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An along-track GEO-SAR MIMO twin formation

RIDE
RADAR IMAGING & DIGITAL EARTH

SPACE IT UP!

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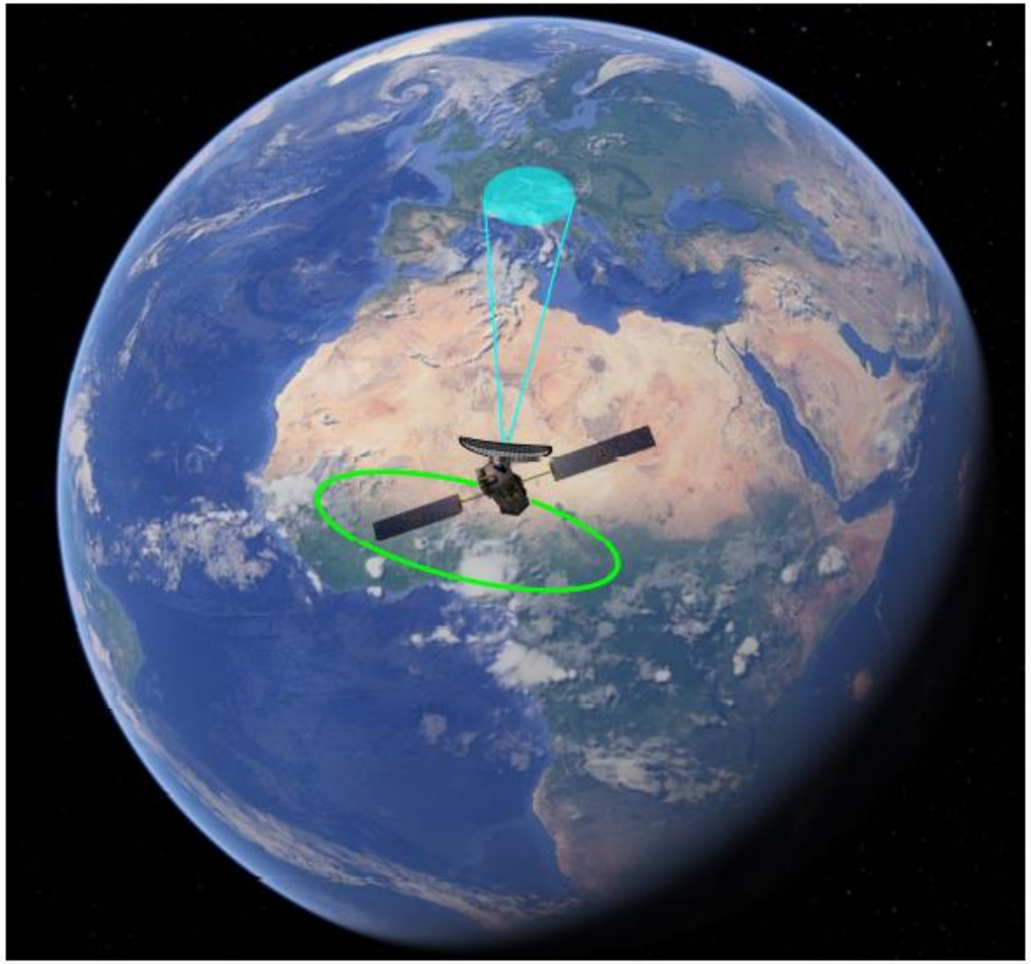
Contents

Introduction

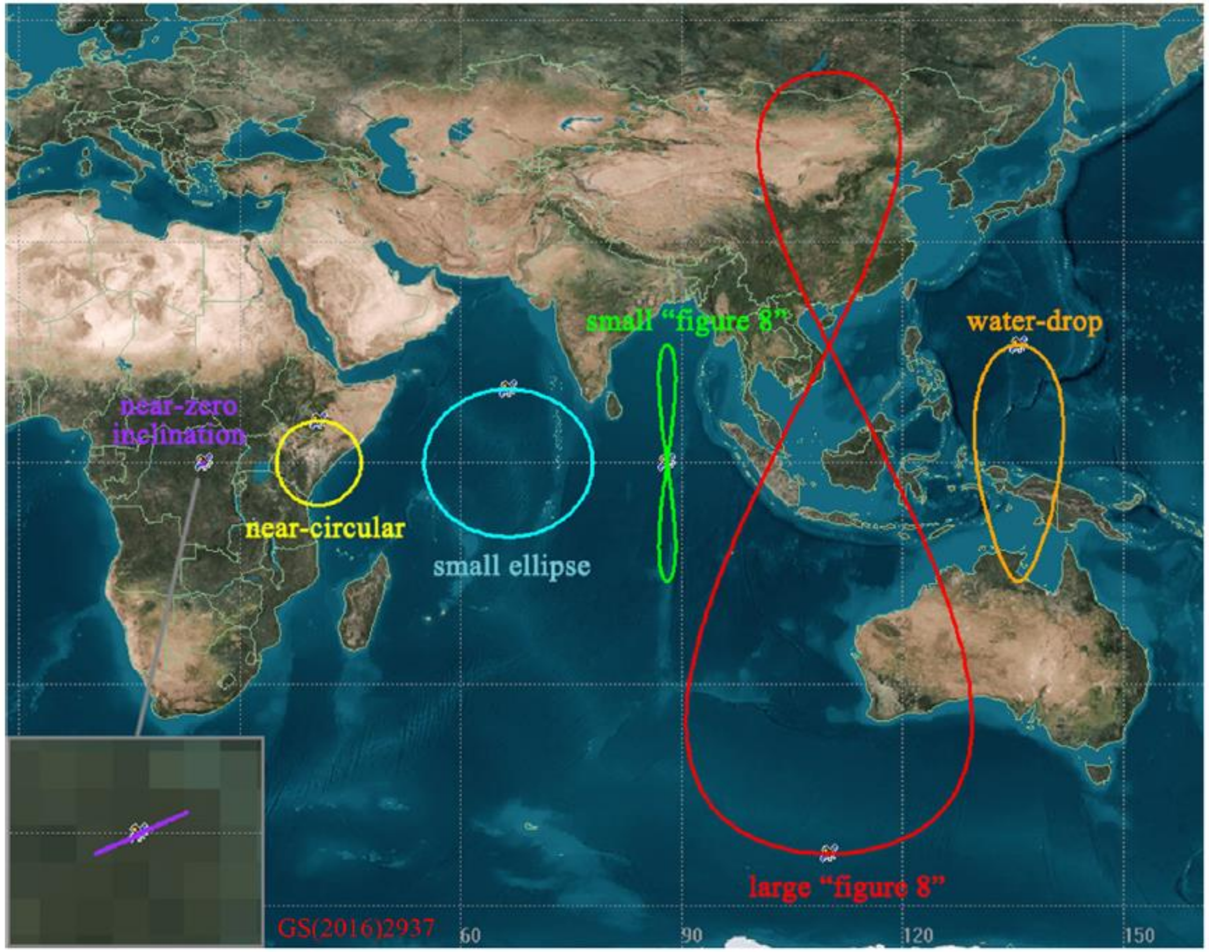
- Low Earth Orbit (LEO) SAR suffers from limited daily coverage. GEO-SAR enables **persistent, super-continental observation**.

