

Secondary InSAR Ionospheric Phase in NISAR Data

Kunyi Chen, Cunren Liang, Fan Yang, Xue Li and Yuhang Wang

Abstract—To understand its effects on InSAR, the ionospheric phase within the synthetic aperture is expanded about both the zero Doppler and Doppler centroid times. The two expansion approaches provide different interpretations of the ionospheric effects and offer insights into the complete removal of the InSAR ionospheric phase under different processing workflows. For the recommended workflow for processing L-band spaceborne SAR data, the combined application of fine coregistration after geometric coregistration and the range split-spectrum method results in a Secondary InSAR Ionospheric Phase (SIIP). In stationary scenarios, the correction of the SIIP is straightforward. For NISAR, which is characterized by a large Doppler centroid frequency, the SIIP is found to be non-negligible and should be corrected. The SIIP is illustrated, and its correction is validated, using L-band NISAR data.

Index Terms—InSAR, ionosphere, L-band, MAI, motion, NISAR

I. INTRODUCTION

WE are entering the golden age of L-band Synthetic Aperture Radar (SAR) satellites, which can effectively overcome some of the current bottlenecks of SAR interferometry (InSAR), such as decorrelation and phase unwrapping errors. Most of these newly developed SAR satellites achieve enhanced imaging capabilities through the implementation of advanced technologies. Consequently, several mainstream SAR systems are characterized by large Doppler centroid frequencies or squint angles, resulting in linear phase terms with large phase slopes in the signal. Such linear phase components do not carry information of the ground and may contaminate the signal of interest if not properly addressed. For NISAR, the squint angle of the L-band SAR is approximately 0.9° (forward steering along the flight direction) due to the fore-aft arrangement of the L- and S-band feed-arrays in azimuth [1], [2]. For ROSE-L, the squint angle varies in azimuth due to the use of ScanSAR mode [3], [4].

At L-band, the electromagnetic wave is strongly refracted as it propagates through the Earth's ionosphere. In azimuth, the ionospheric effects are complex as the signal from a point target traverses different horizontal regions of the ionosphere, leading to variations in the ionospheric phase advance imposed on the Doppler phase history within the synthetic aperture. Notably, the odd-order components of the phase

advance induce an azimuth shift in the amplitude of the focused image [5], which has been frequently observed in practice [6-11]. The azimuth ionospheric shift is on the order of meters and is often comparable to or even greater than the azimuth resolution, potentially resulting in substantial coherence loss if left uncorrected.

While InSAR has become an established technique, there is still some diversity among the processing workflows. Practical workflows for processing L-band data may address the two most significant ionospheric effects in InSAR: the Constant InSAR Ionospheric Phase (CIIP) and the azimuth ionospheric shift. These effects are further coupled with the linear phase arising from the Doppler centroid frequency. Consequently, different processing strategies may lead to different InSAR results, with some workflows introducing a residual phase error, which is referred to in this paper as the Secondary InSAR Ionospheric Phase (SIIP).

To understand these problems and provide guidance for InSAR processing workflows, we expand the ionospheric phase within the synthetic aperture about both the zero Doppler and Doppler centroid times in Section II-B. Based on these expansions, we provide two interpretations of the ionospheric contribution to the Spectral Diversity (SD) [13] or Multiple-Aperture InSAR (MAI) phase in Section II-C. The impacts of the SIIP on InSAR time series and the correction of the SIIP are investigated in Sections II-D and II-E, respectively. In Section II-F, we analyze the potential impacts on NISAR InSAR motion measurements. In Section III, we present examples illustrating the SIIP using L-band NISAR data. Finally, Section IV concludes the paper.

II. THEORY

A. Background

To simplify the discussion, the azimuth SAR signal received from a point target is approximated as a linear Frequency-Modulated (FM) signal [15]

$$s_{az}(\eta) = A_0 w_a(\eta - \eta_{DC}) \exp \{-j\pi K_a \eta^2\} \quad (1)$$

where A_0 represents the complex reflectivity of the point target, $w_a(\cdot)$ represents the azimuth envelope determined by the two-way antenna pattern, η is the azimuth time with its origin defined at zero Doppler time η_{ZD} ($\eta_{ZD}=0$), η_{DC} is the Doppler centroid time, and K_a represents the azimuth FM rate.

As the radar signal propagates through the ionosphere, it accumulates a two-way phase advance given by [16]

$$\phi_{ion}(\eta) = 4\pi K \frac{TEC(\eta)}{cf_0} \quad (2)$$

where $TEC(\eta)$ denotes the total electron content integrated along the signal path, $K=40.31 \text{ m}^3/\text{s}^2$, c is the speed of light in vacuum, and f_0 is the radar carrier frequency. The azimuth varying nature of the ionospheric TEC is explicitly manifested

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in $TEC(\eta)$. In the presence of the ionosphere, the azimuth SAR signal is expressed as

$$s_{az}(\eta) = A_0 w_a(\eta - \eta_{DC}) \exp\{-j\pi K_a \eta^2\} \exp\{j\varphi_{ion}(\eta)\} \quad (3)$$

The imaging geometry in the presence of the ionosphere is shown in Fig. 1.

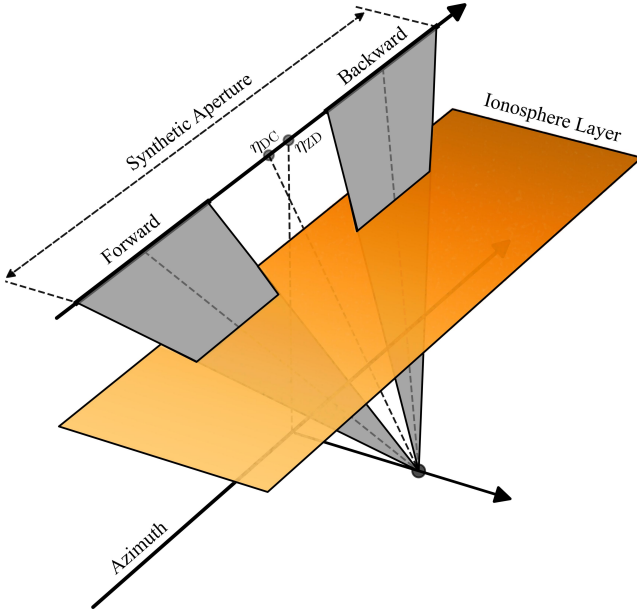


Fig. 1. SAR imaging geometry in the presence of the ionosphere, which is simplified as a thin layer.

B. Two Approaches for Expanding the Azimuth Ionospheric Phase within the Synthetic Aperture

To investigate the contributions of different components of the ionospheric phase, in particular the constant and linear components, it is natural to expand (2) using a Taylor series within the synthetic aperture. The zero Doppler time η_{ZD} and the Doppler centroid time η_{DC} represent the two most suitable expansion points.

