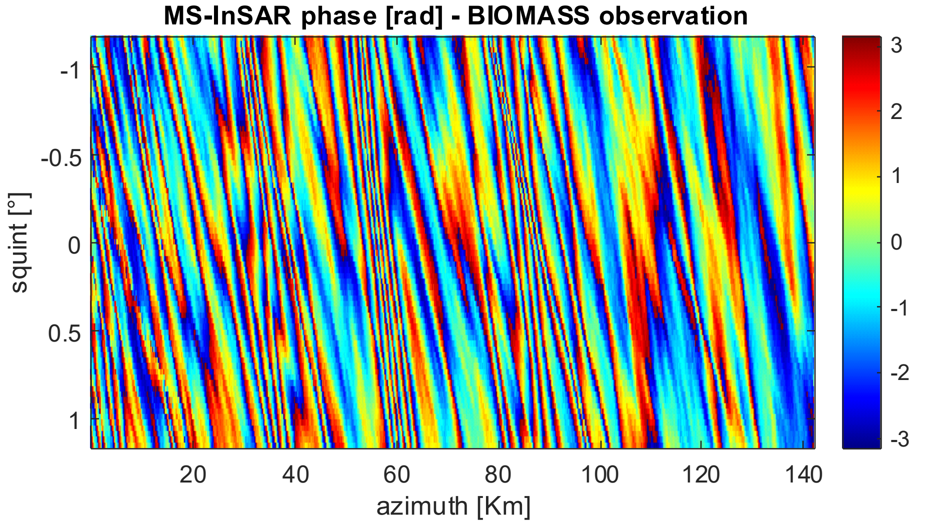


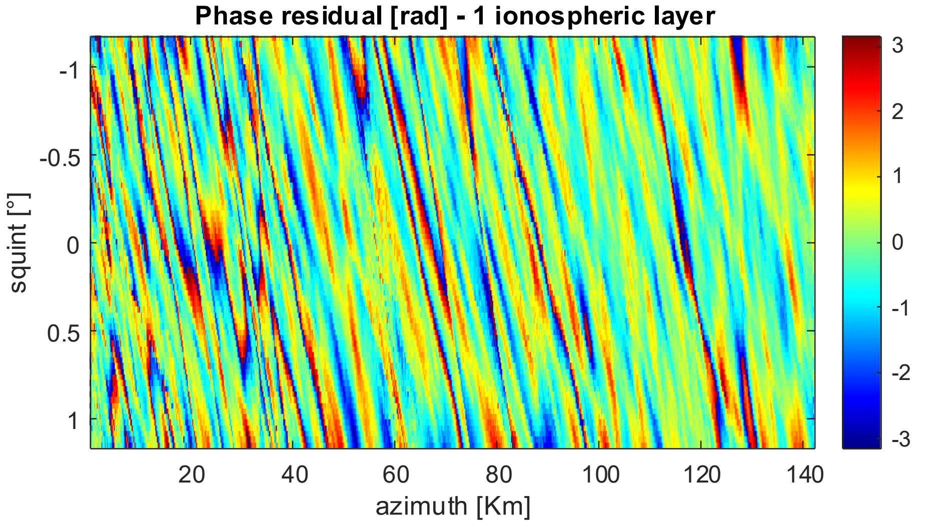


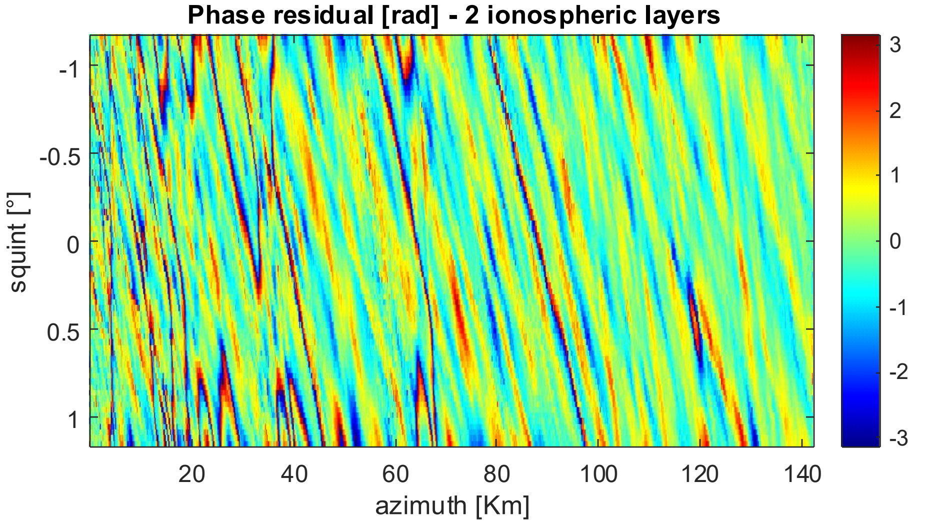
Results – Inner Antarctica

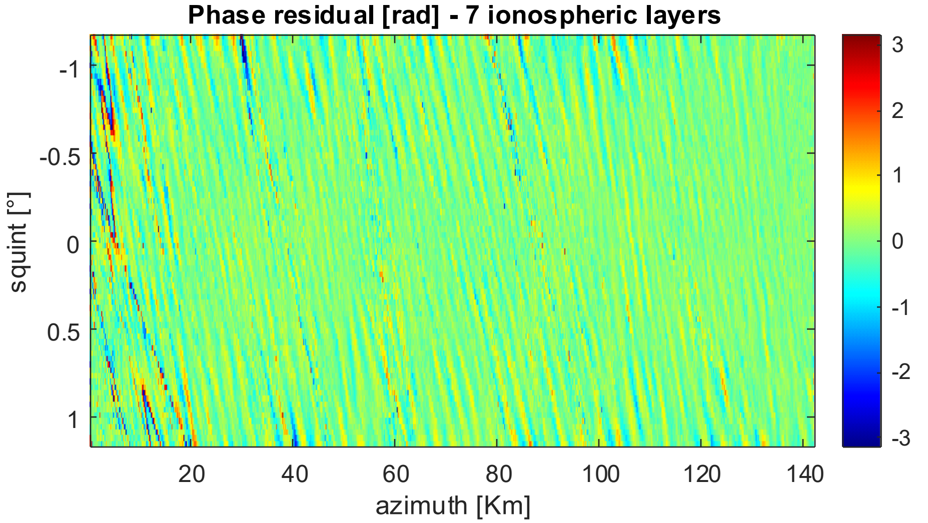
MS-InSAR

- Single-layer Ionospheric inversion provides poor representation of the observed MS-InSAR phase
- In this case, the observed phase can only be reproduced by assuming multiple layers

