Tropospheric Tomography Measurement Using Spaceborne Multi-static SAR

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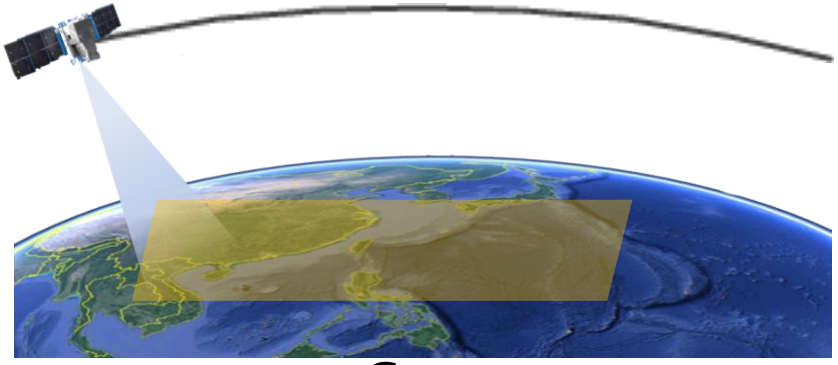
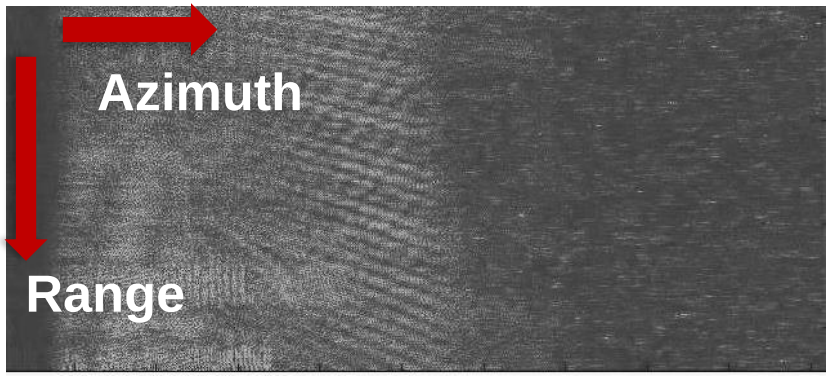
Outline

Spaceborne SAR: high spatial resolution

- Satellite-deployed radar transmits signal to acquire high-resolution 2-D image (range-azimuth)
  - Achieving all-day/all-weather、wide-area/high spatial resolution microwave imaging

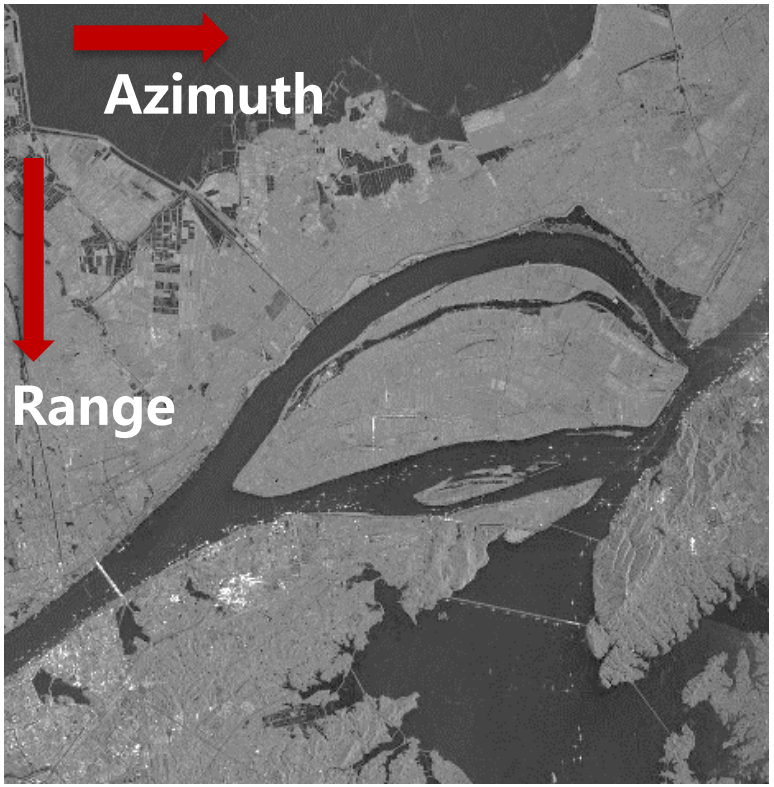


Scene



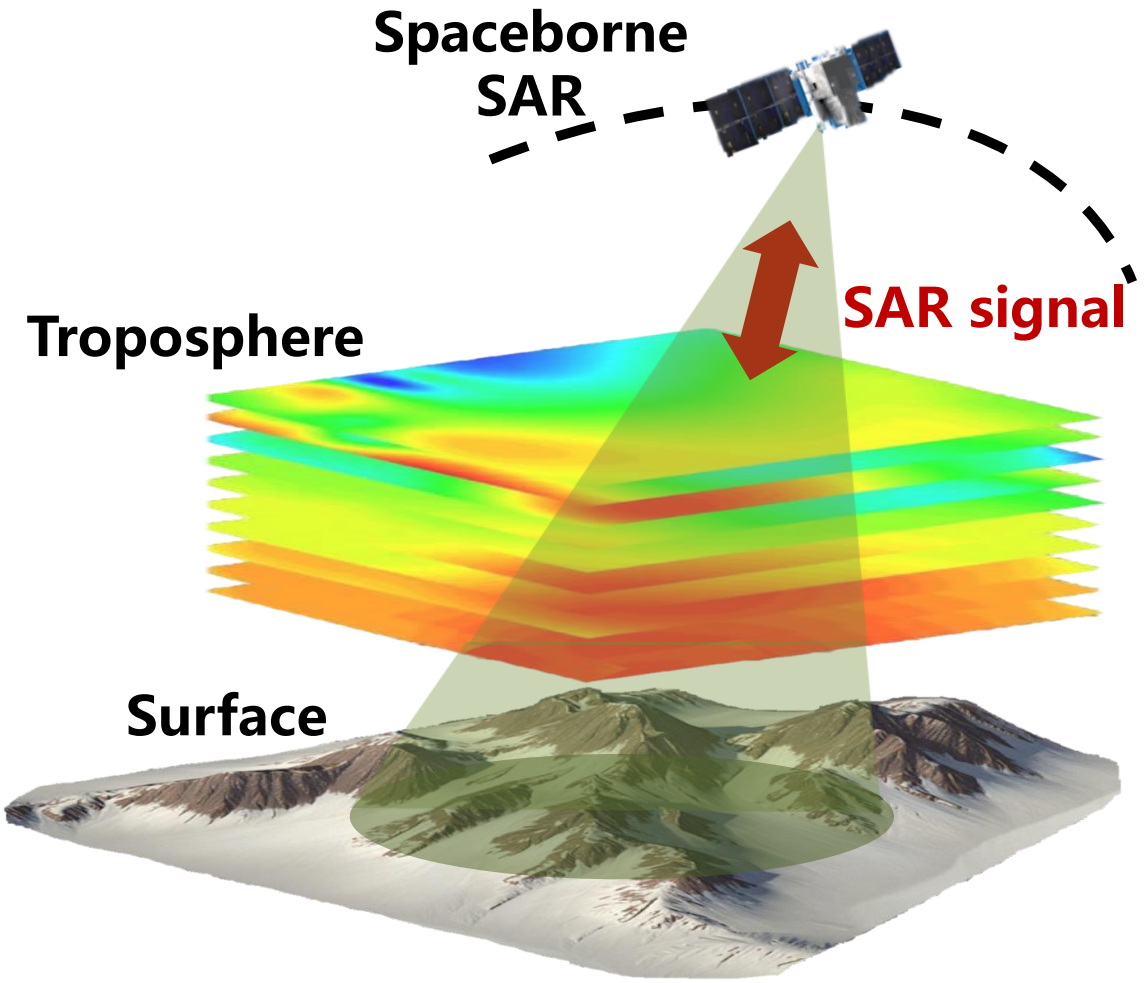
Echo

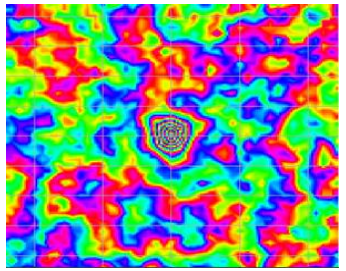
SAR image



Spaceborne SAR: troposphere effect

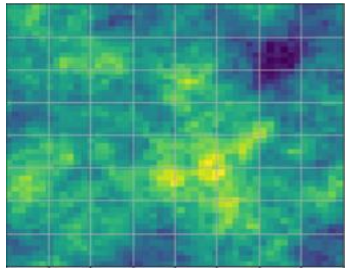
- Its signal propagates through troposphere to observe the Earth's surface, and tropospheric signal component is imposed





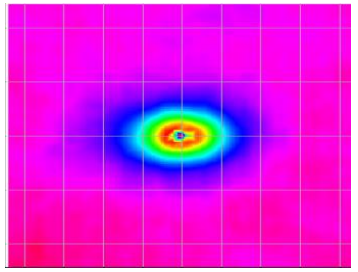
Spaceborne SAR signal (phase)

=



Tropospheric signal (phase)

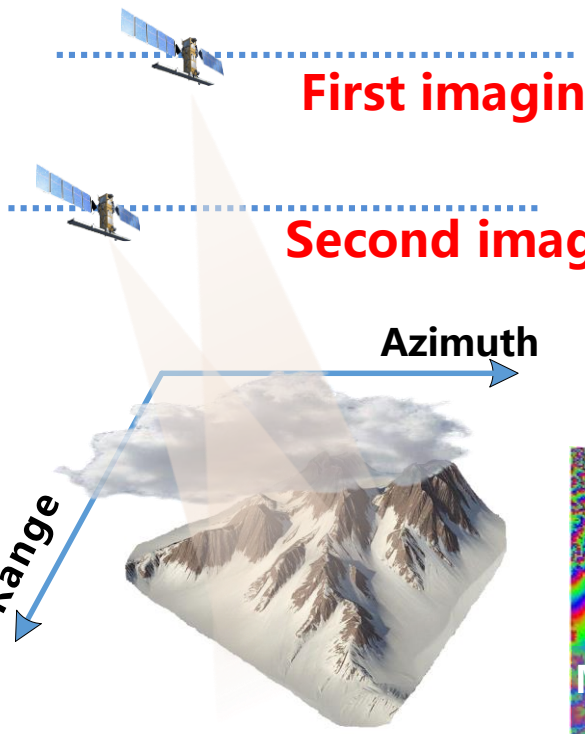
+



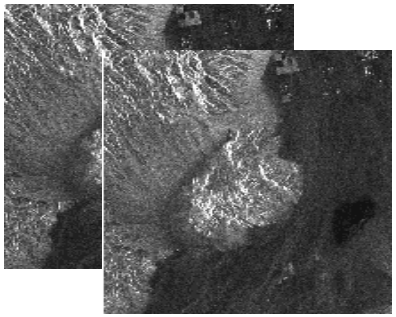
Surface deformation signal (phase)

