Toward Absolute Phase Change Recovery With InSAR: Correcting for Earth Tides and Phase Unwrapping Ambiguities

Xiaohua Xu and David T. Sandwell

Abstract—Radar interferograms provide a map of the phase difference between the reference and repeat acquisitions modulo $2\pi$. Under ideal conditions, the phase can be unwrapped to provide an absolute phase connection across the map, although there is always an unknown integer phase ambiguity (i.e., $N2\pi$) for the entire map. Here, we demonstrate a practical time series method to solve for these integer ambiguities in order to recover the absolute phase change between the first and last SAR images. An important first step is to correct the phase of each SAR image for the well-known solid earth tide, which typically produces a line of sight offset $\pm150$ mm, as well as, trends along and across each image of $\sim20$ mm. This tide correction significantly reduces the noise in the InSAR time series, especially at the L-band. These tidally corrected interferograms are then unwrapped and used to solve for a set of integer ambiguities that achieve phase closure when summing around loops in the stack. There is an infinite number of ambiguity combinations that achieve loop closure. We note that the split-spectrum ionospheric correction can introduce $N\pi$ ambiguities and suggest two approaches for correcting both $N2\pi$ and $N\pi$ ambiguities.

Index Terms—Phase unwrapping ambiguities, signal aliasing, solid earth tide, time series analysis.

I. INTRODUCTION

OVER the past several years, the Interferometric Synthetic Aperture Radar (InSAR) method has been transformed from a research tool for investigating 10s to 100s of SAR images to a research production tool for processing $1000$s and $10000$s of images. This transformation was largely driven by the Sentinel-1A and 1B satellites, which are designed for InSAR time series. Four attributes of Sentinel-1 have enabled this transformation: 1) the satellite orbits are maintained within a $200$-m tube which nearly eliminates baseline decorrelation, 2) the orbit accuracies are better than $30$ mm in the radial direction and better than $70$ mm in the along-track direction, which enables pure geometric coregistration of images [1], [2] discussed below, and 3) the $250$-km interferometric wide-swath mode enables complete coverage of tectonically active areas at a cadence of $12$ days, with the possibility of $6$-day full coverage in the case of a deformation event, and 4) most importantly, the data are completely free and open [3].

An important advantage of pure geometric coregistration of all the slave images to a single master is that it ensures phase closure among all interferograms in the stack [4]. It is clear that the sum of the interferometric phase around a loop consisting of three unfiltered interferograms is zero. Filtering interferograms result in some misclosure in decorrelated areas [5], but the global misclosure errors are always much smaller than the ambiguity phase of $N2\pi$ discussed in this article. The implication is that it is possible to establish an absolute phase connection between the first and last SAR image in a time series if the $N2\pi$ integer ambiguities can be resolved.

Suppose the ambiguities can be resolved for a large set of interferograms; then, for each pixel, the range versus time could be established using, for example, a Small Baseline Subset (SBAS) approach [6], [7]. With no smoothing, one would expect that the accumulated range would be equal to the surface deformation contaminated by the traditional error components associated with all geodetic measurements including, orbital error, atmospheric and ionospheric delay, solid earth tides and ocean loading tides. The largest errors are associated with the atmosphere and ionosphere, and there are many approaches to correcting or mitigating these errors [8]–[13]. Here, we first focus on the solid earth tide, which is known to an accuracy of better than $1$ mm [14], and thus, can be eliminated from the error budget. The ocean loading tide is less well known but also largely correctable [15]–[17]. We then discuss a new type of ambiguity that can be introduced from the split-spectrum ionosphere correction. Finally, we discuss the overall approaches to ambiguity resolution.