- Near-Zero Inclination (NZI) geostationary orbits allow for **very-long integration times** (up to several hours). This compensates for high path losses (~37 000 km) without requiring massive antennas or excessive power.

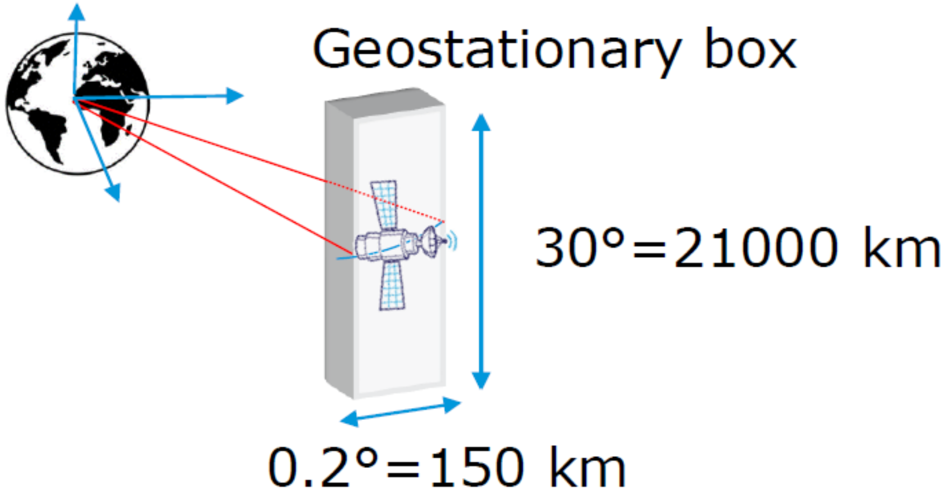
- The extended integration time makes the system highly sensitive to **spatio-temporal variations such as the atmospheric delay** (both troposphere and ionosphere).



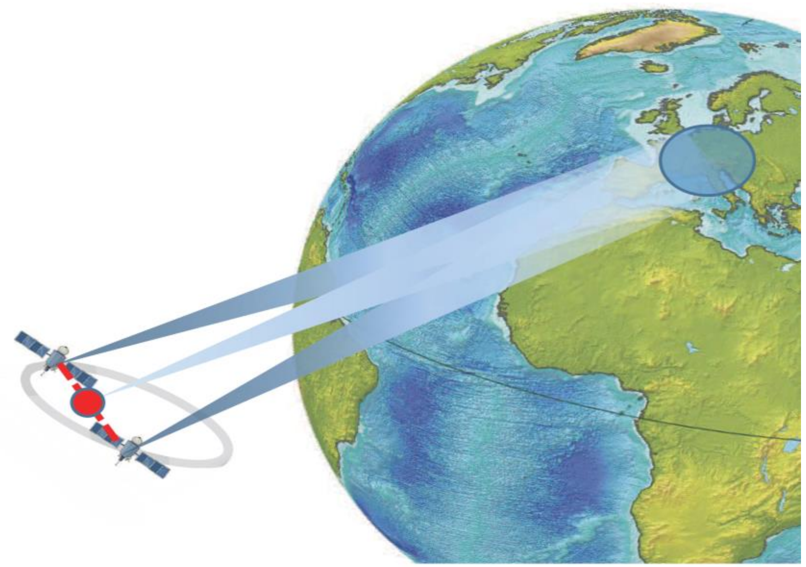
Introduction



- **Near Zero Inclination (NZI) GEO-SAR**
  - Nearly zero inclination and eccentricity
  - Regional coverage
  - Low relative velocity and long integration time
  - ITU regulation:
    - Longitude slot from $\pm 0.1°$ to $\pm 0.5°$

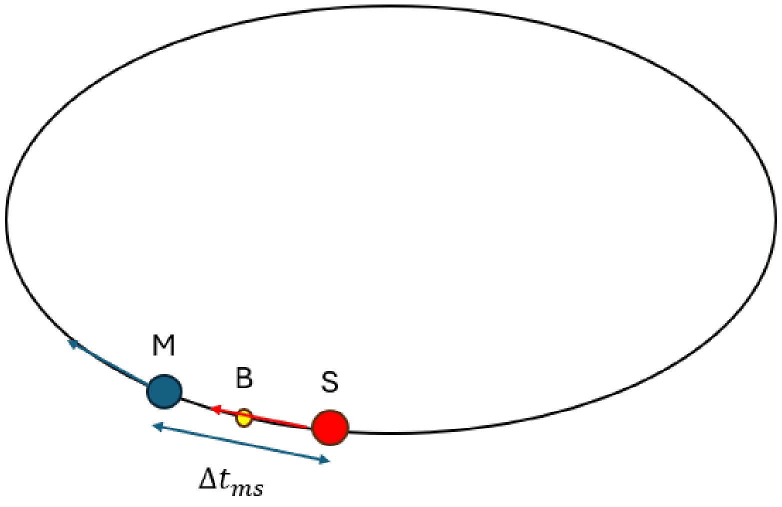


Mission concept



Two-Satellite Ku-band GEO-SAR MIMO Formation

- Ku-band provides **finer resolution** than C or X bands but faces severe decorrelation and higher power constraints.
- It **quadruples the Signal-to-Noise Ratio (SNR)** by leveraging the MIMO N^2 gain.
- **Short revisit** times guarantee **high coherence**, enabling multiple interferograms and solving decorrelation issues.
- Unlocks highly coherent, continuous monitoring for **near-real-time change detection**.