Differential Interferometric SAR (D-InSAR)

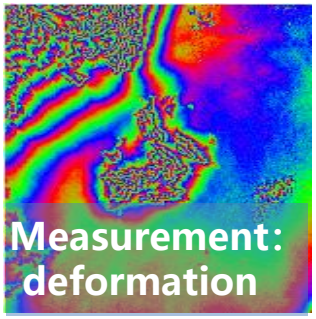
- **Repeatedly** observe the same area at **different** times, and use **interferometric phase** to invert **surface deformation**
- **Tropospheric phase** is considered as an **error term** in this case

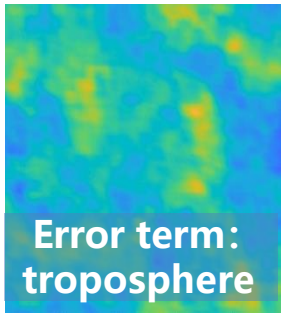


D-InSAR sketch map



Interferometric phase





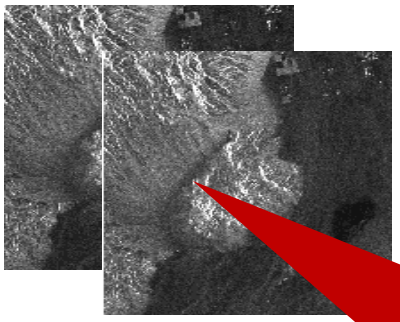
Landslide early-warning

Subsidence survey

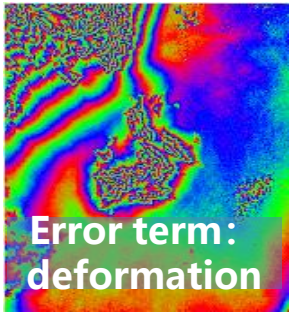
Differential Interferometric SAR (D-InSAR)

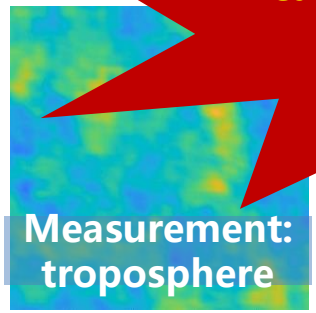
- When Surface deformation is negligible, tropospheric information can be measured
- Interferometric phase change mainly derives from differential tropospheric refractivity

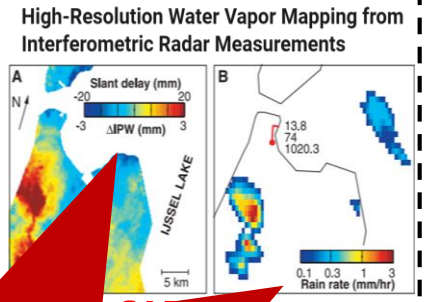
D-InSAR sketch map



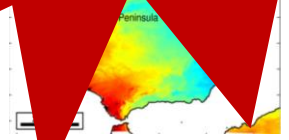
Interferometric phase



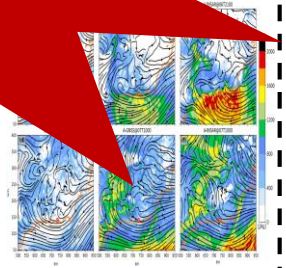




Preliminary verification has been carried out in several meteorological scenarios



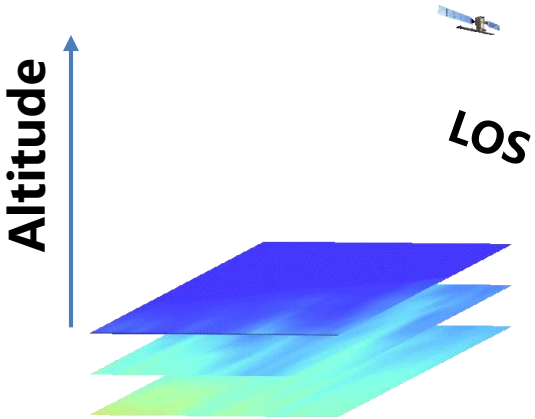
Large-scale tropospheric measurement (*TGRS*,2017)



Heavy rainfall forecast (*JGR*,2018)

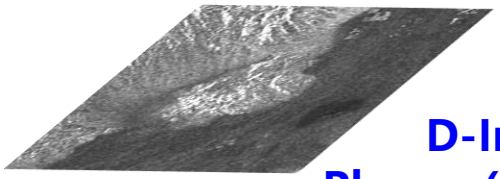
Drawback: dimension deficiency

Due to limitation of SAR imaging, vertical-dimension information is lost

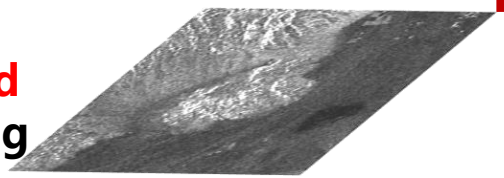


LOS

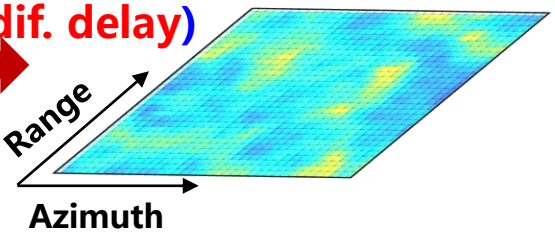
First imaging



Second imaging

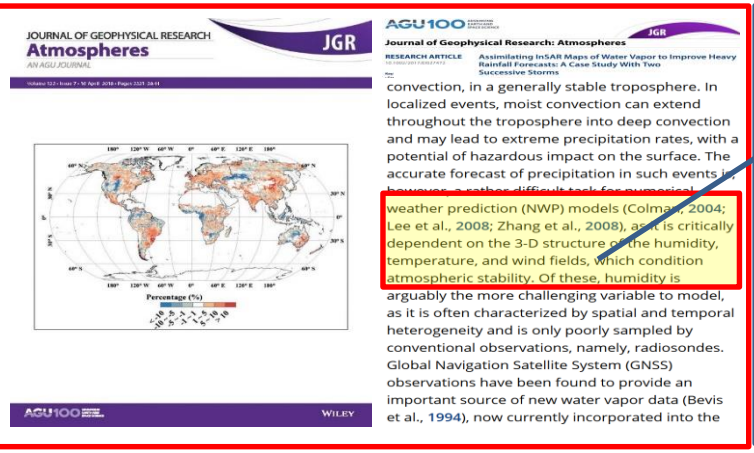


D-InSAR Phases (dif. delay)



Imaging theory: projection of 3-D space into 2-D space

Differential integrated tropospheric refractivity



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RESEARCH ARTICLE
Assimilating InSAR Maps of Water Vapor to Improve Heavy Rainfall Forecasts: A Case Study With Two Successive Storms

convection, in a generally stable troposphere. In localized events, moist convection can extend throughout the troposphere into deep convection and may lead to extreme precipitation rates, with a potential of hazardous impact on the surface. The accurate forecast of precipitation in such events is, however, a rather difficult task for numerical weather prediction (NWP) models (Colman, 2004; Lee et al., 2008; Zhang et al., 2008), as it is critically dependent on the 3-D structure of the humidity, temperature, and wind fields, which condition atmospheric stability. Of these, humidity is arguably the more challenging variable to model, as it is often characterized by spatial and temporal heterogeneity and is only poorly sampled by conventional observations, namely, radiosondes. Global Navigation Satellite System (GNSS) observations have been found to provide an important source of new water vapor data (Bevis et al., 1994), now currently incorporated into the

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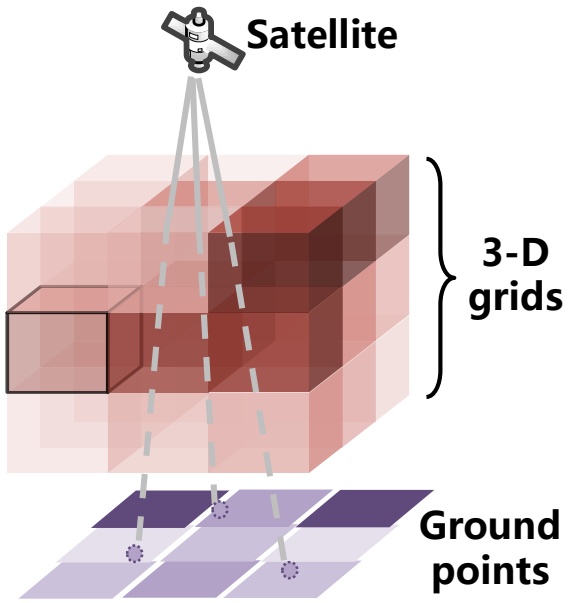
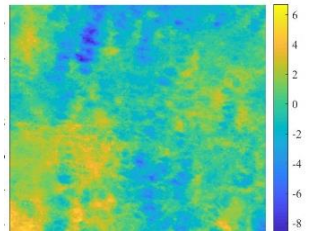
"… accurate prediction of numerical weather forecast models critically depends on the 3-D structure of atmospheric elements such as humidity…. …." (*JGR atmosphere, 2018*)

Only integrated refractivity is measured, analysis and prediction error is large

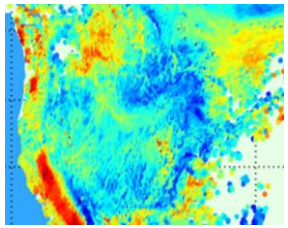
Drawback: dimension deficiency

- Integrated refractivity → Only PWV, missing 3-D structure
- Only assimilating PWV to NWP models is insufficient