II. EFFECTS OF SOLID EARTH TIDE ON SBAS TIME SERIES

Previous studies suggested that the solid earth tide is not a significant error source for radar interferometry because it is largely a constant over distances of $100$ km (i.e., typical of the...
TABLE I
TIDAL ALIASES FOR INSAR SATELLITE SAMPLING

<table>
<thead>
<tr>
<th></th>
<th>repeat days</th>
<th>M2</th>
<th>S2</th>
<th>K1</th>
<th>O1</th>
<th>P1</th>
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<td></td>
<td></td>
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<tr>
<td>ERS/Envisat</td>
<td>35</td>
<td>94.50</td>
<td>-</td>
<td>365.23</td>
<td>75.06</td>
<td>365.23</td>
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<tr>
<td>RADARSAT</td>
<td>24</td>
<td>64.07</td>
<td>-</td>
<td>365.23</td>
<td>77.70</td>
<td>365.23</td>
</tr>
<tr>
<td>ALOS-1</td>
<td>46</td>
<td>389.63</td>
<td>-</td>
<td>365.23</td>
<td>190.60</td>
<td>365.23</td>
</tr>
<tr>
<td>ALOS-2</td>
<td>14</td>
<td>270.08</td>
<td>-</td>
<td>365.23</td>
<td>1036.73</td>
<td>365.23</td>
</tr>
<tr>
<td>Sentinel-1A/B</td>
<td>12</td>
<td>64.07</td>
<td>-</td>
<td>365.23</td>
<td>77.04</td>
<td>365.23</td>
</tr>
<tr>
<td>NISAR</td>
<td>12</td>
<td>64.07</td>
<td>-</td>
<td>365.23</td>
<td>77.04</td>
<td>365.23</td>
</tr>
<tr>
<td>Sentinel-1A&amp;B</td>
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<td>14.77</td>
<td>-</td>
<td>365.23</td>
<td>14.19</td>
<td>365.23</td>
</tr>
</tbody>
</table>

previous generation of SAR satellites) [16]. However, there are two important enhancements provided by the new generation of SAR satellites, regular cadence with short baselines and swath widths and lengths of 250 km or greater. Here, we show how the solid earth tide contaminates InSAR time series and show that it can be easily corrected.

A. Tidal Aliasing
Unlike atmospheric or ionospheric contamination, which is largely random in time, the sun-synchronous orbits of the current generation of SAR satellites cause the diurnal and semidiurnal tides to be aliased into much longer periods. For example, the semidiurnal solar tide S2 has a period of one day and an amplitude of 180 mm (Table I). This tide component is aliased into zero frequency when sampled at an exact integer number of days. In general, the alias frequency \( f_a \) due to sampling a tide of frequency \( f_t \) at a frequency \( f_s \) is given by the following formula:

\[
 f_a = f_t - f_s \cdot \text{round}(f_t/f_s).
\]

For example, the M2 tide, with a period of 0.517542 days, when sampled at an interval of 12 days, has an alias period of 64.07 days (Table I). The next largest tidal component K1 has an alias period of 365.23 days when sampled at an integer number of days. The overall result is the 12-day sampled tide has alias periods of 64.07, 365.23, and 77.04 days (Table I). The aliases at 64 and 77 days could be smoothed out with smoothness in an SBAS analysis. However, the aliases having a 1-year period could be confused with real deformation signals associated with seasonal variations in water loading [18], [19]. So, we need to understand how these tide signals contaminate InSAR time series.

B. Contamination of InSAR Time Series by Solid Earth Tide
To illustrate the effects of the solid earth tide on InSAR time series, we decompose the tide change between the reference and repeat images into three components, as shown in Fig. 1.

1) The first component [Fig. 1(a)] is a spatially uniform range change. Below, we discuss how this uniform component introduces noise into an InSAR time series.
2) The second component is due to the variation in incidence angle across the scene [Fig. 1(b)]. This results in a phase ramp in the range direction because of the variations in look angle with range.
3) The third component [Fig. 1(c)] is due to the spatial variations in tidal height within the scene mostly associated with very long InSAR swaths. We call the first component, the absolute tide, and the combined second and third components, the relative tide.

C. Absolute Tide
To investigate the adverse effects of the absolute value [Fig. 1(a)] of the solid earth tide on InSAR time series from Sentinel-1 at (C-band) and the future NISAR at (L-band), first, we sample the tidal signal at the cadence of Sentinel-1 and NISAR, and analyze that signal using a standard InSAR time series analysis to recover the amplitude and period of the noise. Fig. 2 (left) shows the solid earth tide at Los Angeles, CA, as sampled by the 12-day exact repeat orbits of Sentinel-1 and NISAR for a 3-year time interval. As discussed above, the sampled tide has alias periods of 64.07, 365.23, and 77.04 days (Table I). Also shown is the wrapped tide, which is the only part of the signal that is available in a single-look complex (SLC) image because phase is modulo \( 2\pi \). The wrapped tide adds noise to the time series. Note that the amplitude of the wrapped tide is larger for L-band than C-band so the tidal contamination will also be larger.