Mission requirements

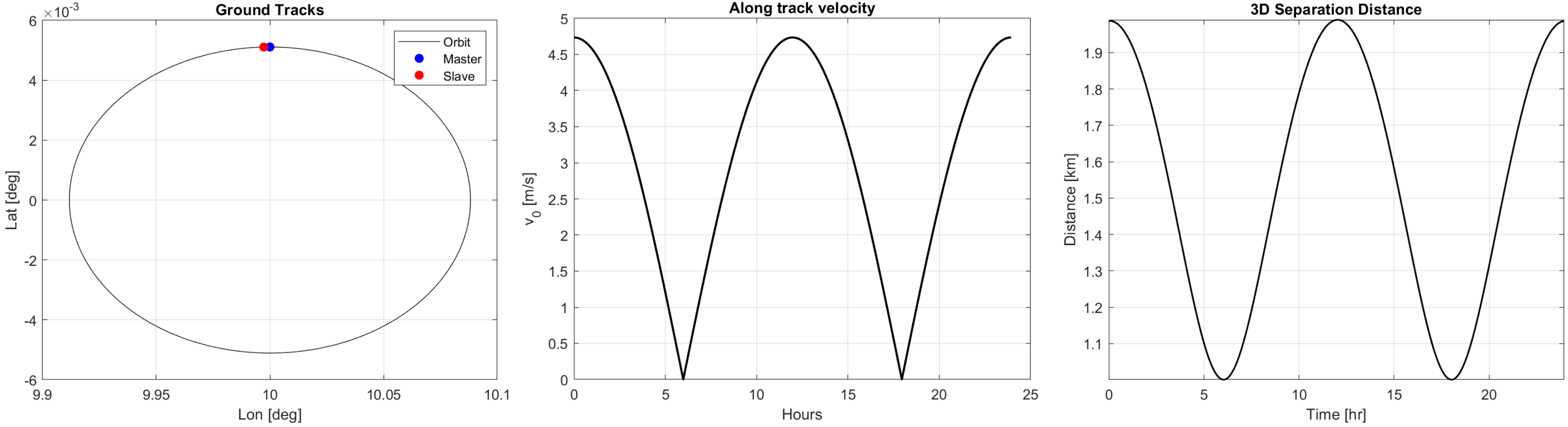
- The satellite shall remain between $\pm\mathbf{0.1^\circ}$ **of its nominal longitude** (ITU regulations).
- To ensure collision and interference avoidance, the **inter-satellite distance** shall always exceed **1 km**.
- The **normal baseline** between the two satellites shall not exceed **4 km**.
- The **integration time** for each image shall be **1 hour**.
- To achieve up to three times the spectral bandwidth and resolution of a single satellite over a 1-hour integration time, **the temporal separation** between the satellites shall not exceed **2 hours**.

ORBITAL PARAMETERS

Semi-major axis	Eccentricity	Inclination	Argument of perigee	Mean longitude
$42164\ km$	0.00077	0.0051°	90°	10°

Orbital configuration: temporal baseline

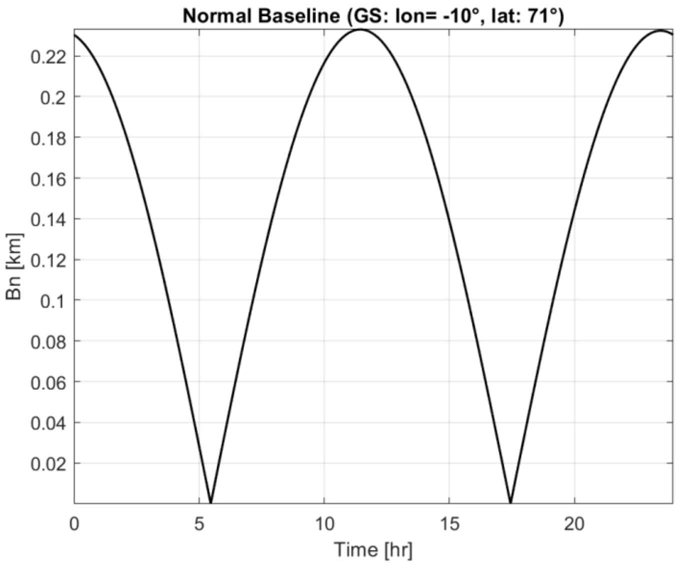
The minimum relative separation requirement of 1 km translates to a minimum temporal baseline between the two satellites of $\boldsymbol{\Delta T = 7\ min}$