We first consider the Taylor expansion about the zero Doppler time η_{ZD} . Then (2) can be expressed as

$$TEC(\eta) = TEC(\eta_{ZD}) + \frac{\partial TEC(\eta)}{\partial \eta} \Big|_{\eta=\eta_{ZD}} \eta + \frac{1}{2} \frac{\partial^2 TEC(\eta)}{\partial \eta^2} \Big|_{\eta=\eta_{ZD}} \eta^2 + \dots + \frac{1}{n!} \frac{\partial^n TEC(\eta)}{\partial \eta^n} \Big|_{\eta=\eta_{ZD}} \eta^n + \dots \quad (4)$$

Since the variation of a physical quantity is generally dominated by low-order components, we further simplify the analysis by retaining only the constant and linear terms of the TEC variation. Then (3) reduces to

$$s_{az}(\eta) = A_0 w_a(\eta - \eta_{DC}) \exp\{-j\pi K_a \eta^2\} \exp\{j[\varphi_{ion, ZD} + 2\pi f_{ion} \eta]\} \quad (5)$$

where

$$\begin{cases} \varphi_{ion, ZD} = \frac{4\pi K}{c f_0} TEC(\eta_{ZD}) \\ f_{ion} = \frac{2K}{c f_0} \frac{\partial TEC}{\partial \eta} \Big|_{\eta=\eta_{ZD}} \end{cases} \quad (6)$$

By applying the Principle of Stationary Phase (POSP) [17], its spectrum can be derived as

$$S_{az}(f) = A_0 W_a(f - f_{DC} - f_{ion}) \exp\left\{j\pi \frac{(f - f_{ion})^2}{K_a}\right\} \exp(j\varphi_{ion, ZD}) \quad (7)$$

where $f_{DC} = -K_a \eta_{DC}$ is the original Doppler centroid frequency without considering the ionospheric phase, and $W_a(f - f_{DC} - f_{ion})$ represents the envelope of the azimuth spectrum, which is centered at $f_{DC} + f_{ion}$. Here, the constant term arising from the POSP has been omitted.

The matched filter, which ignores the ionospheric phase, is constructed by taking the complex conjugate of the quadratic phase term in $S_{az}(f)$

$$H_{az}(f) = \text{rect}\left[\frac{(f - f_{DC})}{B}\right] \exp\left\{-j\pi \frac{f^2}{K_a}\right\} \quad (8)$$

where $\text{rect}(\cdot)$ denotes the rectangular function, and B is the azimuth bandwidth. Consequently, the spectrum after applying this matched filter is given by

$$S_{az, \text{focused}}(f) = S_{az}(f) \cdot H_{az}(f) \approx A_0 W_a\left(f - f_{DC} - \frac{f_{ion}}{2}\right) \times \exp\left\{j\pi \left[\frac{-2ff_{ion} + f_{ion}^2}{K_a}\right]\right\} \exp(j\varphi_{ion, ZD}) \quad (9)$$

The time-domain focusing result is obtained by an inverse Fourier transform, yielding

$$s_{az, \text{focused}}(\eta) \approx A_0 \text{sinc}\left\{B\left(\eta - \frac{f_{ion}}{K_a}\right)\right\} \times \exp\left\{j\left[2\pi\left(f_{DC} + \frac{f_{ion}}{2}\right)\eta - 2\pi f_{DC} \frac{f_{ion}}{K_a}\right]\right\} \exp(j\varphi_{ion, ZD}) \quad (10)$$

Given that the magnitude of f_{ion} (mostly below 1 Hz) is generally small compared to f_{DC} , (10) can be approximated as

$$s_{az, \text{focused}}(\eta) \approx A_0 \text{sinc}\left\{B\left(\eta - \frac{f_{ion}}{K_a}\right)\right\} \times \exp\left\{j2\pi f_{DC} \left(\eta - \frac{f_{ion}}{K_a}\right)\right\} \exp(j\varphi_{ion, ZD}) \quad (11)$$

The linear phase term in (11) arises from the Doppler centroid frequency f_{DC} .

In the second approach, we expand (2) about the Doppler centroid time η_{DC} as in [5] and again retain the constant and linear terms of the TEC variation. Then, (3) can be expressed as

$$s_{az}(\eta) = A_0 w_a(\eta - \eta_{DC}) \exp\{-j\pi K_a \eta^2\} \times \exp\{j[\varphi_{ion, DC} + 2\pi f_{ion}(\eta - \eta_{DC})]\} \quad (12)$$

where $\varphi_{ion, DC}$ is the ionospheric phase at η_{DC} . Following a similar procedure, the focused azimuth signal in the time domain can be derived as