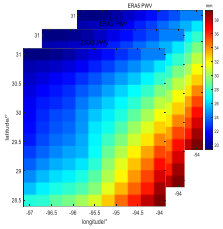


Integrated refractivity

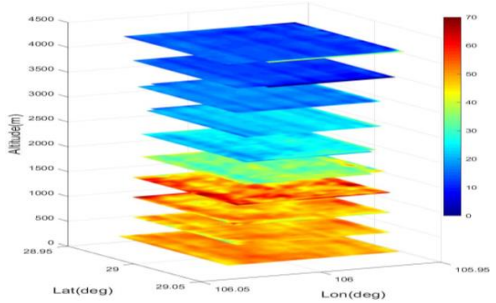


Reconstructed PWV

Assimilate

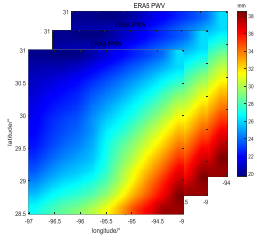


Coarse prediction



3-D troposphere information

Assimilate



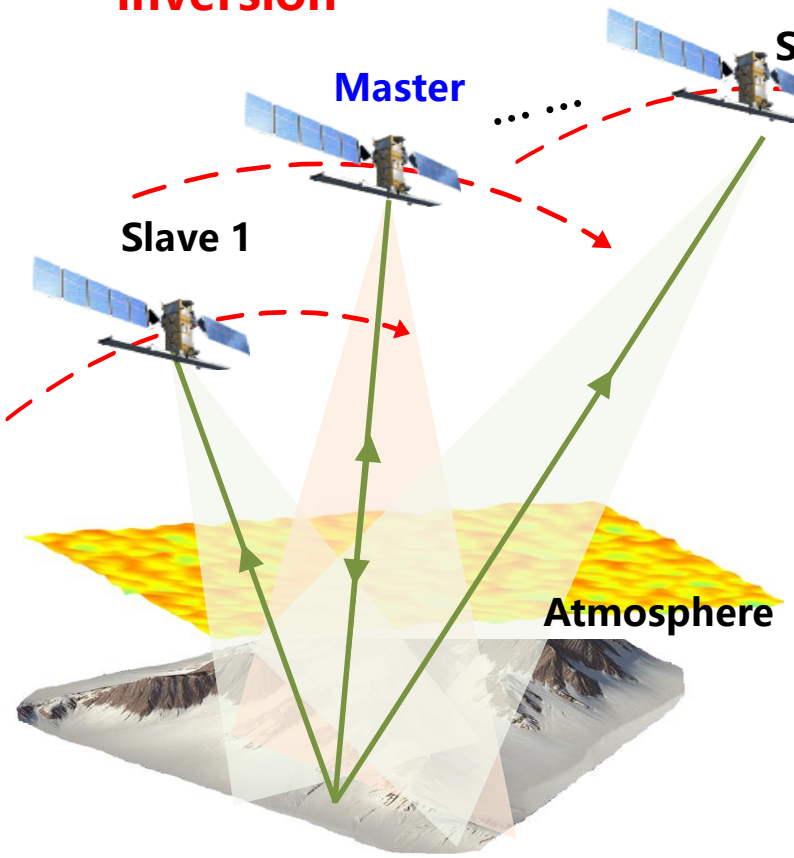
Fine prediction

Vertical dimension cannot be decoupled: limitation in the number of invertible tropospheric parameters +the accuracy of meteorological applications

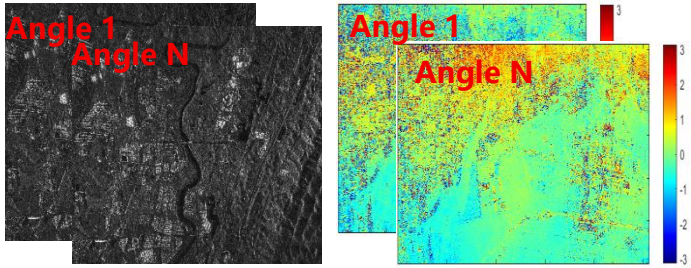
Outline

Method: concept

- **Master-satellite transmits, multiple spaceborne SAR (Multi-angle)**
  - **Signal-level processing acquires multi-angle SAR/D-InSAR images**
  - **Information-level processing enables 3-D tropospheric parameters inversion**

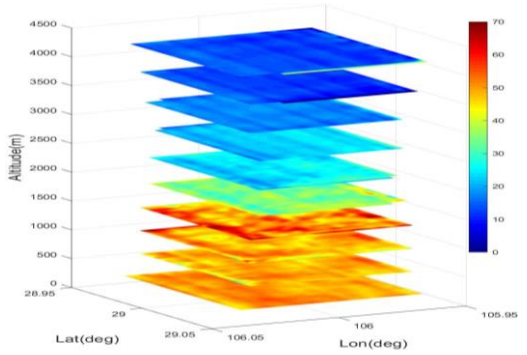


Signal-level



SAR D-InSAR

Information-level



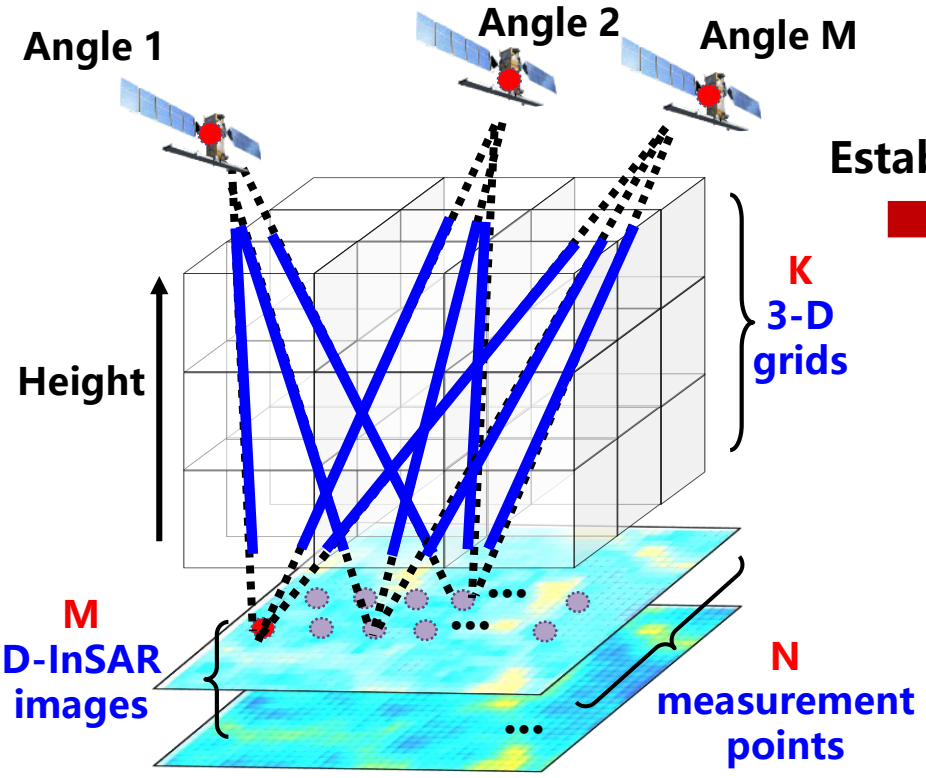
3-D tropospheric refractivity

Y. Li, C. Liu, et al., "Differential Tropospheric Tomography using Spaceborne Simultaneous Multi-angle D-InSAR: Method, Optimization, and Performance Analysis," *IEEE Trans. Geosci. Remote Sens.*, vol. 62, 2024.

C. Hu, Y. Li, et al., "Distributed Spaceborne SAR: A Review of Systems, Applications, and Road Ahead", *IEEE Geosci. Remote Sens. Mag.*, 2025.

Method: model

- **Multi-angle collaborative measurement (equivalent phase centers) to calculate the 3-D tropospheric refractivity**
  - Observation matrix (A) : multi-angle LOS paths
  - Establish interferometric phase - refractivity observation equation
  - Inverse the equation to estimate 3-D tropospheric refractivity



Establish

Observation equation

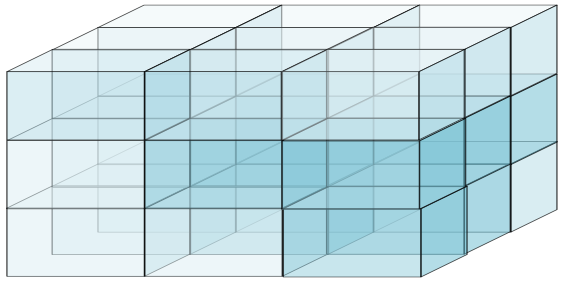
$$y = A \cdot x$$

$M \cdot N \times 1$ — Interferometric phase

A — Observation matrix

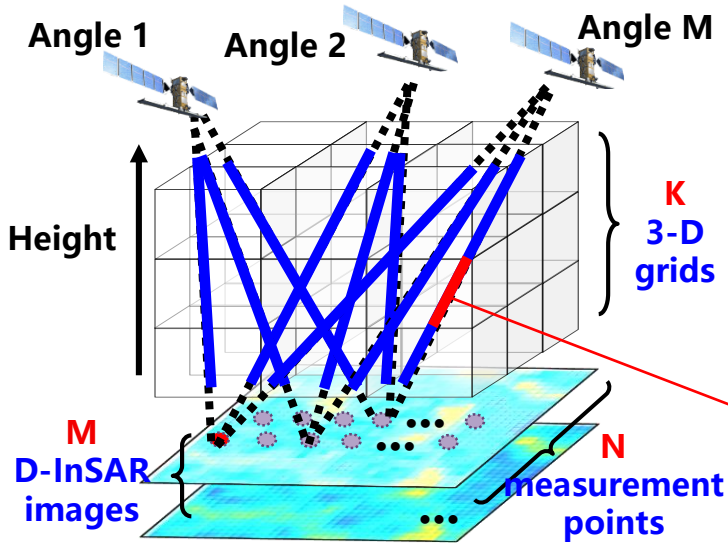
$K \times 1$ — 3-D refractivity

Inverse



3-D tropospheric refractivity

Method: observation equation



Observation equation

$$\underset{M \cdot N \times 1}{\boldsymbol{y}} = \boldsymbol{A} \cdot \underset{K \times 1}{\boldsymbol{x}}$$

Interferometric phase | Observation matrix | 3-D refractivity

Sub-distance l form observation matrix

$$\begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \vdots \\ \varphi_{M\_N} \end{bmatrix} = \frac{4\pi}{\lambda} \cdot 10^{-6} \begin{bmatrix} l_{1\_1} & l_{1\_2} & \cdots & \cdots & \cdots & l_{1\_K} \\ l_{2\_1} & l_{2\_2} & & & & l_{2\_K} \\ \vdots & \vdots & \ddots & & & \vdots \\ \vdots & \vdots & & \ddots & & \vdots \\ \vdots & \vdots & & & \ddots & \vdots \\ l & l & & & & l \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \vdots \\ \varphi_{M\_N} \end{bmatrix} =$$

3-D tropospheric refractivity: help to inverse additional tropospheric parameters (water vapor, cloud, etc.)