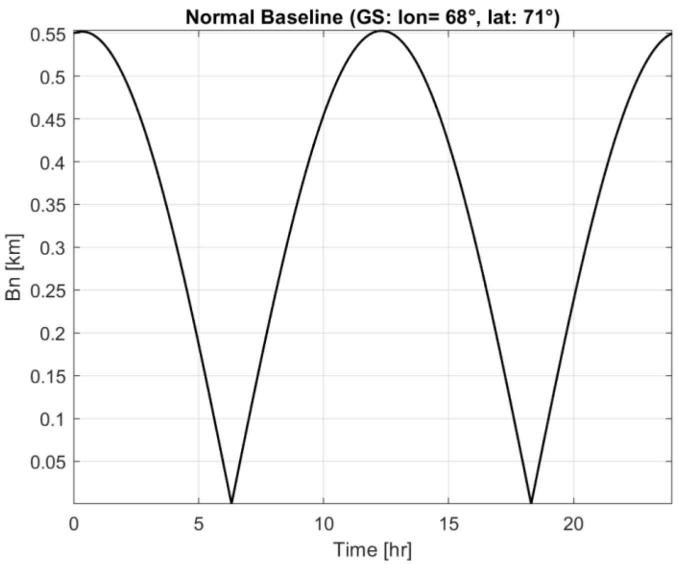


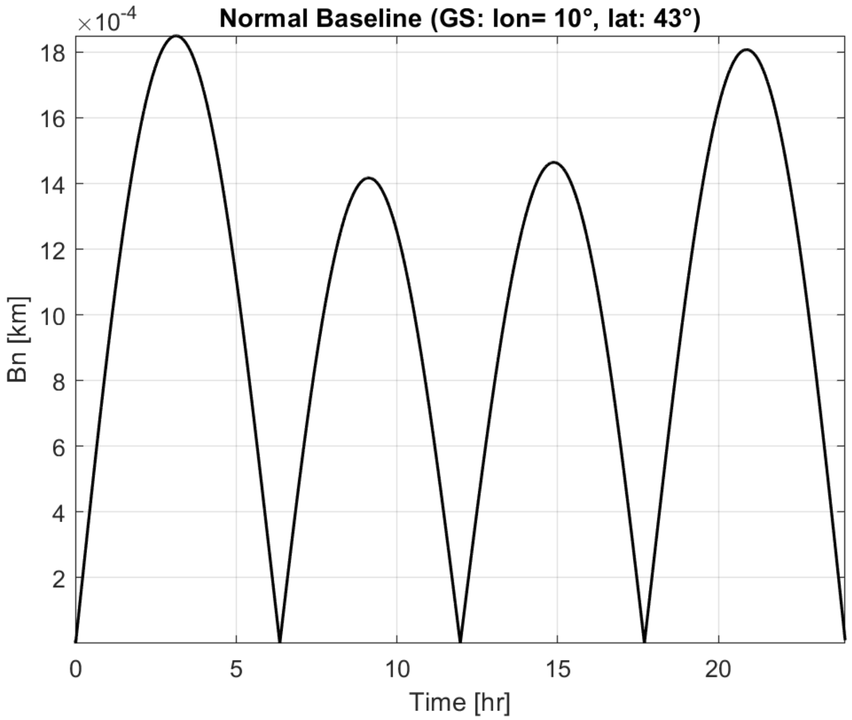
Orbital configuration: normal baseline

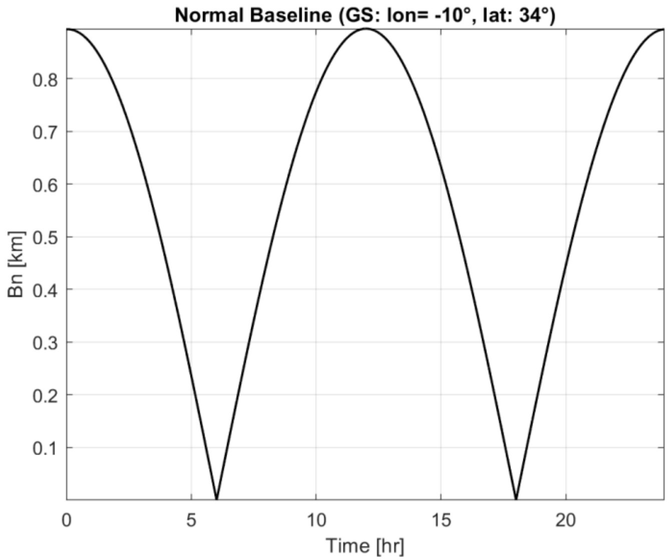
Inter-satellite normal baseline when targeting:

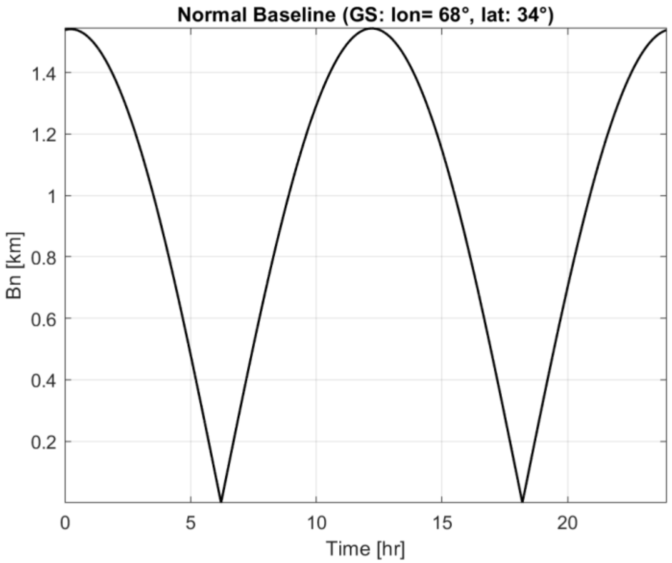
- The nominal ground target
- Extreme points within the European coverage area



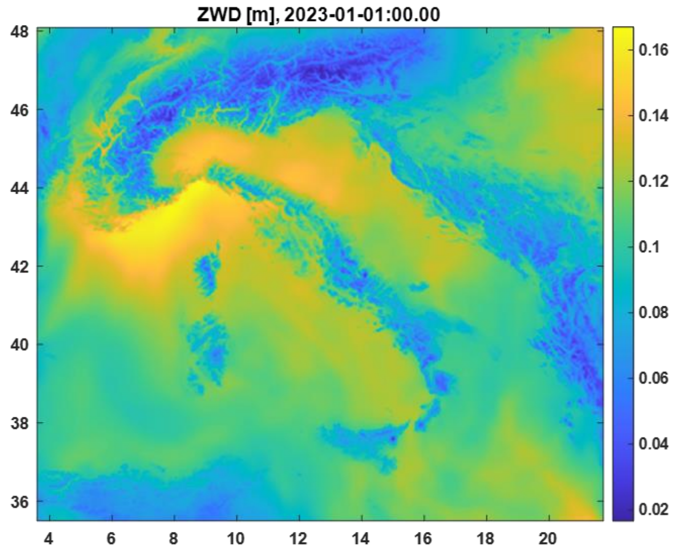


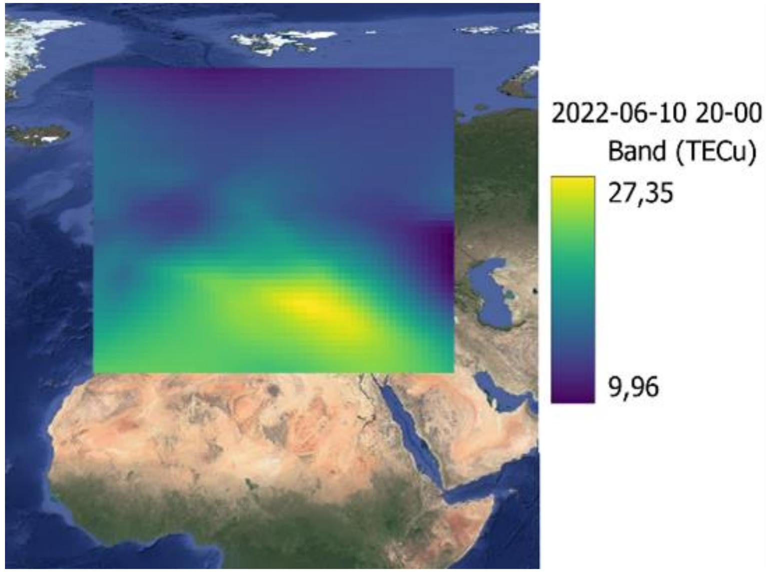






Atmospheric Phase Screen





❑ TROPOSPHERE

- **Joint time-space variogram model** that extends the Kolmogorov power-law. Validation over a 1-year (2023) high-resolution meteorological dataset using the **Weather Research and Forecasting (WRF) model.**

$$d_T = 10^{-6} \int N \, dl$$

$$2V_T(\tau, x) = E[|d_T(t+\tau, \chi + x) - d_T(t, \chi)|^2]$$

$$= \frac{2\sigma_T^2}{\cos^2\theta}\left[1 - e^{-\sqrt{\left(\frac{\tau}{\tau_T}\right)^2 + \left(\frac{x}{x_T}\right)^2}}\right]$$

$$\approx \frac{2\sigma_T^2}{\cos^2\theta}\sqrt{\left(\frac{\tau}{\tau_T}\right)^2 + \left(\frac{x}{x_T}\right)^2}$$

❑ IONOSPHERE

- The ionospheric delay can be efficiently and accurately modelled using a pure **1D temporal variogram.** Validation of 1 year of **Vertical Total Electron Content (VTEC)** maps from the **INGV eSWua database**.

$$d_I = \frac{40.28}{c^2}\lambda^2$$

$$2V_I(\tau) = \frac{2\alpha_I}{\cos^2\theta}|\tau|$$

Performance comparison: SISO X-band vs MIMO Ku-band

Parameters

θ	$50°$
$v_{0_{max}}$	$4.7\ m/s$
$v_{0_{min}}$	$1.8\ m/s$
σ_T^2	$100\ mm^2$
τ_T	$10\ h$
x_T	$10\ km$