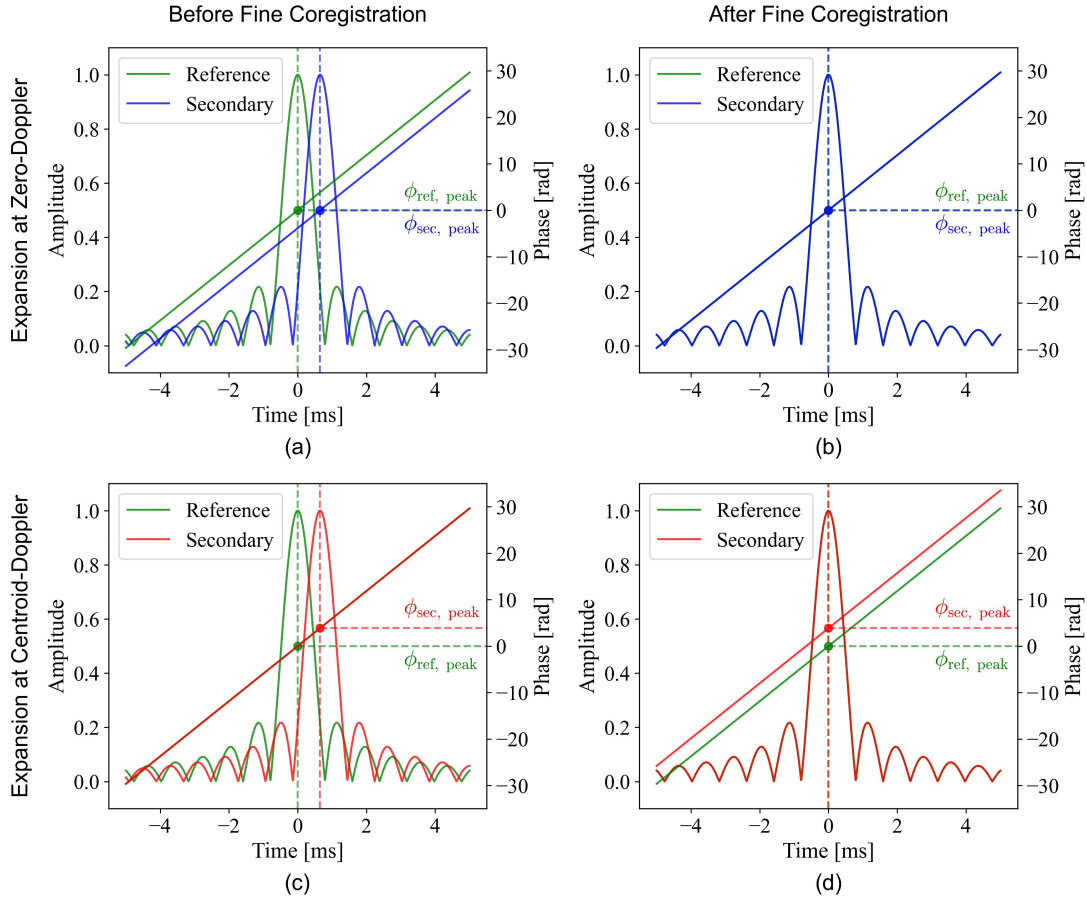


Fig. 2. Illustration of different InSAR processing workflows using focusing results from the two Taylor series expansion approaches. The constant ionospheric phases are neglected. The parameters are those of NISAR, with $K_a=460$ Hz/s and an equivalent PRF of 1520 Hz. The reference is assumed to be ionosphere-free for simplicity. For the secondary, f_{ion} is set to 0.3 Hz, corresponding to an azimuth shift of approximately 1.0 pixel.

$$\begin{aligned}
 s_{az, \text{focused}}(\eta) &\approx A_0 \text{sinc} \left\{ B \left(\eta - \frac{f_{ion}}{K_a} \right) \right\} \times \\
 &\exp \left\{ j2\pi \left(f_{DC} + \frac{f_{ion}}{2} \right) \eta \right\} \exp \{ j\varphi_{ion, DC} \} \\
 &\approx A_0 \text{sinc} \left\{ B \left(\eta - \frac{f_{ion}}{K_a} \right) \right\} \exp \{ j2\pi f_{DC} \eta \} \exp \{ j\varphi_{ion, DC} \} \quad (13)
 \end{aligned}$$

The signal models in (11) and (13) differ primarily in the azimuth ionospheric shift, the linear phase corresponding to the Doppler centroid frequency, and the constant ionospheric phase. Mathematically, (13) and (11) are equal. However, they imply distinct physical interpretations. In (11), the constant ionospheric phase is the one at the zero Doppler time $\varphi_{ion, ZD}$, whereas in (13), it is the one at the Doppler centroid time $\varphi_{ion, DC}$. Neglecting the constant ionospheric phases, the entire focused signal in (11) is shifted by f_{ion}/K_a with respect to the zero Doppler time. In contrast, only the amplitude envelope of the signal is shifted by f_{ion}/K_a in (13), while the linear phase term remains anchored at the zero Doppler time.

While InSAR is an established technique, various processing options and techniques are available, resulting in different processing workflows. In terms of the ionosphere, two effects are generally mitigated. The first is the constant ionospheric phase in either (11) or (13), which gives rise to the

CIIP when forming the interferogram between the reference and secondary images. The widely used range split-spectrum method [18]-[20] estimates the effective average of the ionospheric phase over the synthetic aperture, which can be approximated by the CIIP at the Doppler centroid time arising from $\varphi_{ion, DC}$.

The second concerns the azimuth ionospheric shift. At L-band, the shift f_{ion}/K_a , when converted to a distance, is typically a few meters or greater. Consequently, following an initial coregistration using geometric offsets (hereafter referred to as geometric coregistration) [12], it is generally recommended to further coregister the images to account for these shifts and thus improve coherence (hereafter referred to as fine coregistration), which primarily relies on intensity via incoherent cross correlation.

Workflows differing in their treatment of the two effects lead to different InSAR results:

- 1) For the signal model in (11), the CIIP at the zero Doppler time arising from $\varphi_{ion, ZD}$ is removed. Geometric coregistration leaves an SIIP of $-2\pi f_{DC} f_{ion}/K_a$, while further fine coregistration completely removes the ionospheric phase.
- 2) For the signal model in (13), the CIIP at the Doppler centroid time arising from $\varphi_{ion, DC}$ is removed.

Geometric coregistration completely removes the ionospheric phase, while further fine coregistration leaves an SIIP of $2\pi f_{DC} f_{ion} / K_a$.

Fig. 2 illustrates the differences between the workflows. In the recommended processing workflow for L-band data, the range split-spectrum method is employed to remove the CIIP at the Doppler centroid time. Therefore, the signal model in (13) applies. Furthermore, following geometric coregistration, fine coregistration is implemented to improve coherence. Consequently, an SIIP is induced.

C. Two Interpretations of SD/MAI Phase Arising from the Ionosphere

In the presence of the ionosphere, the azimuth Spectral Diversity (SD) [13] or the Multiple-Aperture InSAR (MAI) [21] phase comprises two components: one arising from azimuth ground motion and systematic errors, and the other induced by the ionosphere

$$\phi_{MAI} = \phi_{MAI, motion} + \phi_{MAI, ion} \quad (15)$$

The imaging geometry in the presence of the ionosphere is shown in Fig. 1.

For azimuth motion and most systematic errors, the amplitude and the linear phase of the focusing result are shifted simultaneously, as in (11). Assume that the secondary signal is shifted in azimuth by a total amount of $\Delta\eta$. Following an initial geometric coregistration, an InSAR phase bias arises from the difference between the original linear phase in the reference signal and shifted linear phase in the secondary signal

$$\phi_{InSAR, bias} = 2\pi f_{DC} \Delta\eta \quad (16)$$

Accordingly, the InSAR phase biases in the two sub-aperture interferograms are given by

$$\begin{cases} \phi_{InSAR, bias, b} = 2\pi f_{DC, b} \Delta\eta \\ \phi_{InSAR, bias, f} = 2\pi f_{DC, f} \Delta\eta \end{cases} \quad (17)$$

where $f_{DC, f}$ and $f_{DC, b}$ are the Doppler centroid frequencies of the forward and backward sub-apertures. The resulting MAI phase $\phi_{MAI, motion}$ is

$$\phi_{MAI, motion} = \phi_{InSAR, bias, b} - \phi_{InSAR, bias, f} = 2\pi (f_{DC, b} - f_{DC, f}) \Delta\eta \quad (18)$$

A further fine coregistration based on amplitude would move both the amplitude and the linear phase of the secondary signal by $\Delta\eta$ and consequently remove both the InSAR phase bias in (16) and the MAI phase $\phi_{MAI, motion}$ in (18).