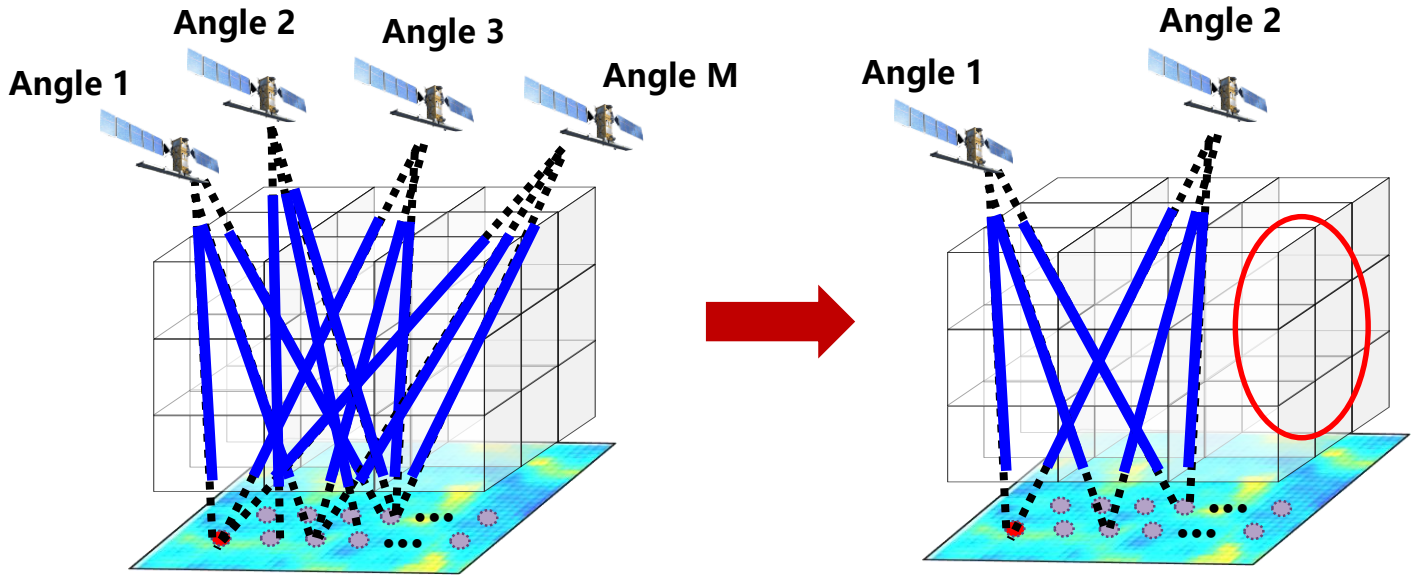
Research difficulties

Problems & Challenges

The observation angles of satellites are **limited** (**sparse observation**)

↓

3-D high resolution refractivity



The traversal grid has **sparsity** and **insufficient observation constraints**

Research difficulties

Problems & Challenges

The observation angles of satellites are **limited** (**sparse observation**)

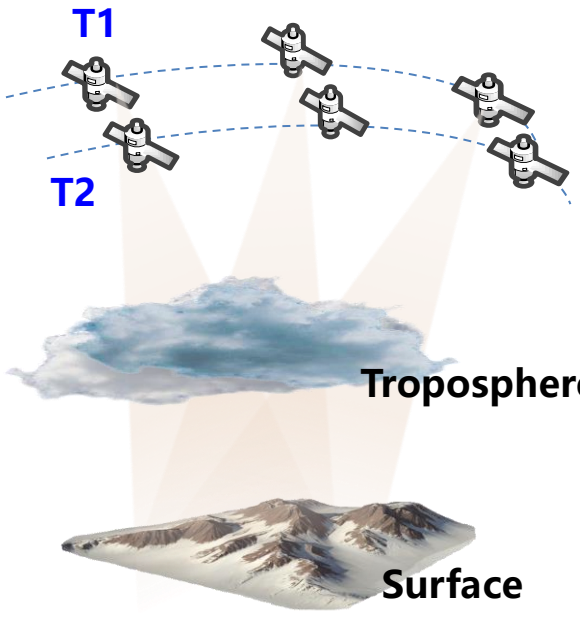
↓

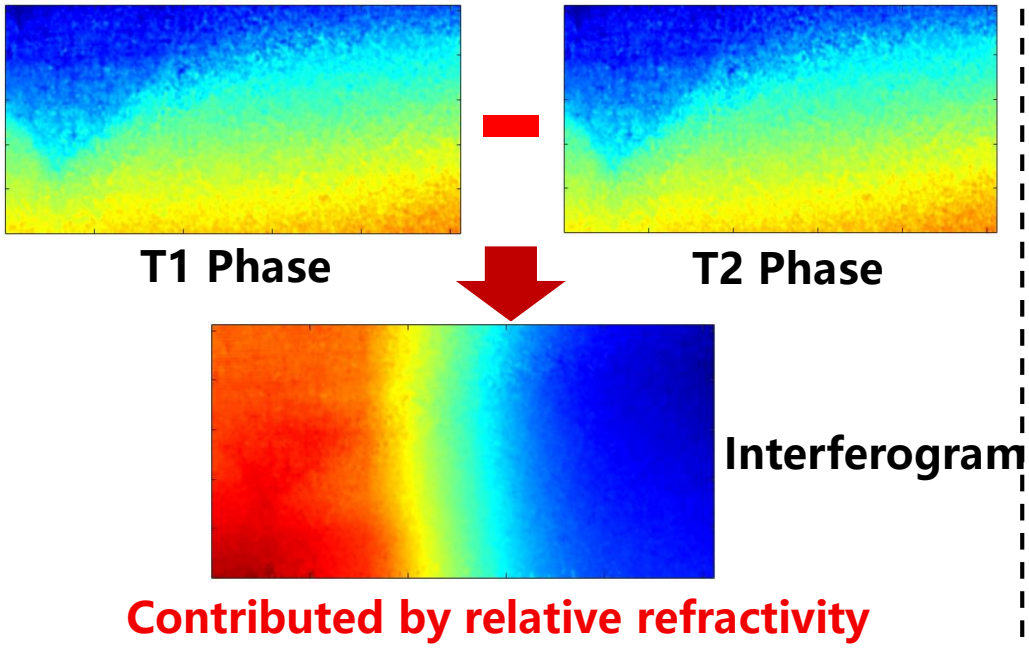
3-D high resolution refractivity

Differential interferometry, **phase ambiguity** at two moments

↓

Accurate restoration of 3-D **absolute** refractivity

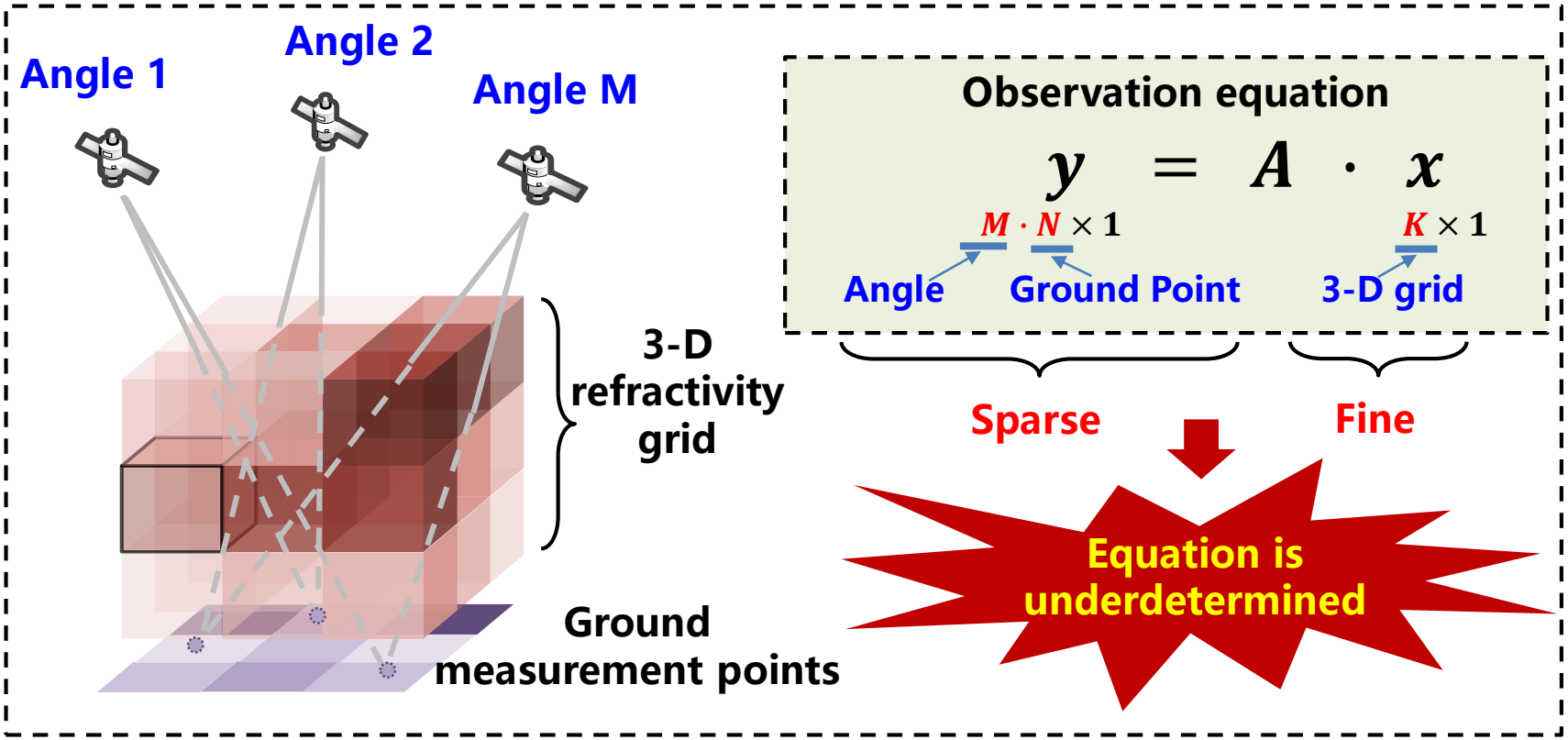




Contributed by relative refractivity

3-D tropospheric refractivity measurement

Challenge ①	Due to sparse observations, equation is **underdetermined** The inverted 3-D refractivity is **low accuracy**
Essential question	Configuration optimization + 3-D refractivity adaptive sparse reconstruction



3-D tropospheric refractivity measurement

Challenge ①

Due to sparse observations, equation is **underdetermined**
The inverted 3-D refractivity is **low accuracy**

Method ①

Intelligent design method for multi-static SAR configuration based on **multi-objective collaborative optimization** strategy

Number of grids passed through

Idle grid rate	$min \quad 1-\frac{V}{K}$
LOS Uniformity	$min \sqrt{\frac{1}{V}\sum(t_v-t_{avg})^2}$
Inversion accuracy	$min \sum diag\langle(A^T C^{-1} A)^{-1}\rangle$
Ground resolution	$min \quad \rho'_{max}$ $min \quad \rho''_{max}$