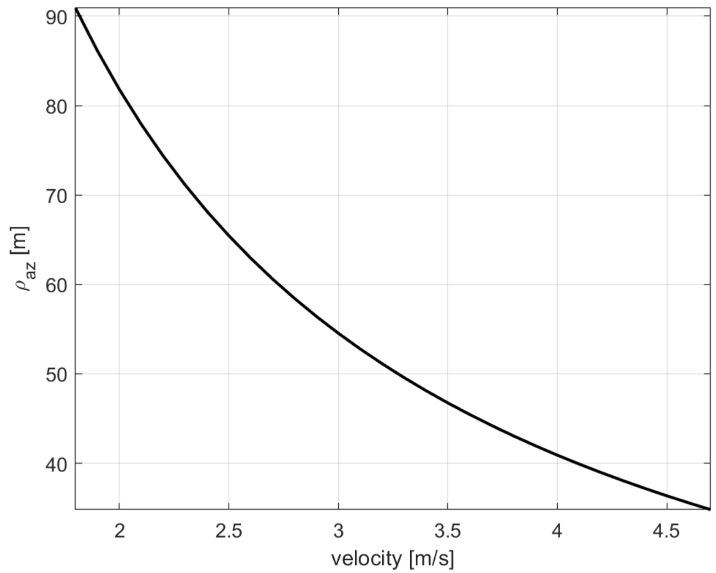
X-band

λ	0.031 m
α_I	0.045 mm^2/s

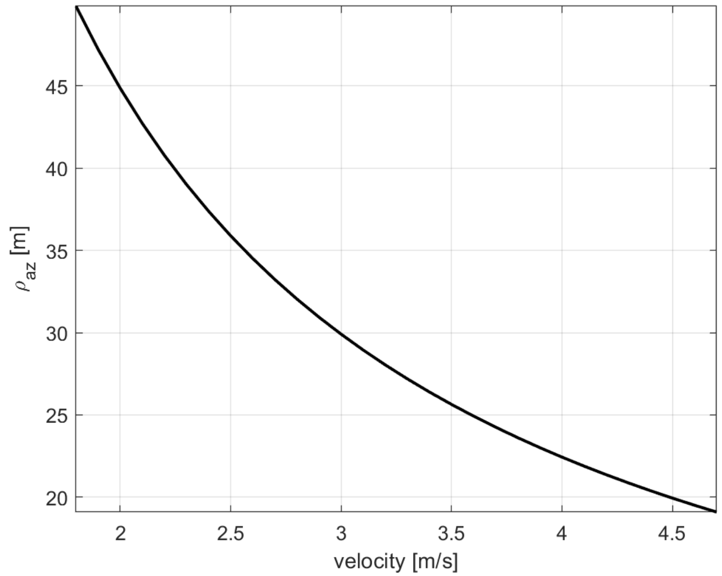
Ku-band

λ	0.017 m
α_I	0.0043 mm^2/s

X-band



Ku-band



Performance comparison: SISO X-band (24 hours temporal baseline)

Sources of decorrelation

- **Temporal decorrelation**: direct consequence of the 24 hours baseline
- **Topography:** caused by the presence of normal baseline between daily acquisitions
- **Signal-to-Noise Ratio:** assuming: $SNR = 1 \rightarrow \gamma_{SNR} = 0.5$
- **Atmosphere (intra-image):** combination of temporal and spatial contributions: $\gamma_{APS} = \gamma_{\tau_{TI}} \cdot \gamma_{x_T}$
- **Atmosphere (inter-images):** $\gamma_{APS_{\Delta T}} = e^{-\left(\frac{4\pi}{\lambda \cos\theta}\right)^2 \left(\sigma_T^2\left(1-e^{-\frac{\Delta T}{\tau_T}}\right)+\alpha_I \Delta T\right)}$

$\gamma_{APS_{\Delta T}}$ (only troposphere)	$\gamma_{APS_{\Delta T}}$ (troposphere+ionosphere)
$2 \cdot 10^{-16}$	0

Completely decorrelates

Performance comparison: MIMO Ku-band (7 minutes temporal baseline)

❑ Sources of decorrelation

- **Temporal decorrelation**: lower effect due to the shorter temporal baseline
- **Signal-to-Noise Ratio:** assuming: $SNR = 1 \rightarrow \gamma_{SNR} = 0.5$
- **Atmosphere (intra-image):** combination of spatial and temporal contributions: $\gamma_{APS} = \gamma_{\tau_{TI}} \cdot \gamma_{x_T}$
- **Atmosphere (inter-images):** $\gamma_{APS_{\Delta T}} = e^{-\left(\frac{4\pi}{\lambda \cos\theta}\right)^2 \left(\sigma_T^2\left(1-e^{-\frac{\Delta T}{\tau_T}}\right)+\alpha_I \Delta T\right)}$

$\gamma_{APS_{\Delta T}}$ (only troposphere)	$\gamma_{APS_{\Delta T}}$ (troposphere+ionosphere)
0.22	0.02

⬇

Better results than monostatic case

Performance analysis: MIMO Ku-band (7 minutes temporal baseline)

- **Antenna dimension**

$$D_{Ku} = \frac{\lambda_{Ku}}{\lambda_X} D_X = 0.55 \cdot D_X$$

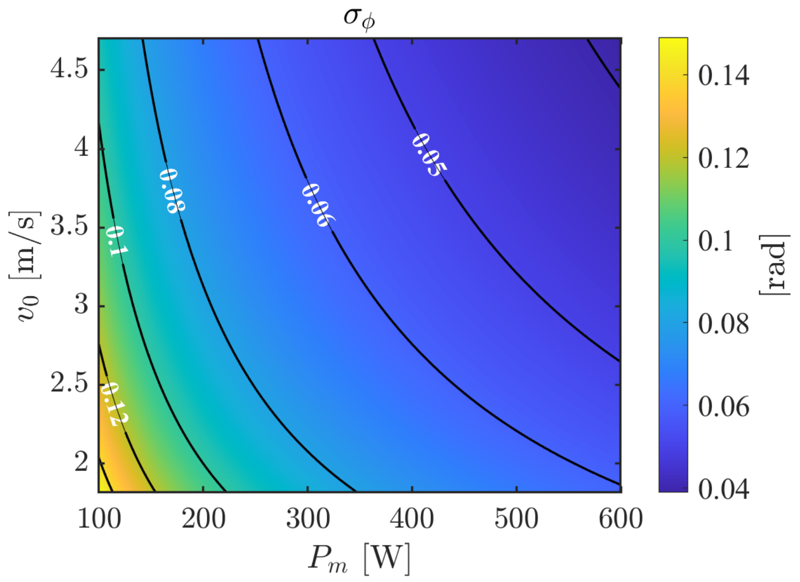
- **Interferometric phase accuracy**

$$K_p = \frac{(4\pi)^3 R_0^4 N_0}{P_m G^2 \lambda^2 \eta \rho_{az} T_s} \qquad \rho_{gr} = \frac{K_p}{\sigma_{NESZ}}$$