For the ionosphere, when the CIIP is estimated by the range split-spectrum method, the focused signal is modeled as (13), and only the amplitude is shifted. Assume that f_{ion, t_1} and f_{ion, t_2} are the coefficients of the linear ionospheric phases in the reference and secondary signals. The relative shift of the amplitude is then $\Delta f_{ion} / K_a = (f_{ion, t_1} - f_{ion, t_2}) / K_a$. No InSAR phase bias is induced following an initial geometric coregistration. A further fine coregistration based on amplitude, however, would introduce an InSAR phase bias of

$$\phi_{InSAR, bias} = 2\pi f_{DC} \frac{\Delta f_{ion}}{K_a} \quad (19)$$

In each sub-aperture, the CIIP represents the average ionospheric phase over the sub-aperture, which can be approximated by the CIIP at the Doppler centroid time of the

sub-aperture. The focused sub-aperture signal should also be modeled as (13). Therefore, the CIIPs in the sub-aperture interferograms can be expressed as

$$\begin{cases} \phi_{ion, DC, f} = \phi_{ion, DC} + \frac{2\pi(f_{DC, f} - f_{DC, b})}{K_a} \Delta f_{ion} \\ \phi_{ion, DC, b} = \phi_{ion, DC} + \frac{2\pi(f_{DC, b} - f_{DC, f})}{K_a} \Delta f_{ion} \end{cases} \quad (20)$$

where $\phi_{ion, DC} = \phi_{ion, DC, t_1} - \phi_{ion, DC, t_2}$ is the difference between the constant ionospheric phases at the Doppler centroid time in the reference and secondary signals. The resulting MAI phase $\phi_{MAI, ion}$ is

$$\phi_{MAI, ion} = \phi_{ion, DC, f} - \phi_{ion, DC, b} = \frac{2\pi(f_{DC, b} - f_{DC, f})}{K_a} \Delta f_{ion} \quad (21)$$

In the second interpretation of the InSAR phase bias and MAI phase associated the ionosphere, we follow the approach used for the scenario of azimuth motion. Assume that a method is available to remove the CIIP at the zero Doppler time. Then the focused signal should be modeled as (11), and both the amplitude and the linear phase are shifted in the presence of ionosphere. The secondary signal is shifted relative to the reference signal by $\Delta\eta = \Delta f_{ion} / K_a$ as in the first interpretation. Following an initial geometric coregistration, an InSAR phase bias arises from the difference between the original linear phase in the reference signal and shifted linear phase in the secondary signal as in (16)

$$\phi_{InSAR, bias} = 2\pi f_{DC} \Delta\eta = 2\pi f_{DC} \frac{\Delta f_{ion}}{K_a} \quad (22)$$

In each sub-aperture, let the CIIP represent the ionospheric phase at the zero Doppler time. Then, the InSAR phase biases in the two sub-aperture interferograms are given by

$$\begin{cases} \phi_{InSAR, bias, b} = 2\pi f_{DC, b} \Delta\eta = 2\pi f_{DC, b} \frac{\Delta f_{ion}}{K_a} \\ \phi_{InSAR, bias, f} = 2\pi f_{DC, f} \Delta\eta = 2\pi f_{DC, f} \frac{\Delta f_{ion}}{K_a} \end{cases} \quad (23)$$

The resulting MAI phase $\phi_{MAI, ion}$ is

$$\phi_{MAI, ion} = \phi_{InSAR, bias, b} - \phi_{InSAR, bias, f} = 2\pi (f_{DC, b} - f_{DC, f}) \frac{\Delta f_{ion}}{K_a} \quad (24)$$

leading to the same result as in (21).

While (21) and (24) are mathematically equal, (21) has a more solid physical basis. In the first interpretation, the ionospheric contribution to the MAI phase is the difference between the CIIPs at the Doppler centroid times of the two sub-apertures. This interpretation is consistent with the interpretation of MAI [21]. In the second interpretation, the ionospheric contribution to the MAI phase results from the combined effect of the azimuth ionospheric shift and the linear phase corresponding to the Doppler centroid frequency. This interpretation is consistent with that of SD [13].

D. Impacts on InSAR Time Series

For repeat-pass SAR observations, the ionospheric state varies over time. Following the recommended processing workflow for L-band data, the focused signal should be modeled as (13). Geometric coregistration aligns the zero Doppler positions rather than the peak amplitude positions of

the $\text{sinc}(\cdot)$ functions. By substituting $\eta=0$ into (13), the InSAR ionospheric phase is given by

$$\phi_{\text{ion, geom}}(t_1, t_2) = \phi_{\text{ion, DC}, t_1} - \phi_{\text{ion, DC}, t_2} \quad (25)$$

where $\phi_{\text{ion, DC}, t_1}$ and $\phi_{\text{ion, DC}, t_2}$ are the constant ionospheric phases at the Doppler centroid time at times t_1 and t_2 , respectively. Subsequent fine coregistration aligns the peak positions, and the InSAR ionospheric phase becomes

$$\phi_{\text{ion, fine}}(t_1, t_2) = (\phi_{\text{ion, DC}, t_1} - \phi_{\text{ion, DC}, t_2}) + 2\pi f_{\text{DC}} \Delta\eta(t_1, t_2) \quad (26)$$

where $\Delta\eta(t_1, t_2)$ is the azimuth offset estimated via the fine coregistration. If the peak positions are perfectly aligned, (26) can be expressed as

$$\phi_{\text{ion, fine}}(t_1, t_2) = (\phi_{\text{ion, DC}, t_1} - \phi_{\text{ion, DC}, t_2}) + 2\pi f_{\text{DC}} \frac{f_{\text{ion}, t_1} - f_{\text{ion}, t_2}}{K_a} \quad (27)$$

In (26) and (27), the second terms are the SIIPs. $(\phi_{\text{ion, DC}, t_1} - \phi_{\text{ion, DC}, t_2})$ is the CIIP and removed by the range split-spectrum method, leaving only the SIIP.

A stack of SAR images can be similarly coregistered, i.e., all secondary images are first coregistered to the reference image using geometric offsets, followed by fine coregistration. Assume that the stack consists of n images with the first image serving as the reference. Then, the SIIPs with respect to the reference are given by

$$\begin{aligned} \phi_{\text{InSAR, bias}}(t_1, \dots, t_n) &= 2\pi f_{\text{DC}} \cdot \\ [0 \quad \Delta\eta(t_1, t_2) \quad \Delta\eta(t_1, t_3) \quad \dots \quad \Delta\eta(t_1, t_n)]^T \end{aligned} \quad (28)$$

The image stack can be processed using the Permanent Scatterer [22], Small Baseline Subset (SBAS) [24], or Phase Linking (PL) [25-27] technique to estimate the motion time series. Similar to ground motion, the SIIP is a deterministic function of $\Delta\eta$ and remains consistent across all InSAR pairs. In principle, (28) will propagate unaltered through any of the above stack processing techniques into the estimated time series. The mean or linear motion velocity is commonly estimated using a least-squares inversion of the motion time series. The velocity bias induced by the SIIP is thus given by

$$\mathbf{v}_{\text{bias}} = (\mathbf{H}_v^T \mathbf{W}_v \mathbf{H}_v)^{-1} \mathbf{H}_v^T \mathbf{W}_v \mathbf{M}_{\text{InSAR, bias}} \quad (29)$$

where $\mathbf{H}_v$ is the velocity design matrix, $\mathbf{W}_v$ is the weighting matrix, and $\mathbf{M}_{\text{InSAR, bias}} = \lambda / 4\pi \phi_{\text{InSAR, bias}}(t_1, \dots, t_n)$ denotes the motion biases induced by the SIIP.