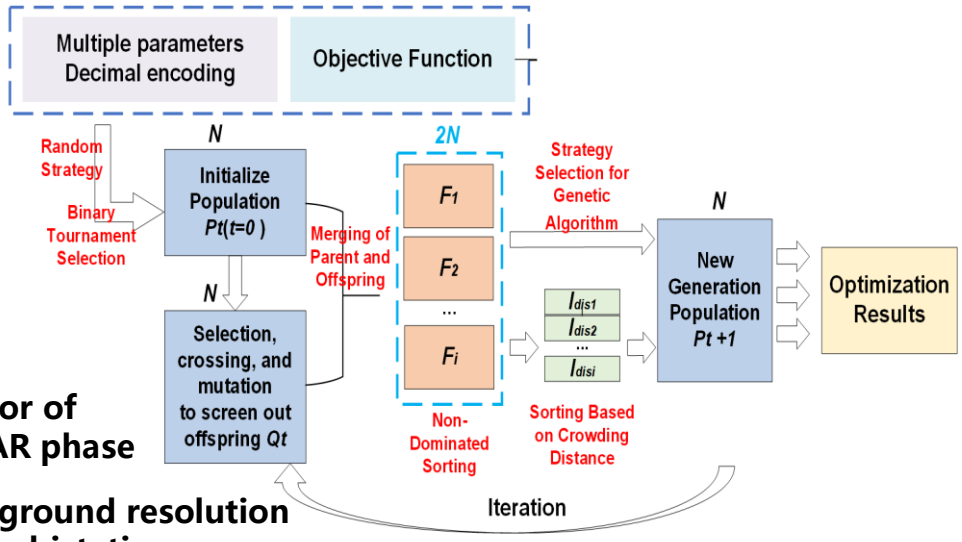
Error of D-InSAR phase

The worst ground resolution for bistatic

The number of times the grid has been passed through

Performance index system

Optimization algorithm



Multi-parameter joint optimization based on NSGA-II

Y. Li, C. Liu, et al., "Differential Tropospheric Tomography using Spaceborne Simultaneous Multi-angle D-InSAR: Method, Optimization, and Performance Analysis," *IEEE Trans. Geosci. Remote Sens.*, vol. 62, 2024.

3-D tropospheric refractivity measurement

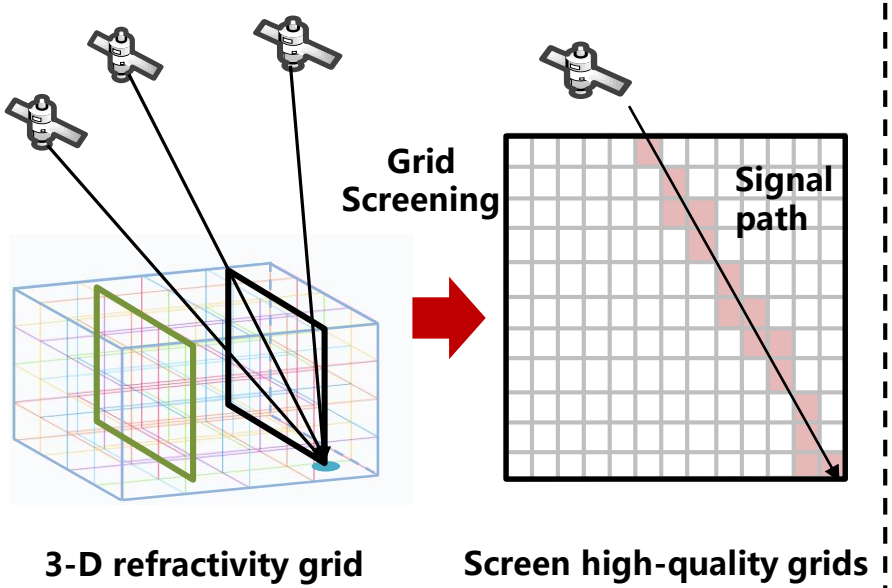
Challenge ①

Due to sparse observations, equation is **underdetermined**
The inverted 3-D refractivity is **low accuracy**

Method ②

3-D refractivity reconstruction based on **precise ray-tracing** and **component screening dimensionality reduction**

Multi-angle ray-tracing: Reduce the scale of the parameters to be estimated

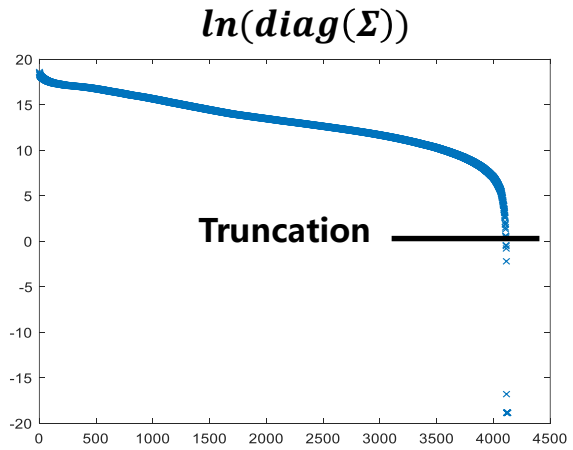


Singular value screening: Truncate near-zero singular values, improve the condition number of matrix A

$$\mathbf{A}=\mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{\mathrm{T}} \Rightarrow \mathbf{x}=\mathbf{V}'\boldsymbol{\Sigma}'^{-1}\mathbf{U}'^{\mathrm{T}}\mathbf{y}$$

Singular value

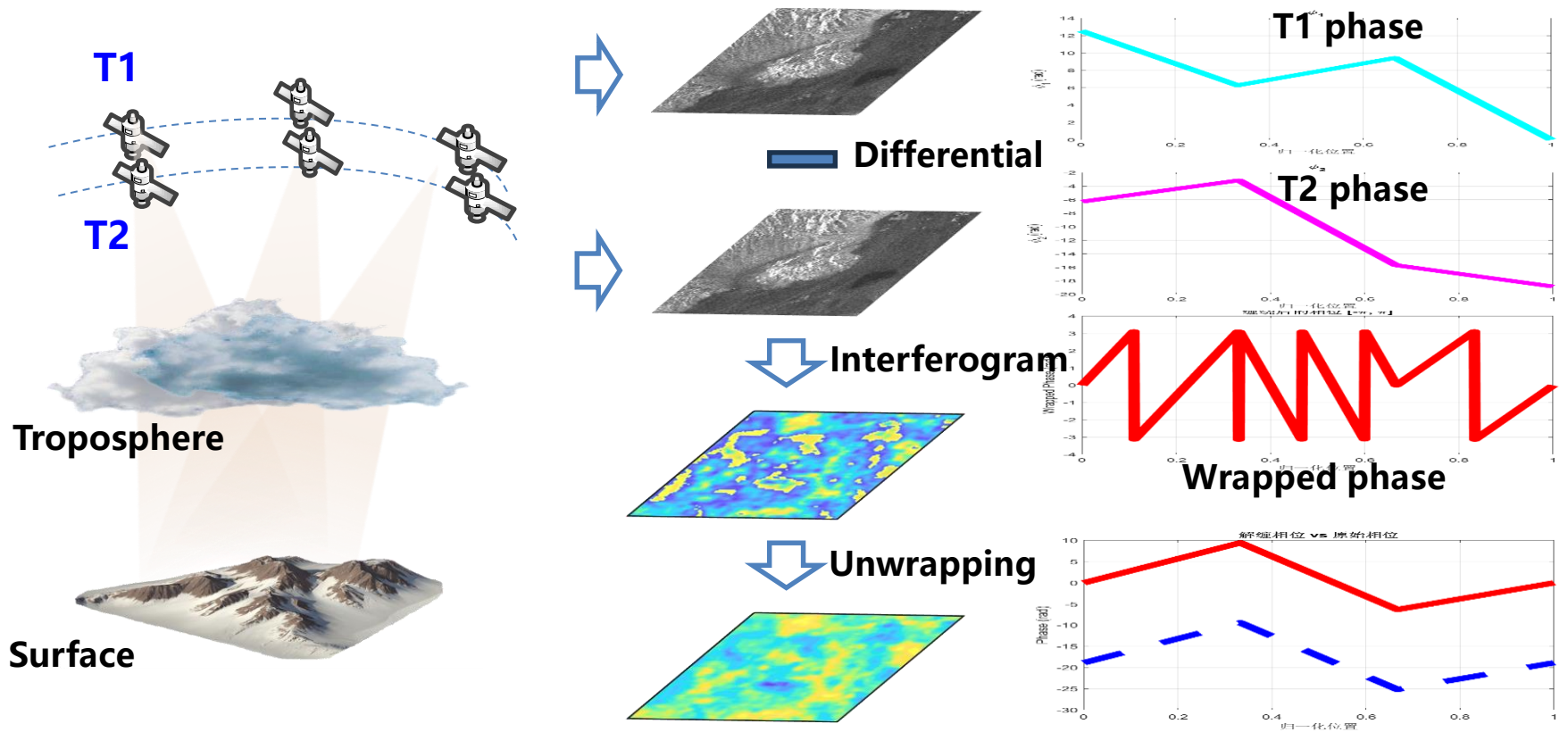
Solve after processing



Y. Li, C. Liu, et al., "Differential Tropospheric Tomography using Spaceborne Simultaneous Multi-angle D-InSAR: Method, Optimization, and Performance Analysis," *IEEE Trans. Geosci. Remote Sens.*, vol. 62, 2024.

3-D tropospheric refractivity measurement

Challenge ②	D-InSAR can only obtain the **relative variation**, there is **ambiguity** in the refractivity measurement
Essential question	Restoration of tropospheric absolute refractivity



3-D tropospheric refractivity measurement

Challenge ②

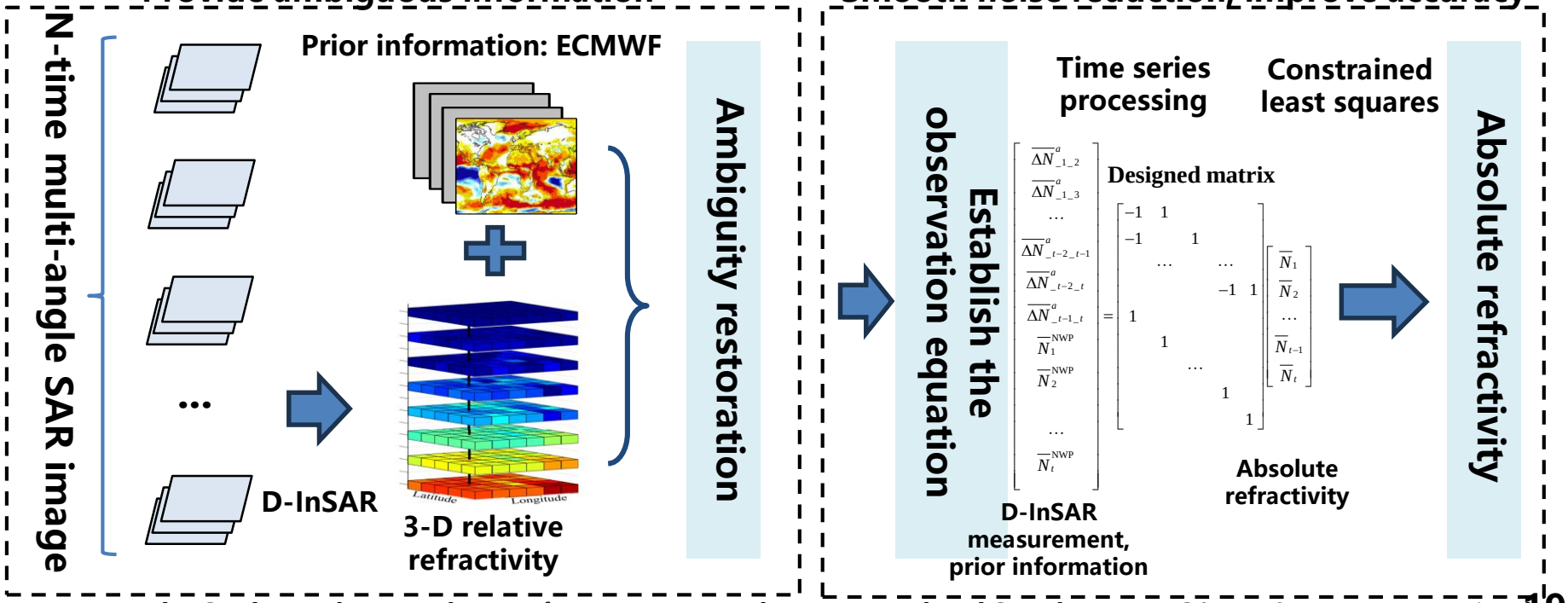
D-InSAR can only obtain the relative variation, there is ambiguity in the refractivity measurement