Next, we form all possible, wrapped interferograms within a 60-day moving window and add a linear trend to represent a real tectonic signal. Finally, we use these redundant interferograms in an SBAS analysis with moderate smoothing to recover the time series that is contaminated by the tide. The results are shown in Fig. 2 (right). Tidal contamination is fairly small at C-band (\( \sim 10\)-mm maximum and 1.03-mm rms) and significantly larger at L-band (\( \sim 60\)-mm maximum and 19.9-mm rms) in this specific case. Fortunately, the solid earth tide is known to have an accuracy of better than 1 mm [14], so after tidal correction, these errors in the SBAS time series will be very small.

D. Relative Tide
The previous analysis is based on a uniform value for the tide over the SAR scene. However, with the large frames being provided by Sentinel-1 and NISAR, there is a trend in the tide that varies along with range and azimuth. The trend in the range is mostly due to the change in look angle...
The results show an error curve having an amplitude of ∼12 mm and a period of about 1 year with sub-oscillations of ∼64/77 days. Without this correction, one could interpret the annual oscillation as a true annual signal when, in fact, it is the tidal signal aliased by the 12-day, sun-synchronous orbit of the SAR satellites.

Several examples of SBAS inversions, when a small number of interferograms have $N2\pi$ integer ambiguities, are provided in Fig. 4. The first case [Fig. 4(a) and (b)] illustrates the effects of two misclosure errors on an SBAS solution for a displacement time series. When the minimum set of 12-day interferograms are used, the displacement time series will have jumps at times between the two ambiguities. Keeping just two ambiguities but adding more interferograms in a 24-day window results in smaller steps in the displacement time series. When the window is increased to 36 days, the steps are much smaller. However, this is an unrealistic case because the number of ambiguities will increase with the number of interferograms. A more realistic case is provided in Fig. 4 (g) and (h) where the window is increased to 60 days, and 30% of the interferograms have both positive and negative ambiguities. The input signal consists of a trend plus an annual cycle deformation observed by continuous GNSS receivers in the scene [23]. However, this type of correction is dependent on the GNSS station density, which is not ideal for all situations.

III. IDENTIFYING AND CORRECTING INTEGER PHASE AMBIGUITIES

A. Inversion Approach

An important step in the Global Navigation Satellite System (GNSS) data processing is to measure the integer number of wavelengths between the satellites and the receiver to provide an absolute position. Errors in this integer count are called integer phase ambiguities or cycle slips, and there is a large body of literature devoted to resolving integer phase ambiguities [20], [21]. Interferograms are inherently phased difference measurements between a reference and repeat image. One example is the geocoded SLC [22], which is an attempt to correct the phase of each SAR image to a common topographic surface and the correction applies an integer and fractional phase shift between the radar pixel and a matching point on the ground. Nevertheless, interferograms made from these SLCs have $2\pi$ integer ambiguities after the phase is unwrapped. If not properly corrected, this ambiguity term will affect every pixel in radar acquisitions and introduce a random walk type error that will bias the time series (Fig. 4). One way to partially correct InSAR time series for this phase unwrapping ambiguity is to set the displacement of some small patch of each map in the stack to zero, thus solving for the displacement time series of all other points relative to that stable location [7]. One problem with this approach is that atmospheric errors in that small patch will impose a phase shift over that entire interferogram, thus introducing phase noise to the resulting InSAR time series. Also, by forcing the patch to zero in a time-series, the resulting velocity uncertainties for that small area will be significantly underestimated. Of course, one could adjust each interferogram to match the line-of-sight deformation observed by continuous GNSS receivers in the scene [23]. However, this type of correction is dependent on the GNSS station density, which is not ideal for all situations.