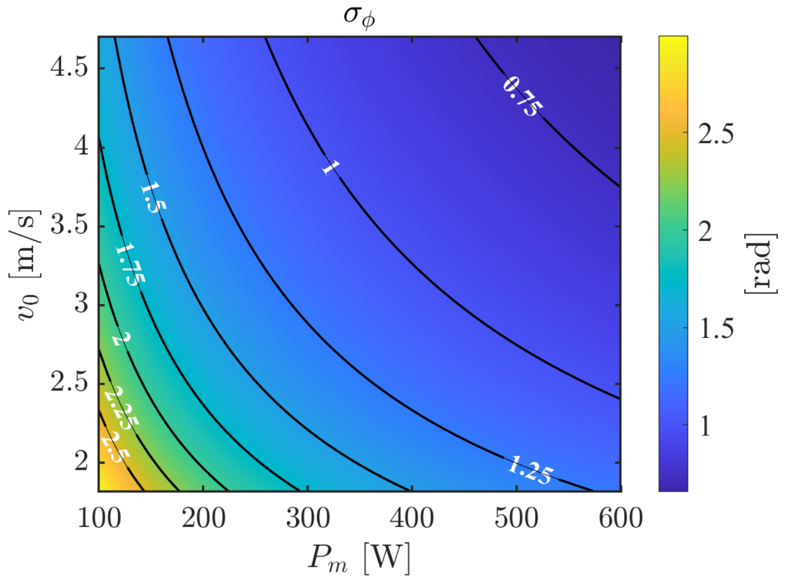
$$\sigma_{\phi_{tot}} = \sqrt{\frac{1-\gamma_{tot}^2}{2\frac{\rho_{la}}{\rho_{az}\cdot\rho_{gr}}\cdot M\cdot\gamma_{tot}^2}}$$