For a SAR system with a large Doppler centroid frequency f_{DC} , such as NISAR, the potential impacts of SIIP on InSAR time series cannot be neglected. This is attributed, first, to its potentially large magnitude, as demonstrated in Sections II-F and III. Second, the SIIP in (28) are temporally correlated as a result of the 11-year solar cycle.

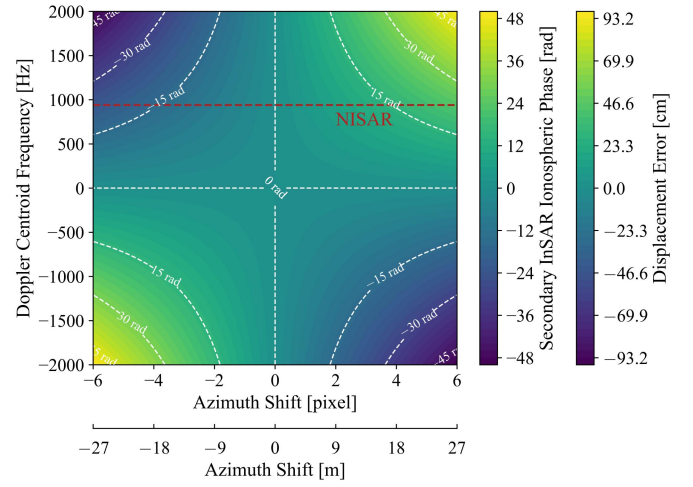


Fig. 3. InSAR motion bias due to the SIIP at L-band assuming NISAR parameters: $K_a=460$ Hz/s, $\text{PRF}=1520$ Hz, and the azimuth pixel size is 4.46 m.

E. Correction of the SIIP

The SIIP can be corrected straightforwardly using the residual azimuth offset field estimated during fine coregistration:

$$\tilde{\phi}_{\text{InSAR, bias}}(t_1, t_2, r, i) = 2\pi f_{\text{DC}} \Delta\eta(t_1, t_2, r, i) \quad (30)$$

where (r, i) is the pixel position, and $\Delta\eta(t_1, t_2, r, i)$ is the estimated offset field.

Current methods, such as incoherent cross correlation, estimate the total residual azimuth offset field, which can be generally expressed as

$$\Delta\eta(t_1, t_2, r, i) = \Delta\eta_{\text{motion}}(t_1, t_2, r, i) + \Delta\eta_{\text{ion}}(t_1, t_2, r, i) \quad (31)$$

where $\Delta\eta_{\text{motion}}(t_1, t_2, r, i)$ is the azimuth motion and systematic errors, and $\Delta\eta_{\text{ion}}(t_1, t_2, r, i)$ is the azimuth ionospheric shift. Unlike $\Delta\eta_{\text{ion}}(t_1, t_2, r, i)$, fine coregistration using $\Delta\eta_{\text{motion}}(t_1, t_2, r, i)$ leaves no phase bias associated with this component in the final interferogram. Therefore, the $\Delta\eta(t_1, t_2, r, i)$ in (30) should be replaced with $\Delta\eta_{\text{ion}}(t_1, t_2, r, i)$ for an accurate correction. Notably, $\Delta\eta_{\text{motion}}(t_1, t_2, r, i)$ is typically negligible compared to $\Delta\eta_{\text{ion}}(t_1, t_2, r, i)$, which is generally on the order of several meters after conversion into a distance. In non-stationary scenarios, such as earthquakes and glaciers, overcorrection by (30) can be significant.

Further secondary InSAR ionospheric phase may arise from the high-order components in TEC given by (4). The odd-order ionospheric components mainly shift the peak position and induce a phase bias proportional to the Doppler centroid frequency as the linear component, whereas the even-order components mainly induce a phase error in the focused signal. Such secondary InSAR ionospheric phase is generally much smaller than that arising from the linear component.

F. Impacts on NISAR InSAR Motion Measurements

According to (6) and (19), the bias in the measured motion can be derived as

$$\begin{aligned}
m_{\text{InSAR, bias}} &= \frac{\lambda}{4\pi} \phi_{\text{InSAR, bias}} \\
&= f_{\text{DC}} \frac{\lambda \Delta f_{\text{ion}}}{2K_a} \\
&\approx f_{\text{DC}} \cdot \frac{\lambda}{2} \cdot \frac{\lambda R_0}{2V_r^2} \cdot \frac{2K}{cf_0} \cdot \frac{\partial \Delta \text{TEC}}{\partial \eta} \Big|_{\eta=\eta_{\text{DC}}} \quad (32) \\
&= f_{\text{DC}} \lambda^3 \frac{R_0}{2c^2 V_r^2} K \frac{\partial \Delta \text{TEC}}{\partial \eta} \Big|_{\eta=\eta_{\text{DC}}} \\
&= \lambda^2 \frac{R_0 \sin \theta_{r,c}}{c^2 V_r} K \frac{\partial \Delta \text{TEC}}{\partial \eta} \Big|_{\eta=\eta_{\text{DC}}}
\end{aligned}$$

In deriving the last expression, we used the relationship between the Doppler centroid frequency and the squint angle $\theta_{r,c}$, given by $f_{\text{DC}} = 2V_r \sin \theta_{r,c} / \lambda$ [15]. Similar to the previously reported motion biases induced by the ionosphere in InSAR and MAI measurements, $m_{\text{InSAR, bias}}$ is proportional to the square of the radar wavelength. Therefore, this bias is significantly larger at L-band than at C-band. Nevertheless, it may be more useful to evaluate the resulting motion bias using the second line of (32).

Fig.3 illustrates the resulting InSAR motion bias due to the

SIIP at L-band. It is evident that this bias is substantial for NISAR, which is characterized by a large Doppler centroid frequency of approximately 940 Hz.