Method

Absolute quantity recovery method based on prior coarse meteorological information and time series processing

Prior rough meteorological information:
Provide ambiguous information

Time series processing:
Smooth noise reduction, improve accuracy



C. Liu, Y. Li, et al., "Single-Epoch Tropospheric Refractivity Tomography using Distributed Spaceborne D-InSAR," *2024 IEEE International Conference on Signal, Information and Data Processing* (ICSIDP), Zhuhai, China, 2024, pp. 1-6, doi: 10.1109/ICSIDP62679.2024.10868406.

Outline

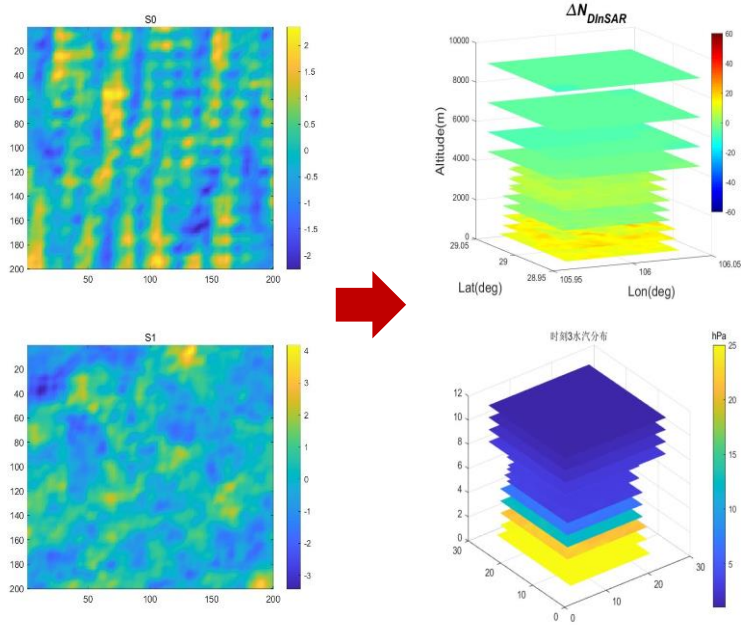
Simulation model

Dutch Atmospheric Large Eddy Simulation(DALES)

- Providing high-precision dynamics models, supporting atmospheric simulations in complex scenarios
- Capable of outputting high-precision, multi-parameters atmospheric simulation parameters under different conditions

Parameter Categories	Parameter Name	Symbol/Variable
Basic Meteorological Field	Horizontal wind speed (East/North)	u/v
	Temperature	T
	Water vapor pressure	e
⋮	⋮	⋮

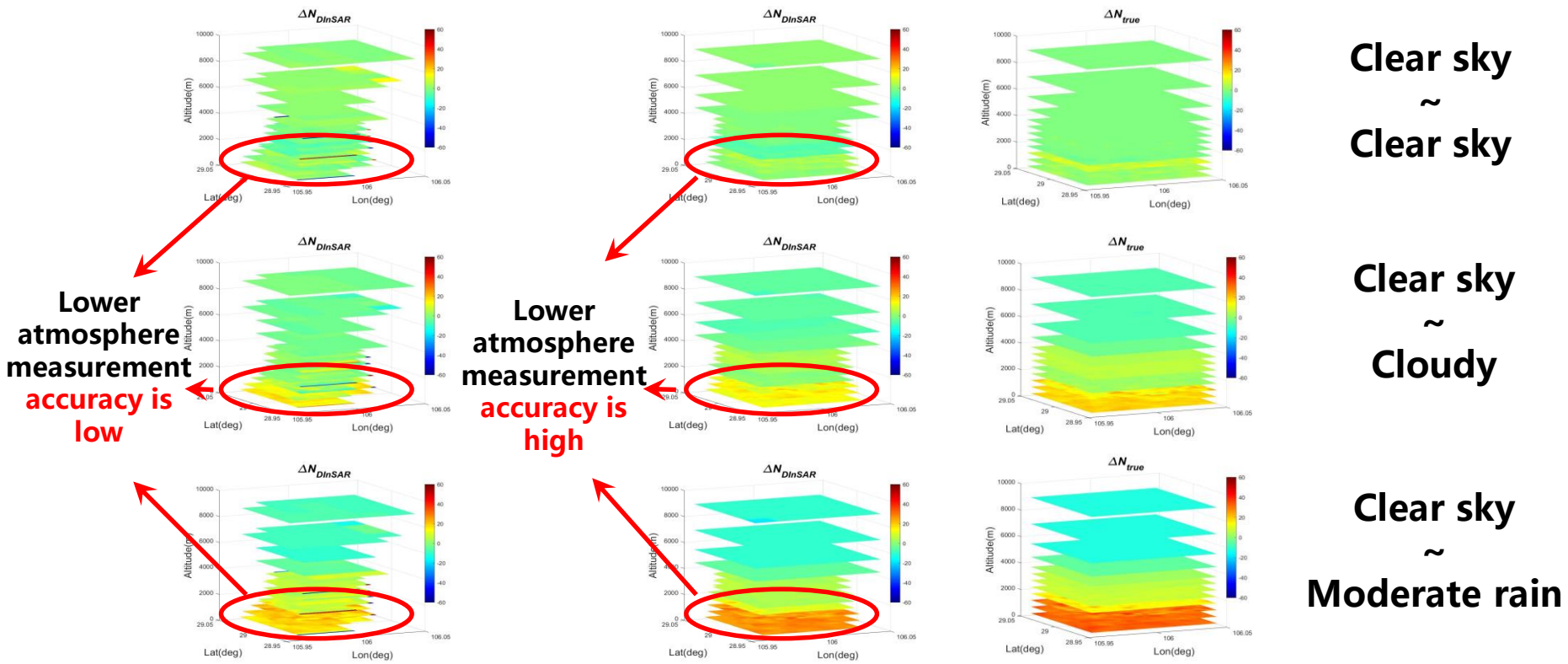
Output multiple high-resolution atmospheric parameters



Support high-precision simulation and analysis under different conditions

Result: 3-D relative tropospheric refractivity

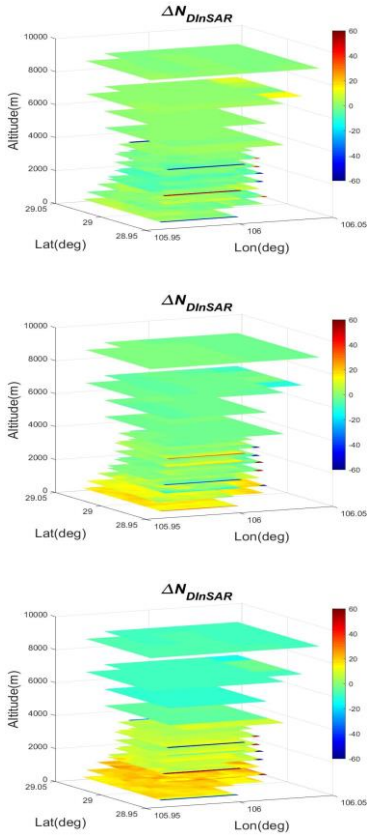
- Simulation condition: 10km×10km×10km, under three weather conditions
- Configuration optimization significantly enhances 3-D refractivity measurement performance, particularly in the lower tropospheric layers with high water vapor concentration



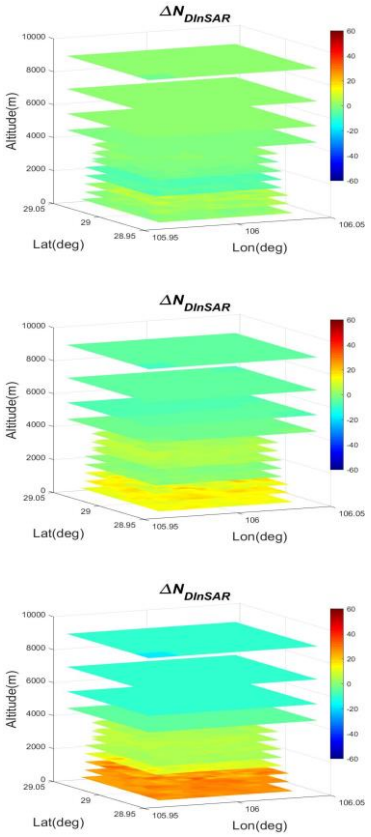
Result: 3-D relative tropospheric refractivity

Accuracy analysis of relative refractivity (△N) inversion

- Resolution: 400 m (≤4km), 1-2 km (＞4km)
- Retrieval accuracy: 4–12, with clear-sky conditions outperforming rainy conditions; optimized configurations can achieve an enhancement of 35–64%