We have **three independent interferograms ($M = 3$)**

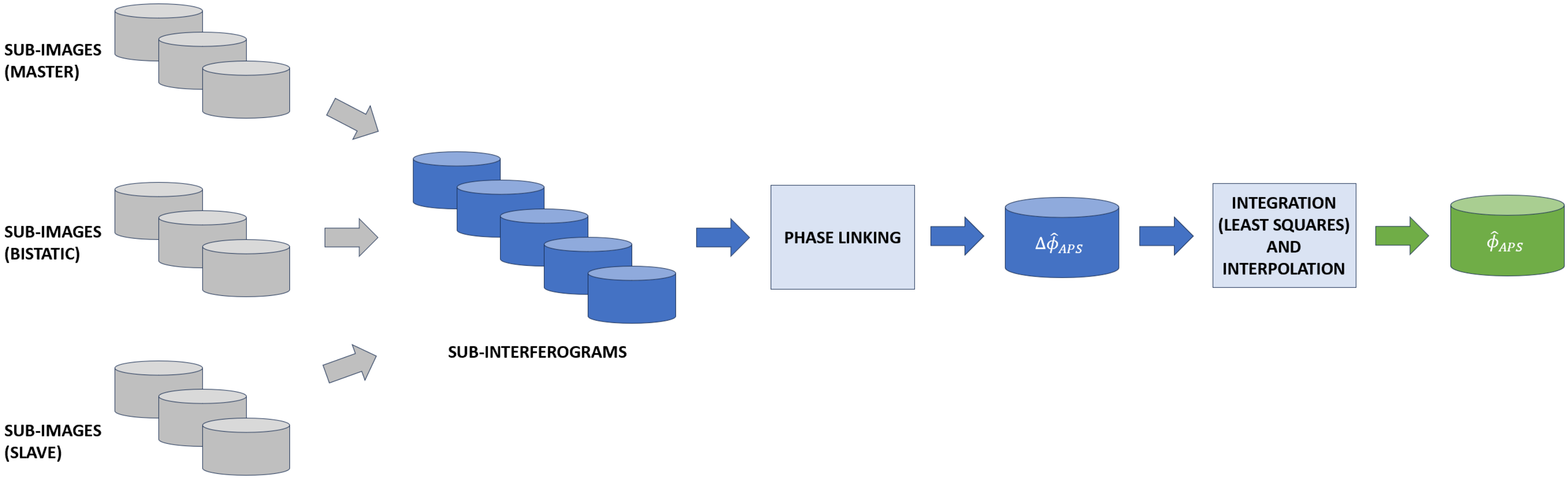
Only troposphere



Troposphere and Ionosphere



Preliminary APS estimation and compensation: ATI Phase Linking

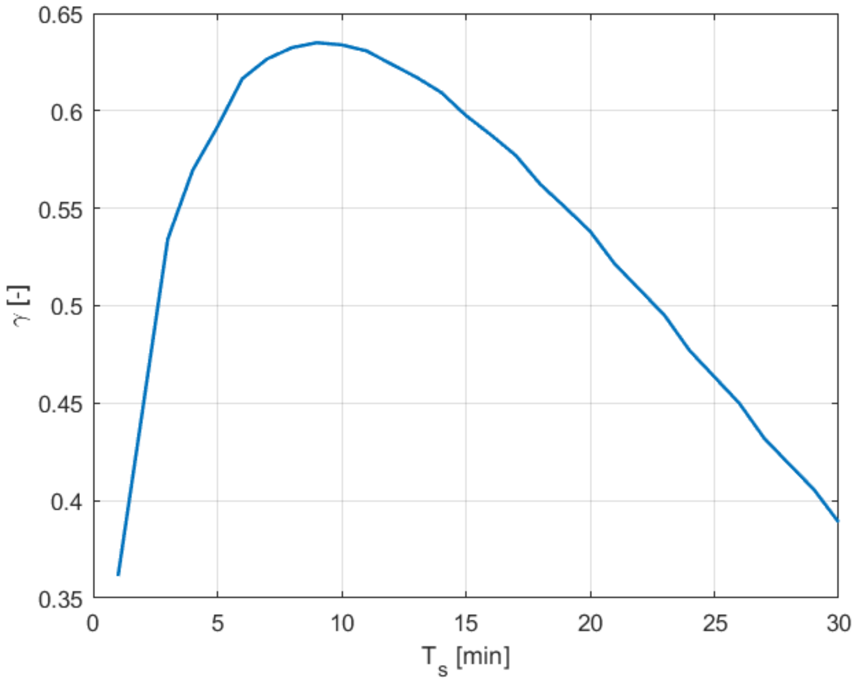


Preliminary APS estimation and compensation: ATI Phase Linking

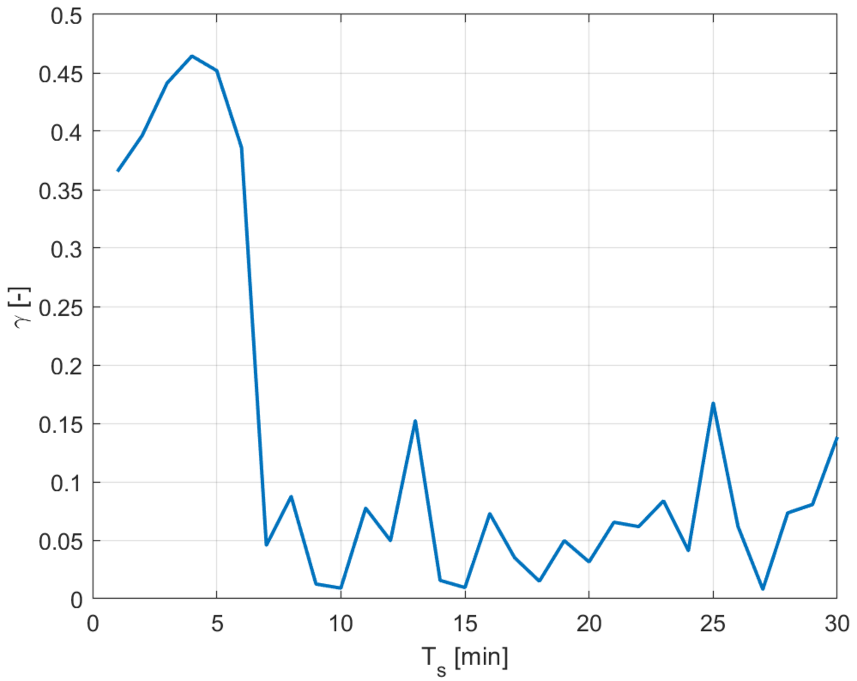
- **Simulation parameters**
  - Mono-dimensional scene of width $X_s = 10\ km$
  - Minimum velocity $v_0 = 1.8\ m/s$
  - Temporal baseline between satellites $\Delta\mathrm{T} = 7\ \mathrm{min}$
  - Two scenarios: only troposphere and both troposphere and ionosphere
  - Noise coherence applied: $\gamma_n = 0.84$