III. EXPERIMENT

A. Data

To validate the theory, we use L-band NISAR data acquired over India and Argentina as shown in Fig. 4. The data over India were acquired on October 17 and 29, 2025 (Track 5, Frames 76–80). The data feature a 40 MHz range bandwidth, with an additional 5 MHz sideband. The region, located in the equatorial ionospheric anomaly (EIA) due to the fountain effect, is characterized by high ionospheric TEC and variations, which induce strong azimuth ionospheric shifts. Over Argentina, we use six acquisitions spanning the period from October 22, 2025, to January 14, 2026 (Track 75, Frames 153–160). These data feature a 20 MHz main band and a 5 MHz sideband. The ionospheric effects in this region are moderate. In this region, we also use GPS measurements processed by the Nevada Geodetic Laboratory [28] to validate the InSAR time series. While the data have two polarizations, we only use the HH polarization.

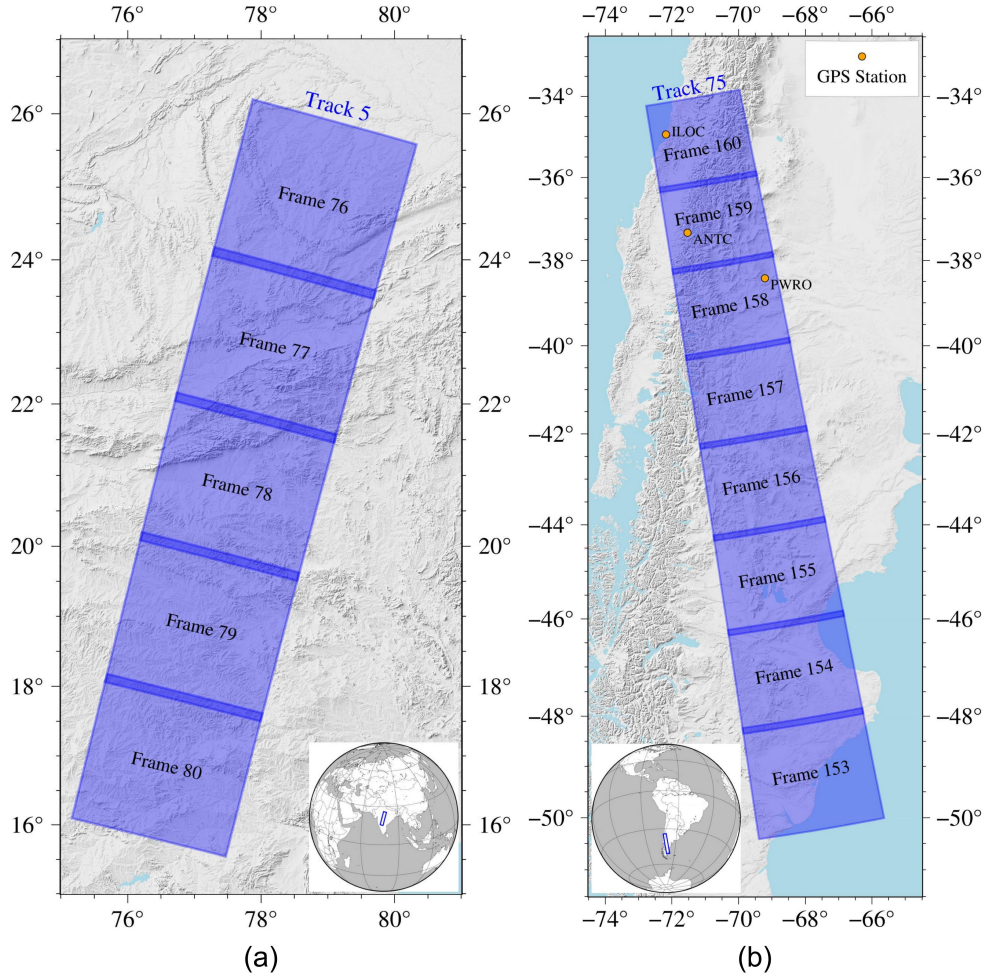


Fig. 4. Coverage of L-band NISAR data and locations of GPS stations. (a) Track 5 in the India region. (b) Track 75 in the Argentina region.