Before-optimization



After-optimization

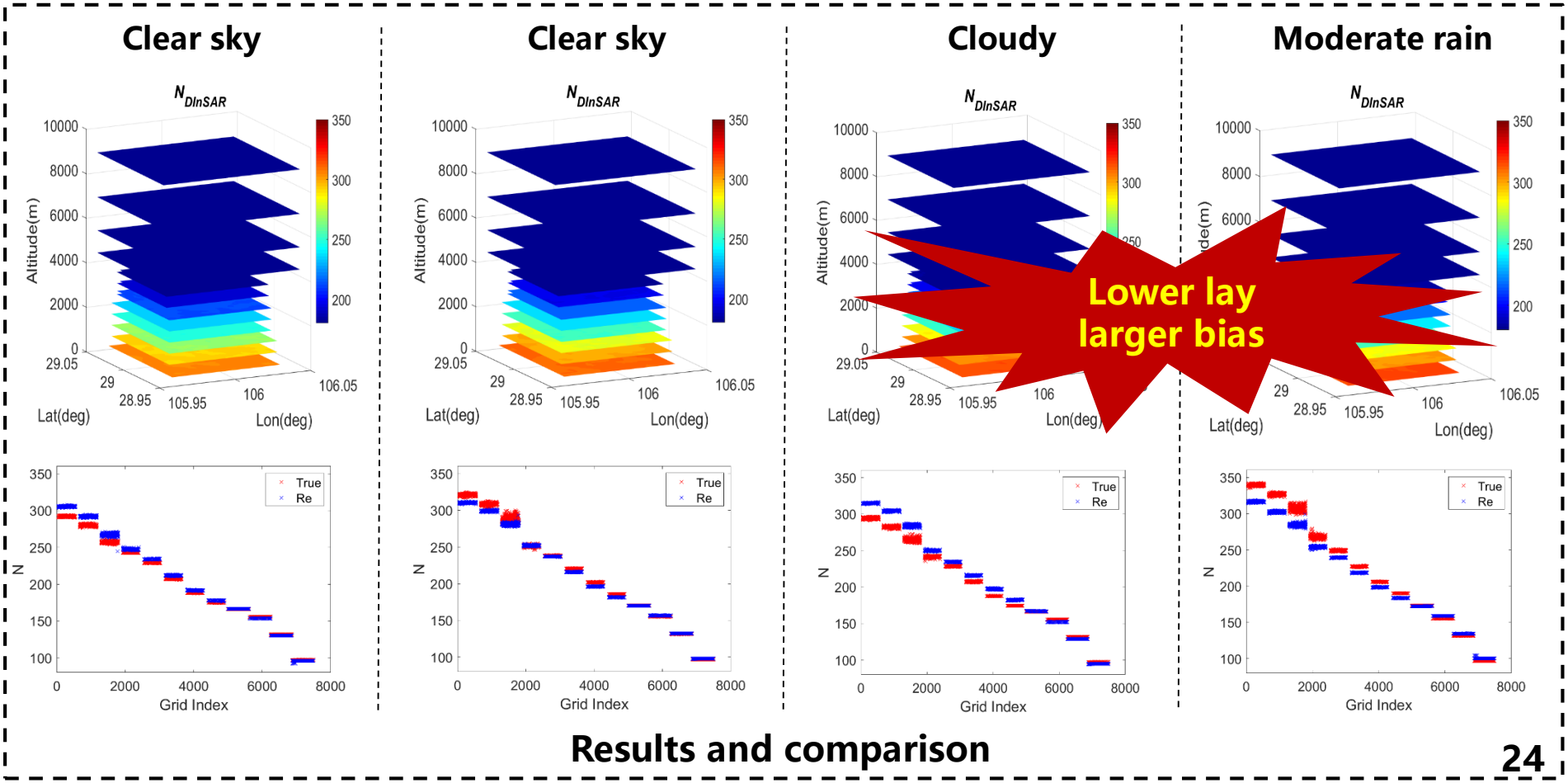
Root Mean Square Error (RMSE) of differential refractivity inversion results

Configuration optimization	Clear sky ~ Clear sky	Clear sky ~ Cloudy	Clear sky ~ Moderate rain
Before	11.949	14.584	17.709
After	4.415	8.864	11.499

Result: 3-D absolute tropospheric refractivity

Accuracy analysis of absolute refractivity (N) inversion

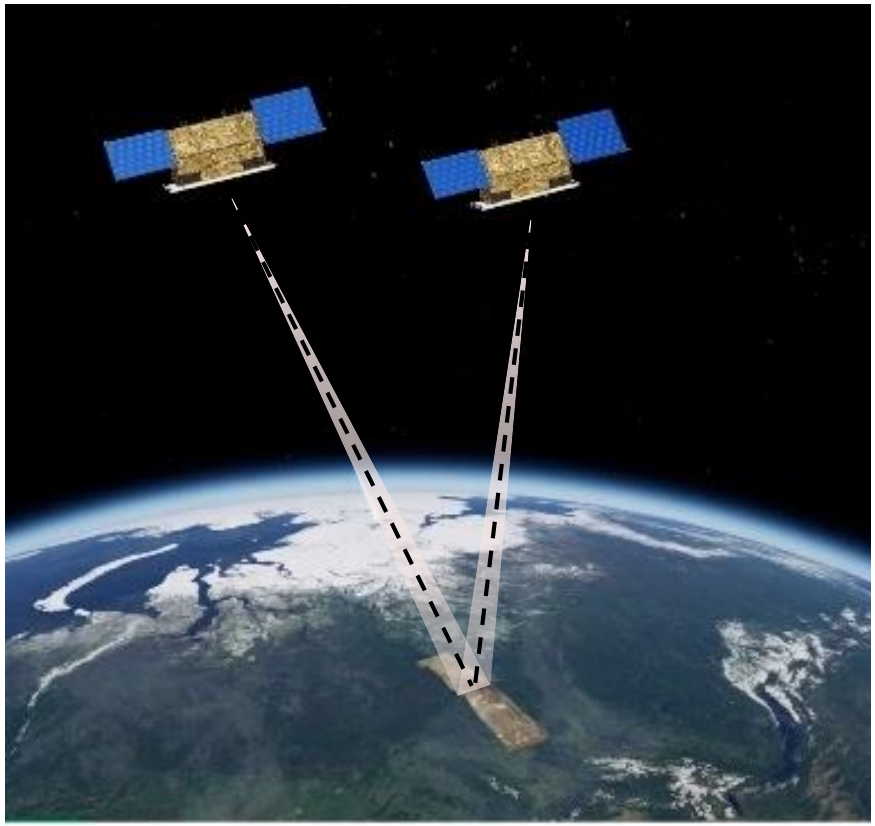
- RMSE is less than 10
- The accuracy of the refractivity correlates with the condition of atmospheric spatial variation, and degrades when spatial variation becomes severe



Results and comparison

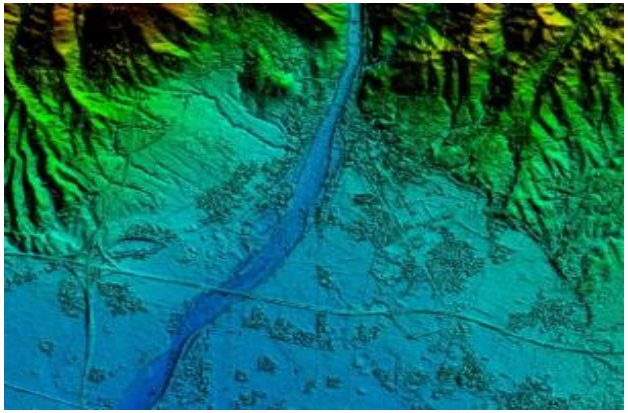
Result: In-orbit data validation

- **SUPERVIEW NEO-2 (launched in November 2024)**
  - **X-band, <1m resolution imaging**
  - **Tandem formation for topographic mapping**
  - **16-day revisit cycle for D-InSAR**



SUPERVIEW NEO-2 observation configuration

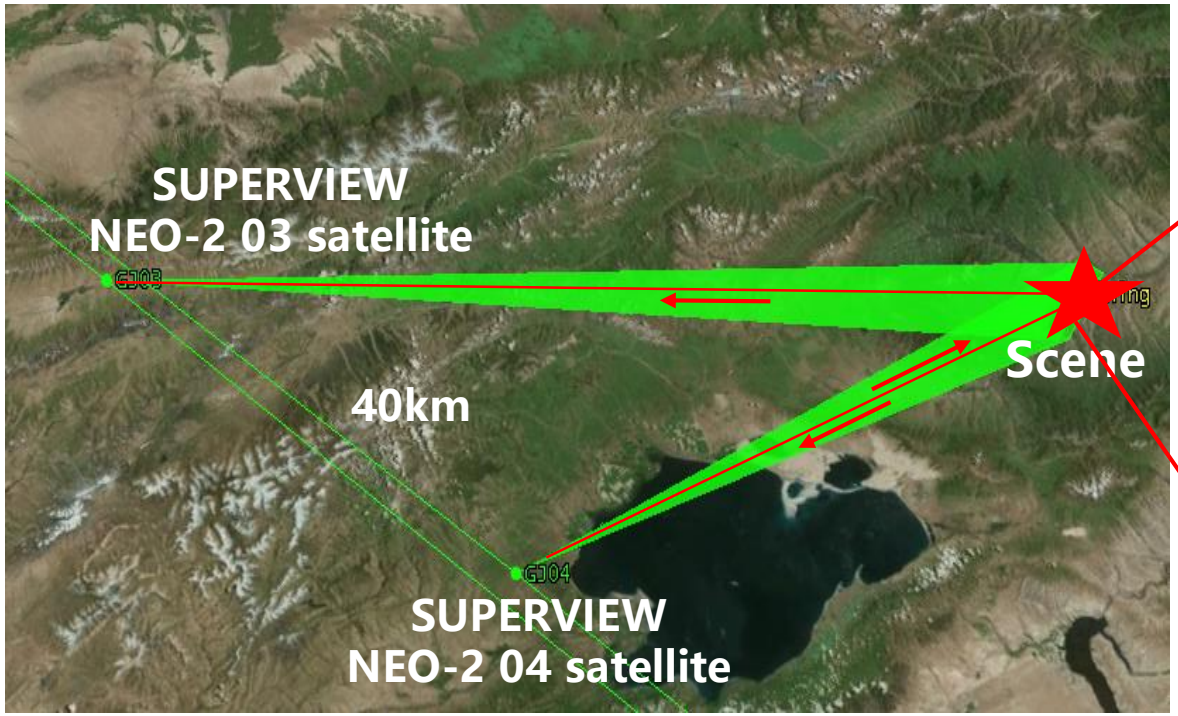
High-resolution SAR image



Topographic mapping

Result: In-orbit data validation

- **In-orbit data validation experiment :**
  - **Along-track long baseline of 40km between two satellites, single-transmitting-dual-receiving, dual-angle simultaneous observation**
  - **Scene: Bayinguoleng, Xinjiang, China**
  - **Acquisition: 4 December 2024 and 20 December 2024**