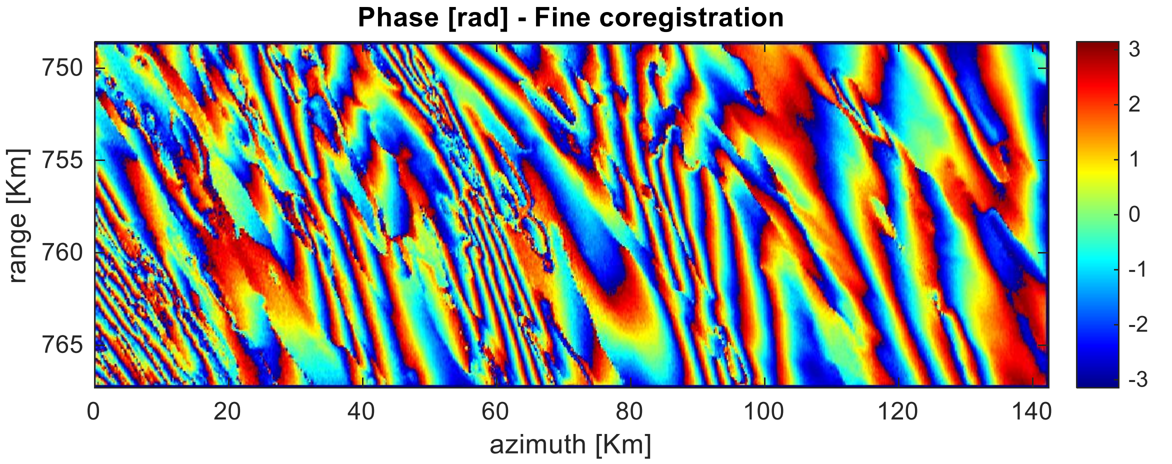


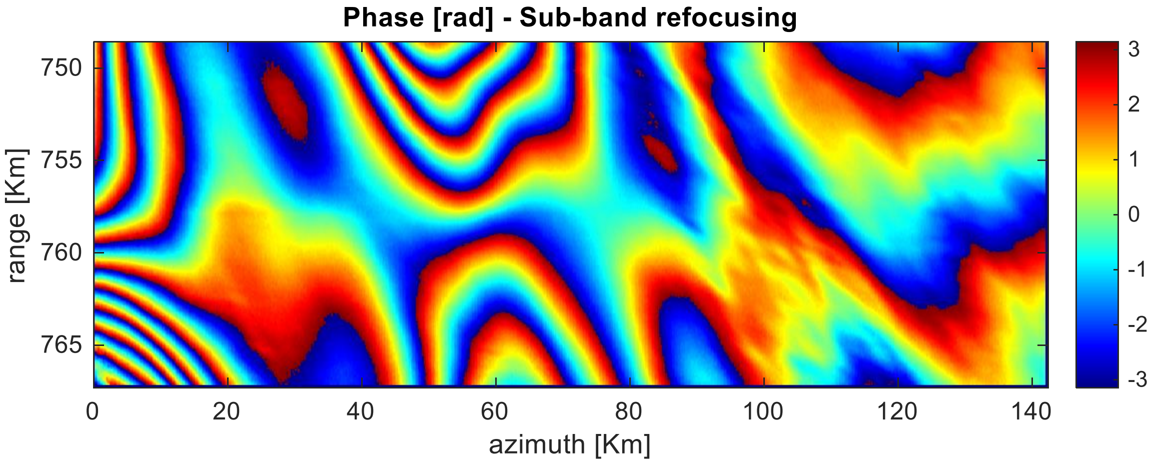


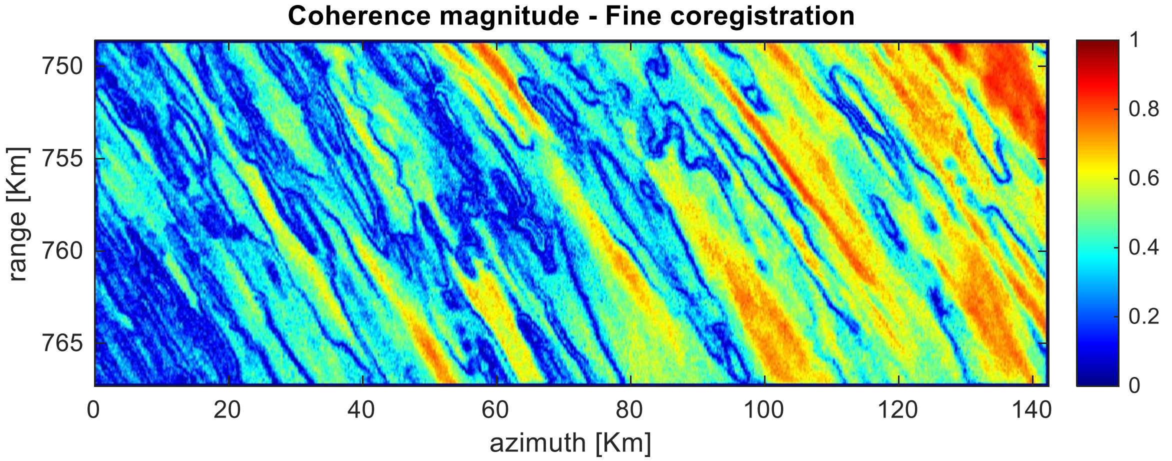


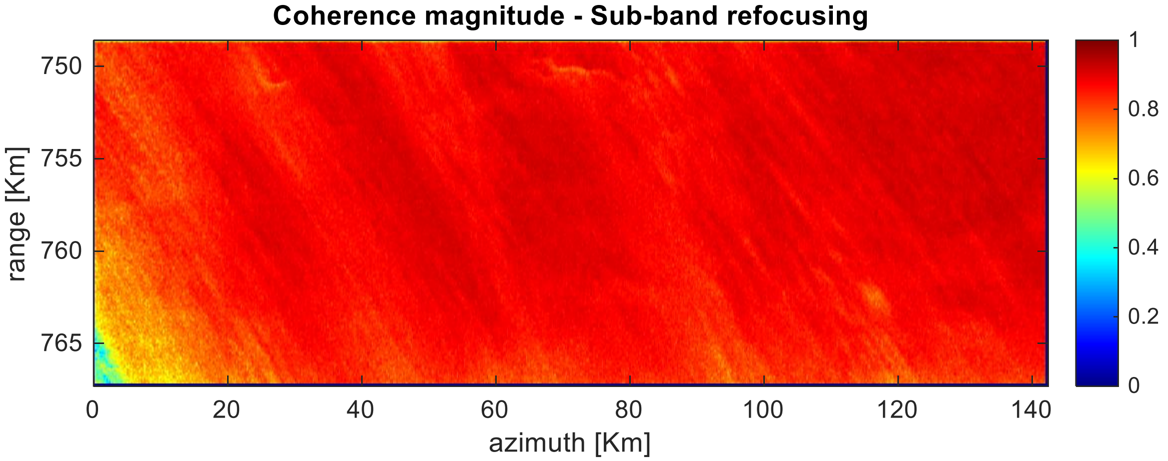


Results – Inner Antarctica



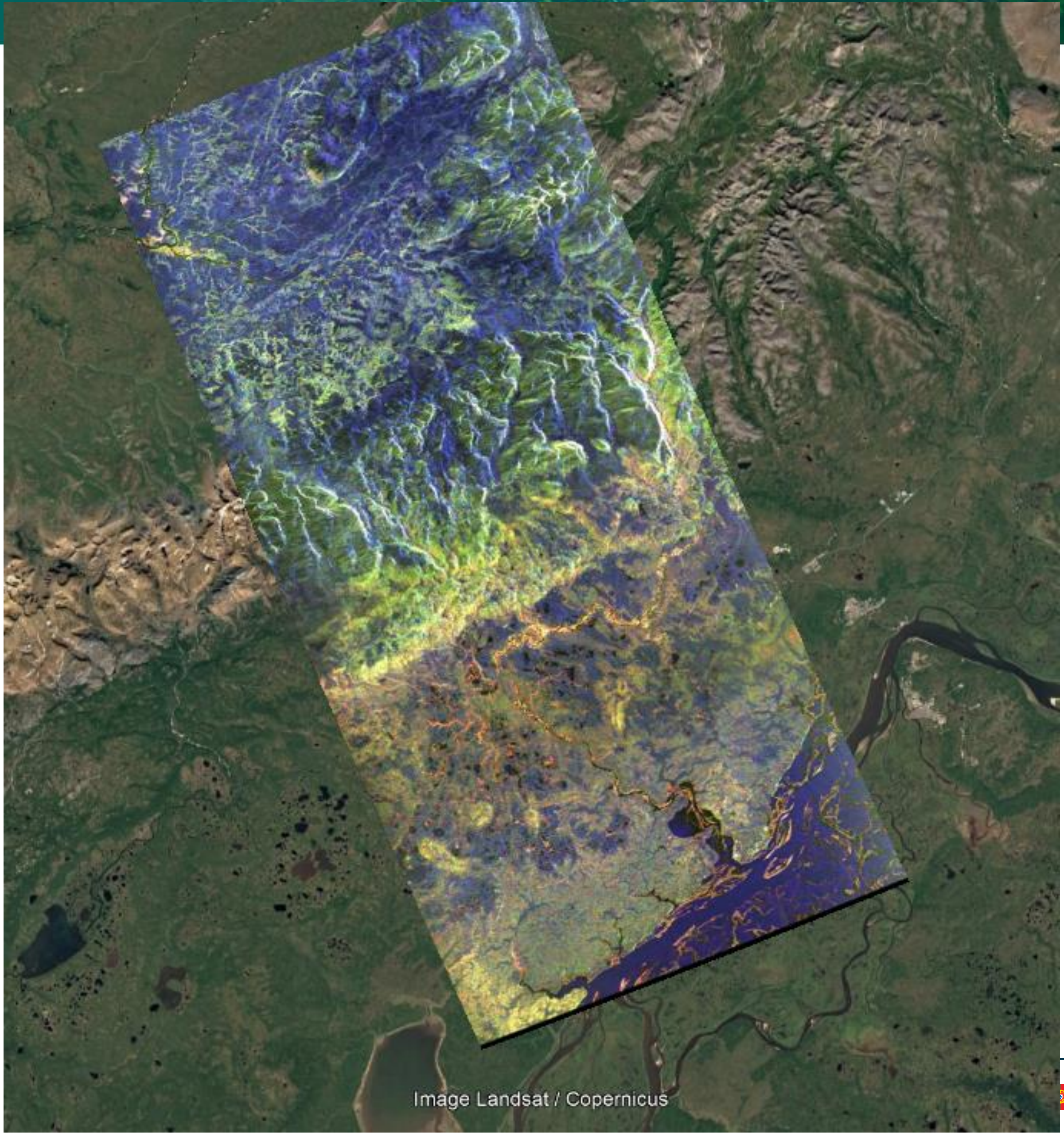






Corrected with 8 layers between 150 Km and 650 Km

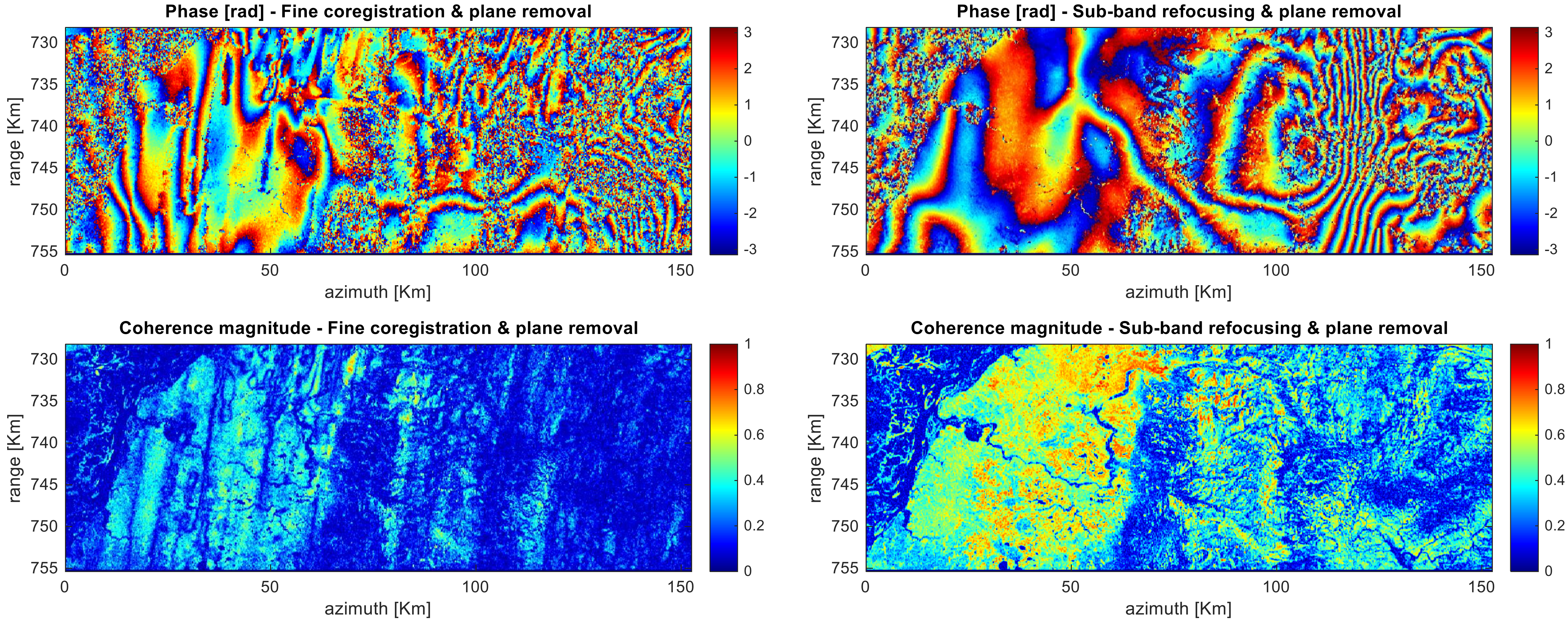
Results – Northern Russia



6-image stack:
'BIO_S1_STA__1S_20250607T235425_20250607T235445_C_G___M___C___T____F
060_01_DB5BQ6'
'BIO_S1_STA__1S_20250610T235424_20250610T235445_C_G___M___C___T____F
060_01_DB5BQW'
'BIO_S1_STA__1S_20250613T235424_20250613T235445_C_G___M___C___T____F
060_01_DB5BRO'