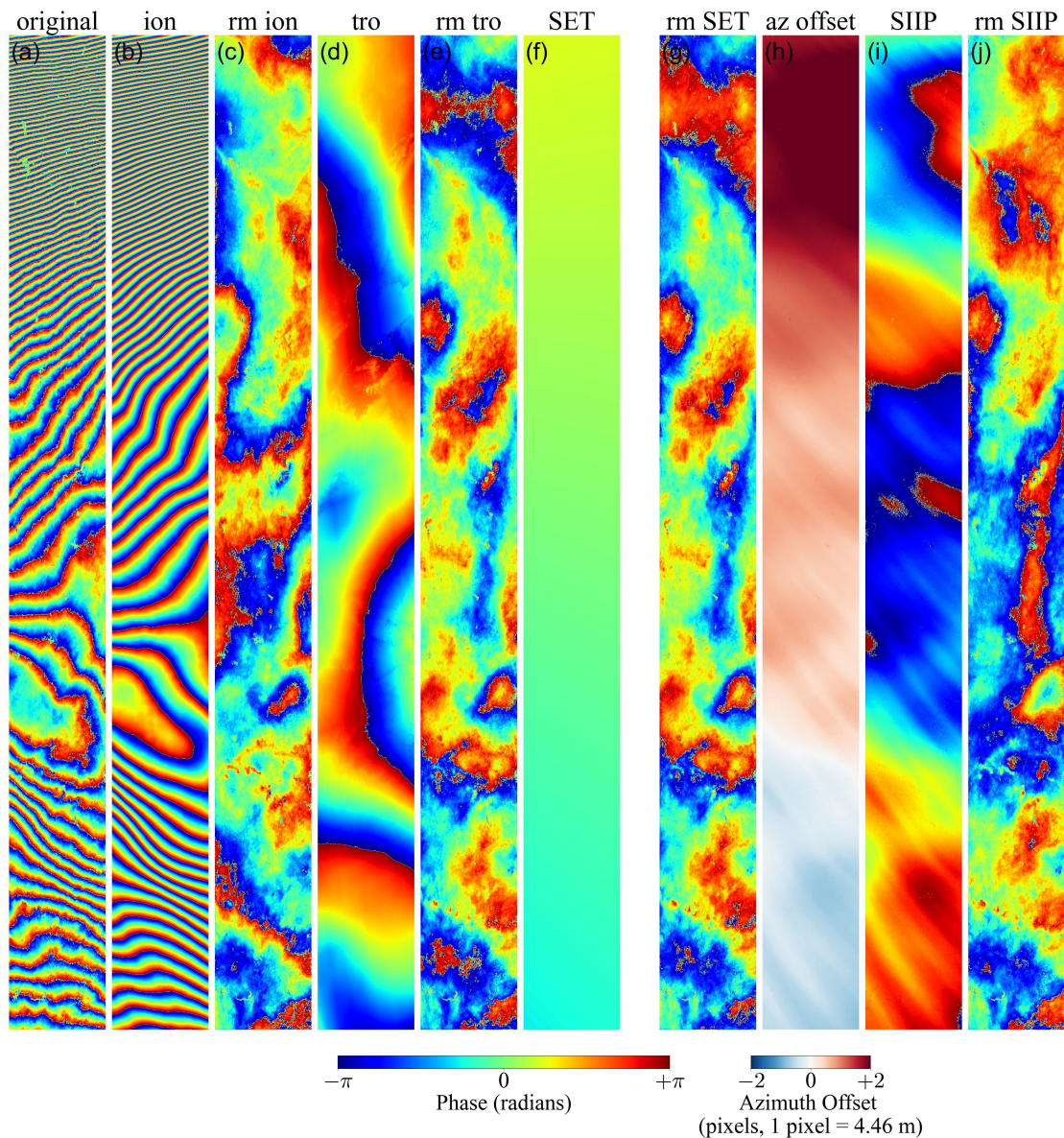


Fig. 5. SIIP of an interferogram over India formed with fine coregistration using a pair of L-band HH polarization NISAR data acquired on October 17 and 29, 2026. (a) Original interferogram with the topographic phase removed. (b) CIIP estimated via the range split-spectrum method. (c) Interferogram with the CIIP removed. (d) Tropospheric phase derived from ERA5 reanalysis data. (e) Interferogram with the tropospheric phase removed. (f) Phase induced by the SET. (g) Interferogram with the SET phase removed. (h) Azimuth offset estimated via incoherent cross correlation. (i) SIIP computed using (30). (j) Interferogram with the SIIP removed. All interferograms are multilooked by 40×50 looks in range and azimuth, respectively.

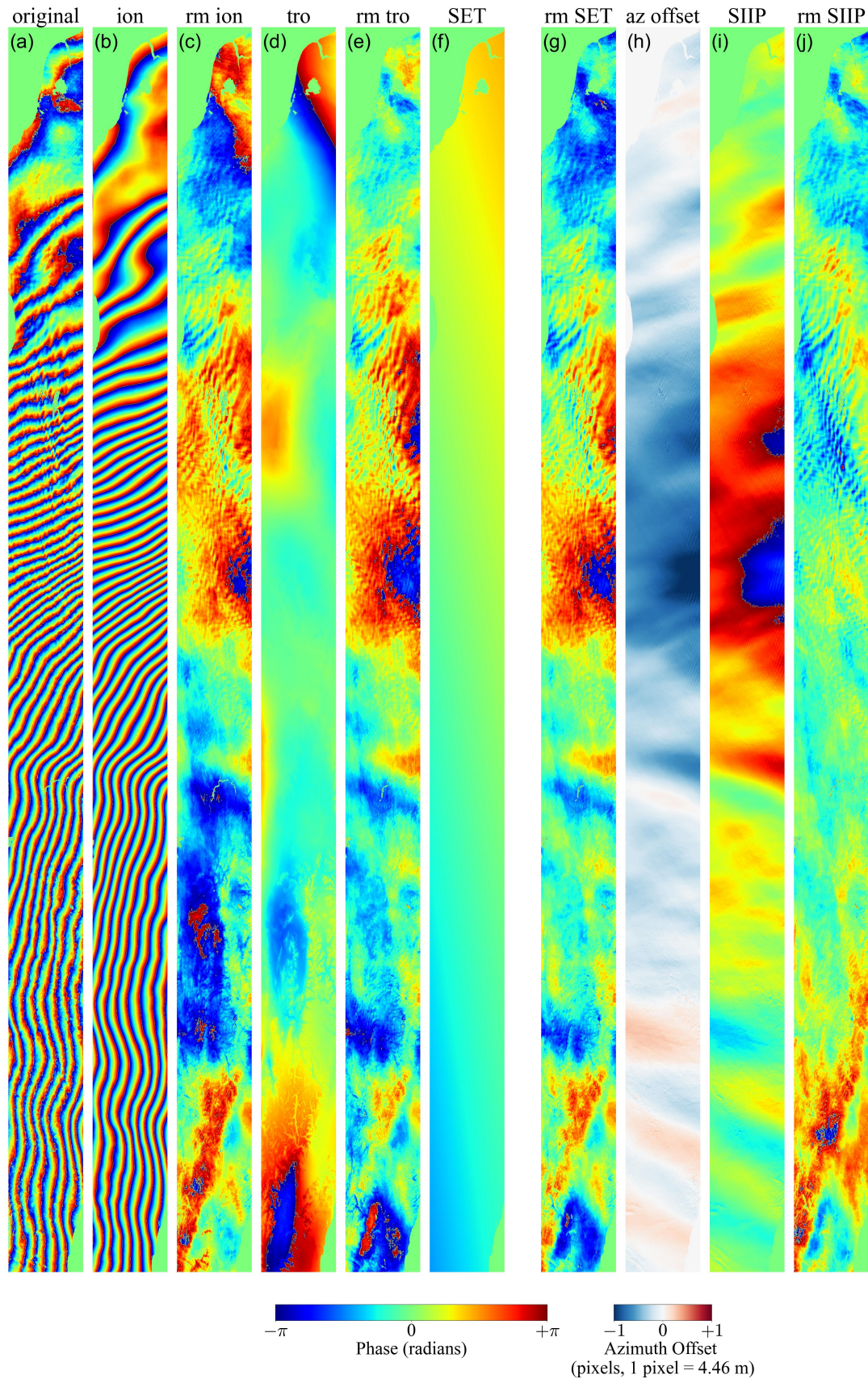


Fig. 6. SIIP of an interferogram over Argentina formed with fine coregistration using a pair of L-band HH polarization NISAR data acquired on January 2 and 14, 2026. (a) Original interferogram with the topographic phase removed. (b) CIIP estimated via the range split-spectrum method. (c) Interferogram with the CIIP removed. (d) Tropospheric phase derived from ERA5 reanalysis data. (e) Interferogram with the tropospheric phase removed. (f) Phase induced by the SET. (g) Interferogram with the

SET phase removed. (h) Azimuth offset estimated via incoherent cross correlation. (i) SIIP computed using (30). (j) Interferogram with the SIIP removed. All interferograms are multilooked by 40×50 looks in range and azimuth, respectively.