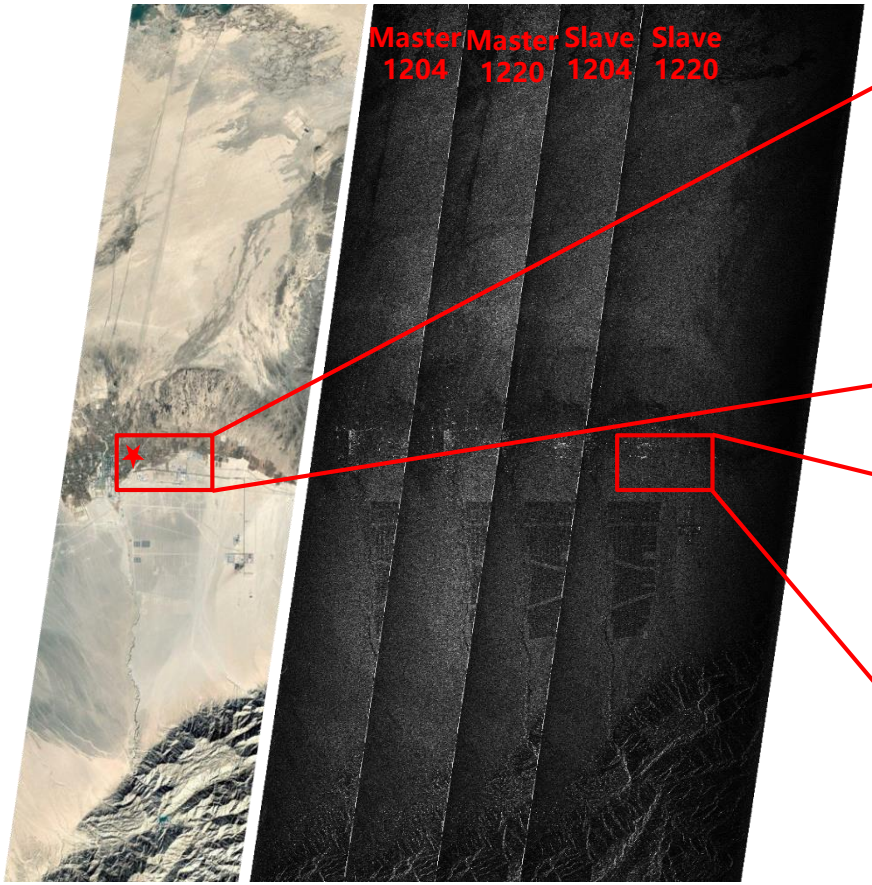


SUPERVIEW NEO-2 experimental observation configuration

Optical image of target scene (100km×20km)

Result: In-orbit data validation

- **In-orbit data validation experiment :**
  - **Selected area: 5km×10km (including radiosonde)**



Original aera

Optical image of selected area

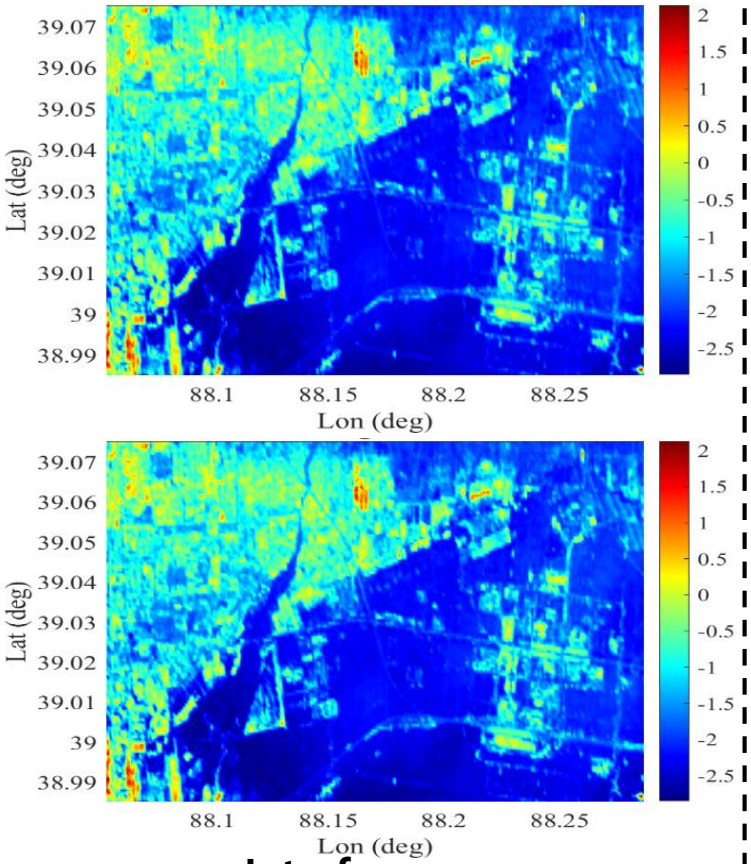
SAR image of selected area

Result: In-orbit data validation

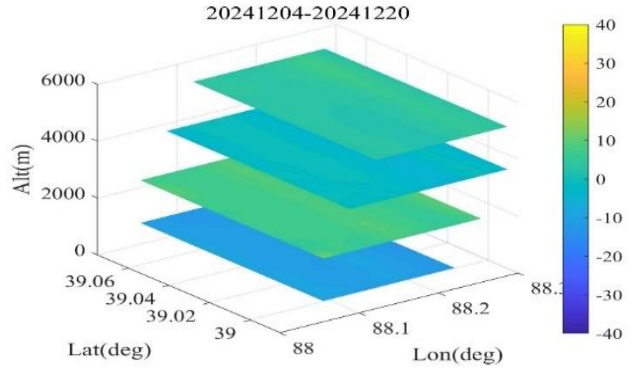
- Inversion grid: horizontal 625×1250m,vertical 1.5km
- RMSE of the inverted relative refractivity (△N) is less than 7 (compared with radiosonde, GFS and ECMWF)

Angle 1

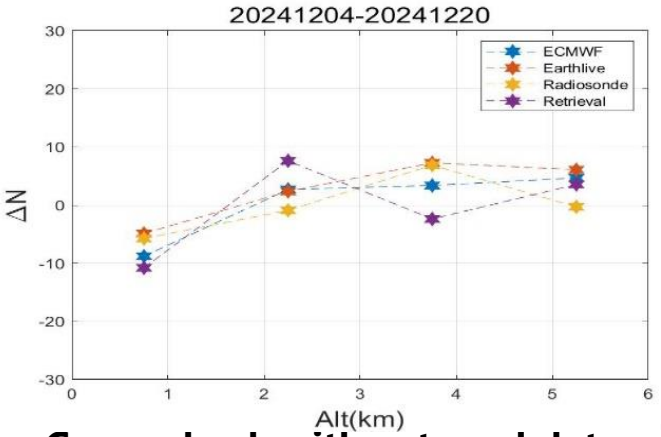
Angle 2



Interferogram



Relative refractivity inversion result



Cross-check with external data

Result: In-orbit data validation

Absolute refractivity inversion and accuracy analysis

- Use ECMWF as the prior coarse meteorological data
- The RMSE of the inverted absolute refractivity (N) is 5-10 (compared with GFS and radiosonde)

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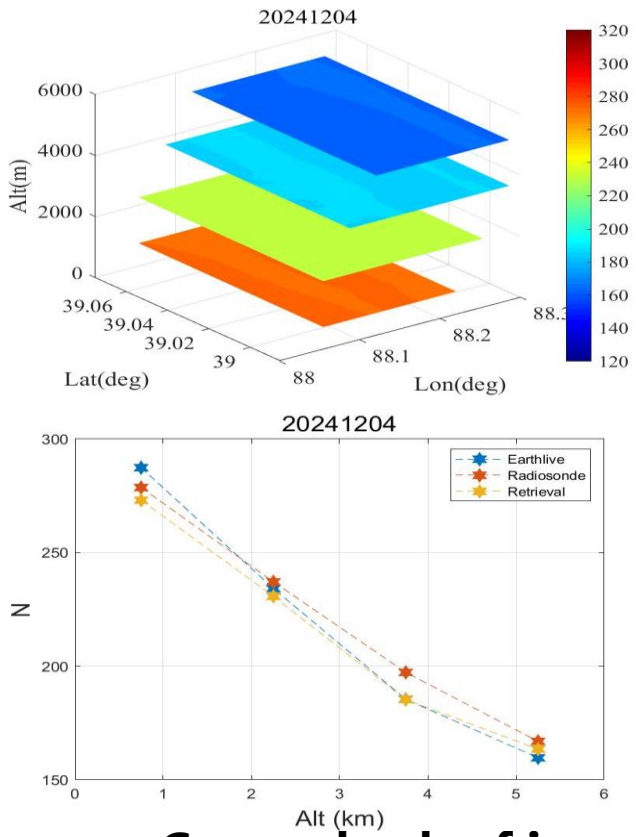

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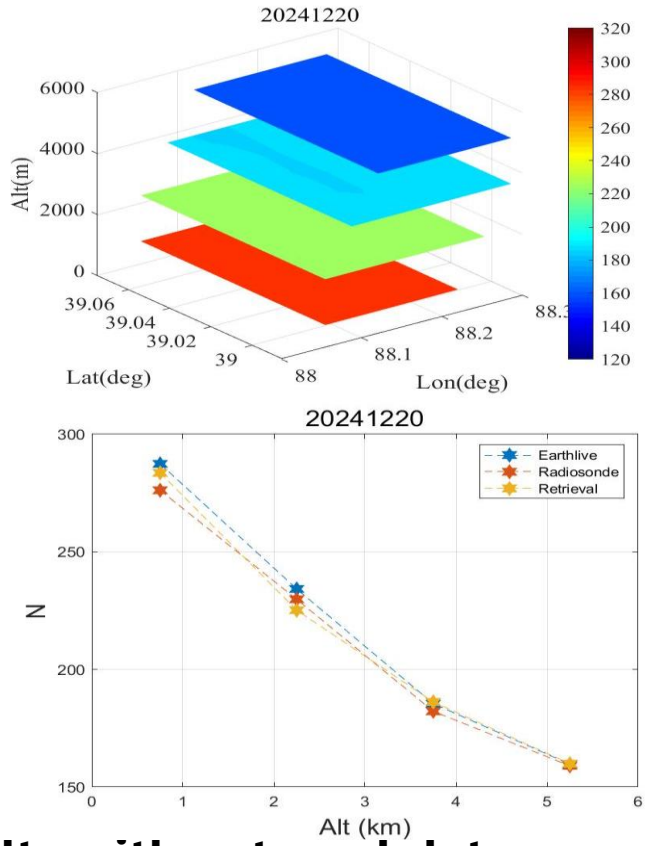

Cross-check of inversion results with external data

Outline

1 Research Background

2 Method

3 Validation and Results

4 Conclusion

Conclusion

Background

Current tropospheric atmospheric measurement techniques remain insufficient in spatial resolution

Concept

Tropospheric atmospheric multi-parameter measurement using distributed spaceborne multi-angle D-InSAR

Challenge

3-D accurate atmospheric measurement under sparse observation condition & absolute parameter inversion

Progress

Relative refractivity Inversion

Absolute refractivity Inversion

In-orbit data validation

Target

Enhances the accuracy of meteorological prediction

Addressing scientific challenges in atmospheric research