'BIO_S1_STA__1S_20250616T235423_20250616T235444_C_G___M___C___T____F
060_01_DB5BSI'
'BIO_S1_STA__1S_20250619T235425_20250619T235446_C_G___M___C___T____F
060_01_DB5BTB'
'BIO_S1_STA__1S_20250622T235427_20250622T235447_C_G___M___C___T____F
060_01_DB5BU4'

Features:
- Forests
- Swamps
- Topographic variations
- Ionosphere
- RFIs

Results – Northern Russia



Corrected with 5 layers between 100 Km and 550 Km

Summary

Ionospheric effects on BIOMASS InSAR are shown to be consistent with the assumption of a complex vertical structure of the ionospheric phase, with fast azimuth variations at Km or sub-Km scale at multiple layers between the ground and the satellite orbit

This triggered the development of new methods for treating multi-layer propagation in InSAR data, which turned out necessary to restore InSAR data quality in many cases

	Amazonia	Australia	Siberia	Antarctica
Data-based coregistration	OK	NO, coherence is not fully restored	NO, coherence is not restored at all	NO, coherence is not restored at all
Single-layer correction	OK, phase is smoother than with coregistration	OK	NO, coherence is not fully restored	NO, coherence is not restored
Multi-layer correction	OK (but overkill)	OK (a bit overkill)	OK	OK

Summary

The main open issues concerns **residual low-pass ionospheric fringes** – not so much of a problem for mild, single-layer ionosphere, but residual can be relevant in case of strong & multi-layer ionosphere.

MS-InSAR cannot solve the problem since it is mostly sensitive to high-frequency components.

No way out without a reliable prior

- Faraday Rotation
- Amplitude features
- Range dispersion
- External data

Luckily enough, most BIOMASS products are based on measuring the phase of the vegetation relative to the underlying terrain.

⇒ **Strongly** impacted by coherence losses, yet **not** impacted by the presence of residual low-pass fringes

⇒ MS-InSAR can already be used **operationally** for the generation of all mission products worldwide