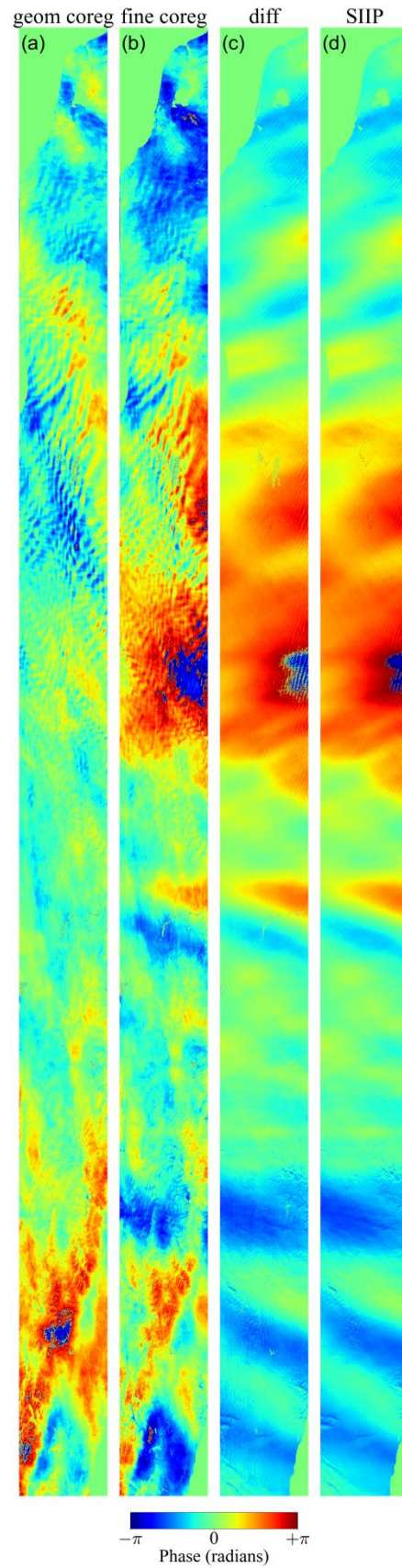


Fig. 7. (a) Interferogram formed with only geometric coregistration. (b) Interferogram formed with fine coregistration. (c) Difference between (a) and (b). (d) SIIP computed using (30). The same data as those in Fig. 6 are used. All other phase components are removed as in Fig. 6. All interferograms are multilooked by 40×50 looks in range and azimuth, respectively.

B. Processing

We processed the data following the standard workflow in the ISCE3 software [29], with a few improvements. In this workflow, the images from different frames are mosaicked after being ingested into the software. The secondary images are first coregistered using geometric offsets and subsequently fine coregistered using offset fields estimated by incoherent cross correlation. The ionospheric phase is estimated using an improved version of the range split-spectrum method. This estimate can be approximated by the CIIP at the Doppler centroid time. Following the removal of this phase, the interferograms formed with fine coregistration are subject to the SIIP, whereas the interferograms formed with only geometric coregistration are free of the SIIP.

To facilitate the investigation of the SIIP, we further mitigated the tropospheric phase using the PyAPS software [30] with ERA5 reanalysis data as input [31] and corrected for the Solid Earth Tide (SET) phase using PySolid [32], [33]. The SIIP was computed according to (30).

For the InSAR time-series analysis, we employed a least-squares approach to invert the motion time series.

C. Results

Fig. 5 and 6 show the results for single interferograms over India and Argentina, respectively. Following the removal of the CIIP at the Doppler centroid time, the tropospheric phase, and the SET phase, the interferogram formed with fine coregistration exhibits a clear phase anomaly that is highly correlated with the azimuth offset field used in fine coregistration. This phase anomaly is effectively removed using (30). The SIIP in the interferogram over India is much larger, but is largely obscured by the residual tropospheric phase.

As explained in Section II, an interferogram formed with only geometric coregistration should be free of the SIIP. Fig. 7 presents a comparison of the interferograms formed with geometric coregistration alone, the interferograms formed with fine coregistration, and the corresponding SIIP. The difference

between the two interferograms represents the SIIP, which has been accurately computed using (30).

To further validate the correction of the SIIP, we compare the motion time series with GPS measurements in Fig. 8. These GPS stations are marked in Fig. 4. It is evident the results with the SIIP removed are more consistent with GPS measurements. The remaining discrepancies are likely caused by the unmitigated tropospheric phases.

IV. CONCLUSION

A Taylor series expansion of the ionospheric phase within the synthetic aperture about the zero Doppler and Doppler centroid times provides new insights into the azimuth ionospheric shift, the linear phase corresponding to the Doppler centroid frequency, and the CIIP. The ionospheric contribution to the MAI phase can be interpreted either as the difference between the CIIPs at the Doppler centroid times of the two sub-apertures, or as a result of the azimuth ionospheric shift and the linear phase corresponding to the Doppler centroid frequency. The latter interpretation holds if the second or higher order terms of the ionospheric phase within the synthetic aperture are neglected. The complete removal of the InSAR ionospheric phase depends on the specific processing workflow. For the recommended workflow for processing L-band spaceborne SAR data, the joint use of fine coregistration following geometric coregistration and the range split-spectrum method introduces an SIIP. The correction of the SIIP is straightforward in stationary scenarios. For NISAR, which is characterized by a large Doppler centroid frequency, the SIIP is non-negligible and should be corrected.

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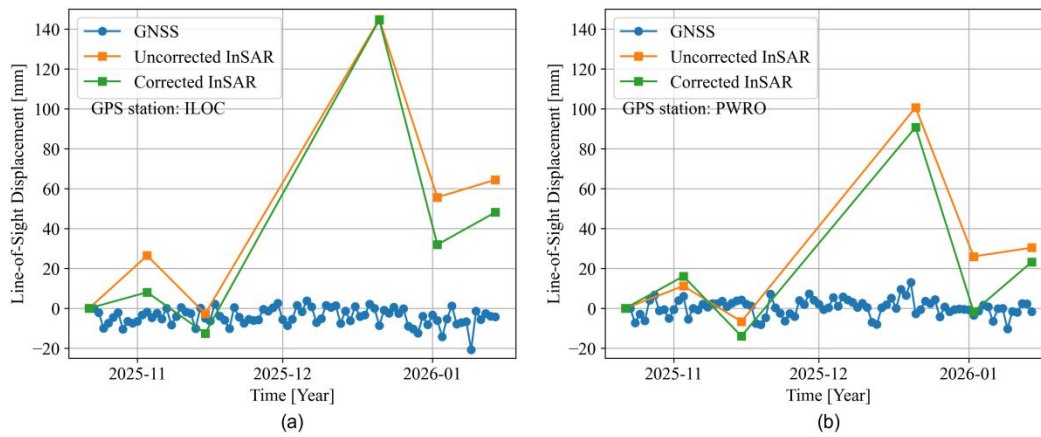


Fig. 8. Comparison of motion time series measured by InSAR and GPS in the Argentina region. (a) GPS station ILOC. (b) GPS station PWRO. GPS station ANTC is selected as the reference station.

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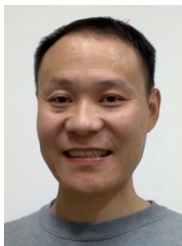
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