Fig. 1. (a) For a uniform incidence angle of $\theta$, the radial component of the tide, projected into the line of sight of the radar, causes a uniform range change. Only the modulus of $1/2$ of the radar wavelength $\lambda$ remains in the interferogram to affect the time series since $\Delta\rho$ is usually larger than $\lambda$. (b) Radial component of the tide maps into the LOS depending on the secant of the look angle. (c) Spatial variations in tide map directly into spatial variations in range. This is primarily a phase ramp in azimuth for mid-latitude regions.
Fig. 2. (Left) Line-of-sight component of the solid earth tide at Los Angeles, California (118.2° W, 33.75° E) when sampled at 12 days by Sentinel-1 and NISAR. This sampling results in aliased components at 64.07, +/−365.23, and 70.04 days. Also shown is the tide wrapped for C-band and L-band as an indication of the noise contribution to interferometry. (Right) Synthetic InSAR time series consisting of a linear displacement versus time (black) and the recovered displacement versus time when the wrapped solid earth tide was included (magenta for L-band, green for C-band).

Fig. 3. (Left) SBAS time series from 3-year of InSAR acquisitions at 12-day sampling and a 60-day window for interferogram formation. This represents the difference in tidal displacement between Los Angeles and Death Valley (300 km) as a function of time. Black curve: assumed underlying linear trend. Blue curve: recovery when the solid earth tide is not corrected. (Middle and Right) Solid earth tide phase/displacement for two Sentinel-1 TOPS interferograms (July 25, 2015–September 11, 2015 and July 25, 2015–April 14, 2015).

The use of the phase closure constraint to solve for $2\pi$ integer ambiguities in unwrapped interferograms is common practice in InSAR time series analysis [16] [24], [25], [27]. The approach is to form all possible three-way loops in a set of interferograms so the problem can be written into the form of

$$Gm = d$$

and

$$G = \begin{bmatrix} 1 & 1 & -1 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & -1 & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 1 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 & \cdots & 0 & 1 & 1 & -1 \end{bmatrix} \quad \text{and} \quad d = \begin{bmatrix} 1 \\ 2 \\ \vdots \\ -1 \\ 0 \end{bmatrix}$$

where $G$ is the matrix denoting the indices of interferograms to add or subtract to form the three-way loops and $d$ is the vector of closure integers after summing interferograms over the loops, computing the median of each sum, and rounding to modulo of $2\pi$. The unknown vector $m$ is the integer ambiguity of each unwrapped interferogram. These can be subtracted from each interferogram to achieve global loop closure, and thus, provide an absolute phase connection between the first and last SAR image in the time series. One issue is that this inverse problem is not unique. To understand the nonuniqueness, consider a set of interferograms where the sums around all loops are zeros. Any solution $m'$ that satisfies $Gm' = d$ can be added to or subtracted from $m$, without affecting the closure vector $d$. A trivial example is for a single triangular loop closing to $2\pi$, the correction could be a $2\pi$ applied to one of the interferogram, or $2\pi$ to all of them. To stabilize the problem, one has to apply regularization to the inverse problem.

Fattahi [26] used an $L_2$-norm minimization to find a solution for the problem. However, this least-squares approach may sometimes complicate the situation. For example, consider a single misclosure error of $4\pi$ in one triangular loop of interferograms. The $L_2$-norm will favor $2\pi$ corrections on two of the sides of the loop rather than a single $4\pi$ correction to one side. Here, we propose to use a lower norm penalty function that will result in fewer, but perhaps larger, ambiguity corrections. The ideal norm is the $L_0$-norm which corresponds to the compressed sensing/sparse recovery technique [28], and can be written as

$$\min \| m \|_0 \quad \text{s.t.} \quad Gm - d \|_2 < \varepsilon$$

where the algorithm finds the minimum number of corrections required for global loop closure. After inversion, the nonzero
The presence of noise \cite{29}. Thus, we convexify the problem
by choosing the Lagrange multiplier \cite{31} to the problem setup so the
solution primarily due to other noise sources, such as atmospheric delay and solid earth tide. This is why we propose to
apply the well-known corrections to the SLCs, such as the solid earth tide or ionospheric correction before solving for the ambiguities.