- **Optimal sub-aperture selection**

Only troposphere



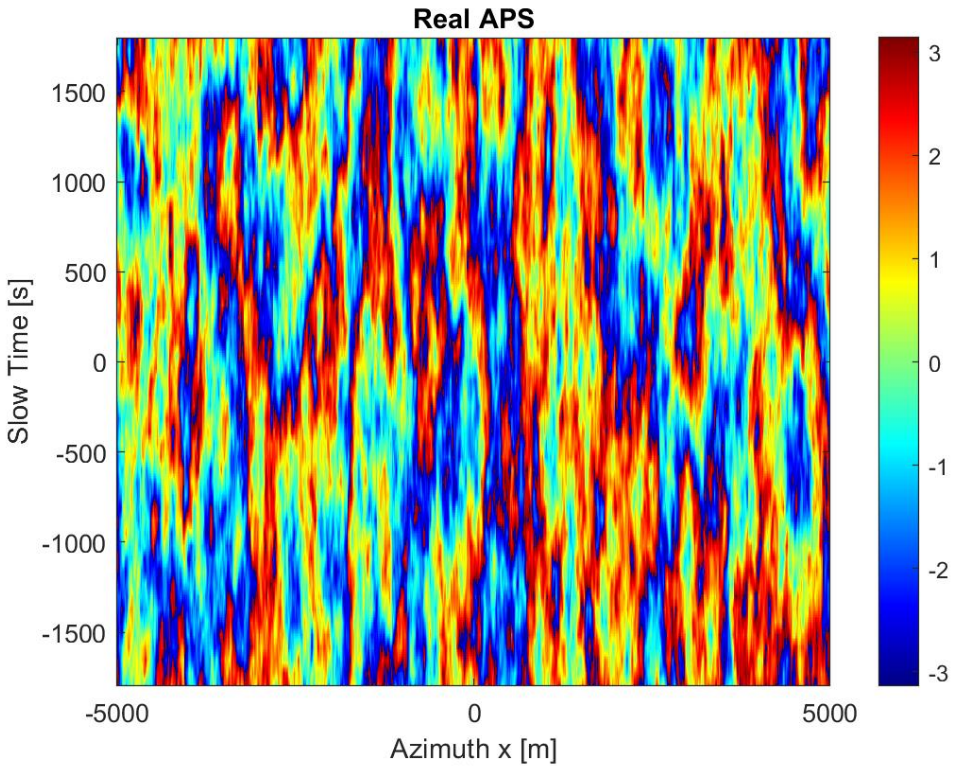
Troposphere+Ionosphere

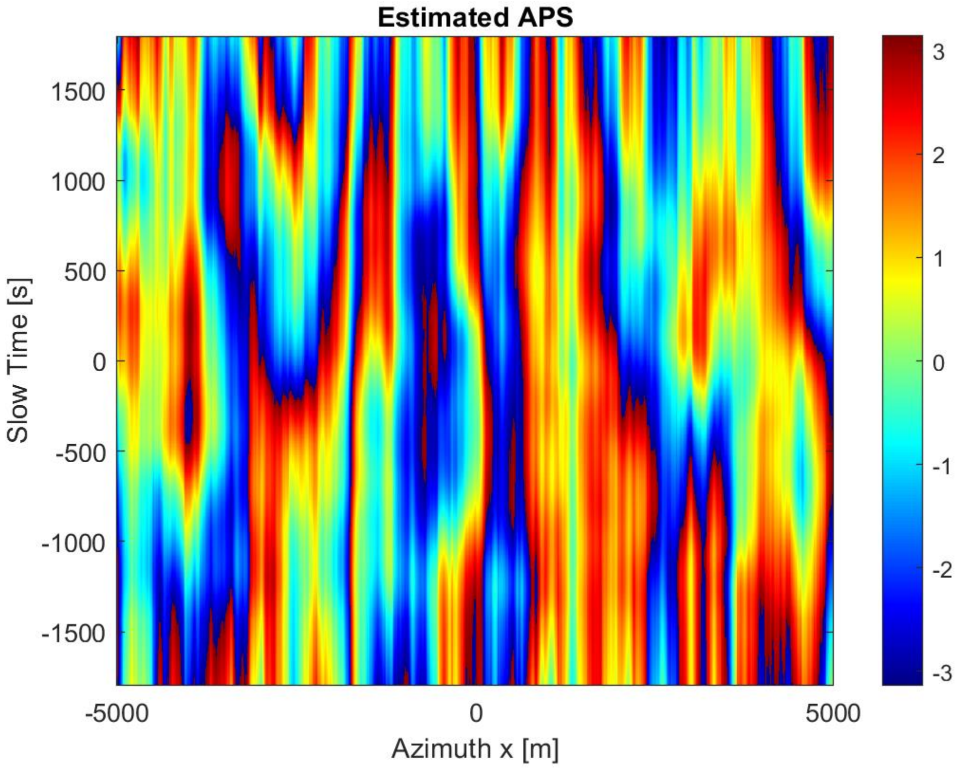


Preliminary APS estimation and compensation: ATI Phase Linking

- **Only troposphere results**

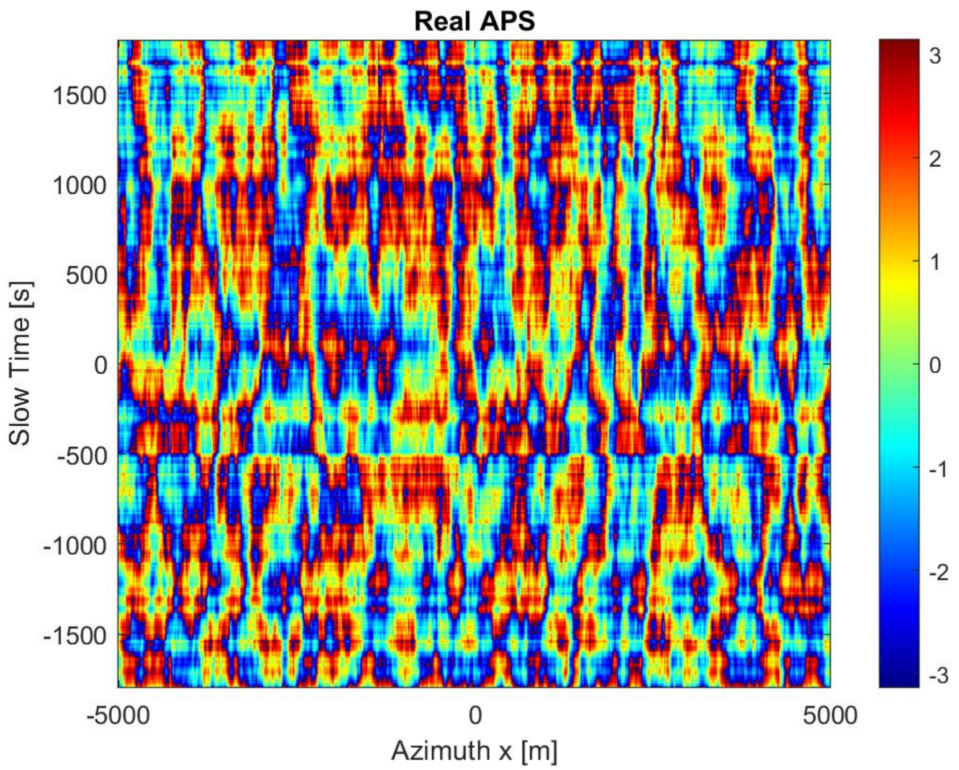
  - **Coherence**
    - Before compensation: $\gamma = 0.07$
    - After compensation: $\gamma = 0.63$
  - **Interferometric phase accuracy**
    - Before compensation: $\sigma_\phi = 1.78\, rad$
    - After compensation: $\sigma_\phi = 1.16\, rad$
    - After compensation and multi-look: $\sigma_\phi = 0.08\, rad$

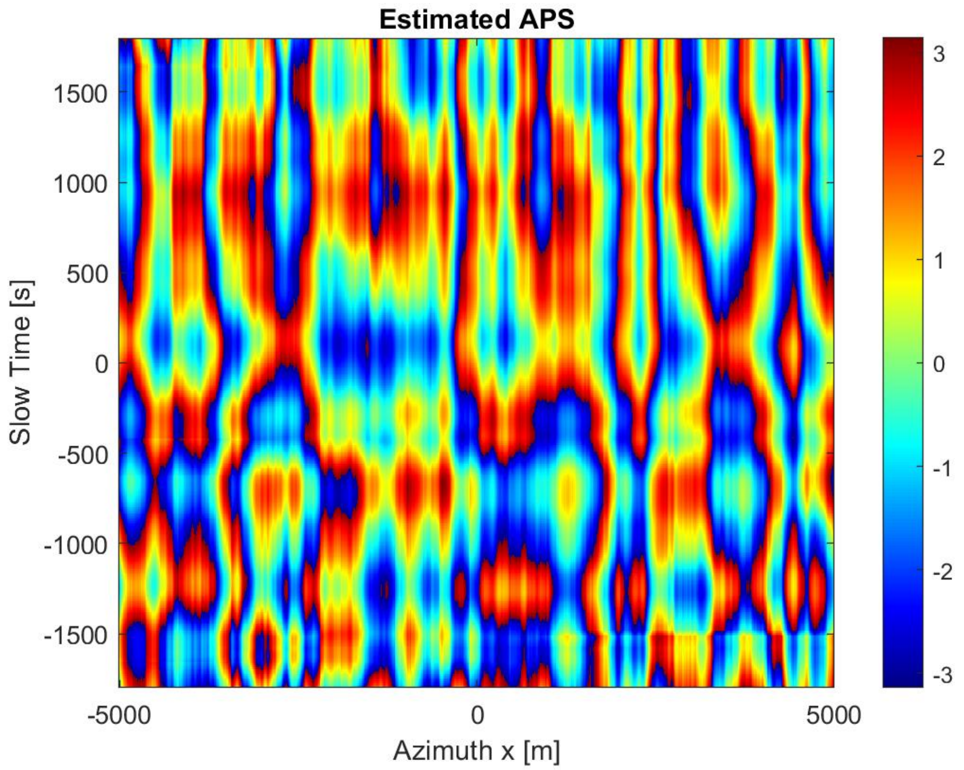




Preliminary APS estimation and compensation: ATI Phase Linking

- **Both troposphere and ionosphere results**
  - **Coherence**
    - Before compensation: $\gamma = 0.03$
    - After compensation: $\gamma = 0.51$
  - **Interferometric phase accuracy**
    - Before compensation: $\sigma_{\phi} = 1.83\ rad$
    - After compensation: $\sigma_{\phi} = 1.31\ rad$
    - After compensation and multi-look: $\sigma_{\phi} = 0.10\ rad$





Conclusions

- **Along-track GEO-SAR** combines wide coverage, fine resolution, and short revisit times. A compact Ku-band MIMO-GEO formation further enhances power and revisit frequency.
- To meet the 1 km minimum satellite distance in a ±0.1° NZI GEO orbit, a **temporal baseline of at least 7 minutes** is required.
- The proposed close formation ensures **almost negligible normal baselines**.
- MIMO formation **enables APS estimation without reference data**, overcoming the 24-hour atmospheric decorrelation limitation of single-satellite systems.
- A preliminary **sub-aperture along-track interferometric strategy**, combined with Phase Linking application Least-Squares integration, is proposed.
- Results demonstrate an **optimal sub-aperture integration time** (distinct from the monostatic case), allowing effective APS compensation—particularly for only tropospheric effects—even at the lowest velocity.

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RIDE

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Thank you for the attention!

Matteo Monti

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