**B. Performance Versus Number of Ambiguities**

The percentage of interferograms having ambiguities will affect the accuracy of the inversion. This percentage will depend on the unmodeled errors in the interferograms as well as the InSAR correlation. Decorrelated interferograms commonly have phase unwrapping errors especially when the decorrelation disconnects regions of a well-correlated phase. We explore the adverse effects of ambiguities on SBAS time series recovery using the same signal characteristics as in Fig. 4(g) \[i.e., \text{trend} + \text{annual} + \text{noise}\] in Fig. 5(a) gray curve]. The first case has 30\% ambiguities of both signs. The recovered displacement time series (green) has a large drift error that is about 50 mm at the end of the time interval. The ambiguity-corrected time series (blue) matches the SBAS solution, where there are no ambiguities (magenta) except at the time of about 650 days when the inversion failed to recover all the ambiguities.

From our statistical tests, the performance curve [Fig. 5(b)] shows the methods works very well when the percentage of incorrectly unwrapped interferograms is low. Our experiences on 5 Sentinel-1 descending tracks in California (Fig. 6) shows the percentage of nonclosing loops [Fig. 5(b) (black curve)] is all below 40\%, \text{i.e.}, less than 20\% of the interferograms have the N2\pi shifts. All these cases fall at the left part of these curves in Fig. 5(b), where the performance of the algorithm is outstanding. The sparse assumption actually divided the problem setup into two subsets: when the number of ambiguities is low (left side, below 30\%), the algorithm recovered the corrected loop closure was nearly zero [Fig. 6(b)]. When the number of ambiguities is high—above 40\%, which is rare from our experience, the loop closure was far from zero [Fig. 5(b)].

In addition to correcting the N2\pi ambiguity of each interferogram, the approach also highlights integer phase unwrapping errors in areas that are decorrelated or have poor phase connections to the bulk of the interferogram. The remaining blocks that do not fully close at zero (\text{e.g.}, area A in Fig. 6(a) and (b)) can be recovered using the same algorithm or can be masked as unreliable. A pixel-wise correction is possible but not recommended since filtering generally destroys the closure criterion, which is the base of this recovery approach.

**IV. Ionosphere Correction Can Cause an N\pi Ambiguity**

Recent advances in InSAR techniques allow scientists to correct ionospheric phase from interferograms using range split spectrum method \cite{8}, \cite{10}, \cite{11}, \cite{13}, where the low \Delta \phi_L and high \Delta \phi_H band-passed interferometric phase can be

*ms* must be rounded to their nearest integer. However, the \(L_0\)-norm is nonconvex so it is hard to solve and unstable in the presence of noise \cite{29}. Thus, we convexify the problem by following the approach in \cite{30} and substitute the \(L_0\)-norm with the \(L_1\)-norm so the problem becomes

\[
\min \| m \|_1 \quad \text{s.t.} \quad \| Gm - d \|_2 < \epsilon. \tag{4}
\]

Again, after inversion, all the \(ms\) must be rounded to their nearest integer. A more practical approach is to introduce the Lagrange multiplier \cite{31} to the problem setup so the minimization can be written as

\[
\min(\| Gm - d \|_2 + \lambda \| m \|_1) \tag{5}
\]

where \(\lambda\) can be chosen by analyzing the variance reduction of the inverse problem. In this case, where \(G\) and \(d\) are always integers, \(\lambda\) should be set as a very small number such as 0.01. If the initial inversion does not result in the closure of every loop, one can apply the partial correction and iterate until all loops close. Note that compared to GNSS ambiguity resolution correction, this algorithm is unable to determine the exact number of integer phase cycles, but rather it tries to bring all interferograms to the same unknown integer cycle, after which a deformation time-series can be correctly constructed.
used to construct of dispersive component (ionosphere) $\Delta \phi_{\text{iono}}$ and non-dispersive (troposphere and deformation) component $\Delta \phi_{\text{non-disp}}$. The formulas are as in [10]

$$\Delta \phi_{\text{iono}} = \frac{f_H f_L}{f_0 (f_H - f_L)} (\Delta \phi_L f_H - \Delta \phi_H f_L) \quad (6)$$

$$\Delta \phi_{\text{non-disp}} = \frac{f_0}{(f_H - f_L)} (\Delta \phi_H f_H - \Delta \phi_L f_L) \quad (7)$$

where $f_0$ is the carrier frequency, $f_H$ is center frequency of the high band, and $f_L$ is the center frequency of the low band. When performing this correction, localized unwrapping errors need to be identified and removed by examining the unwrapped high and low interferograms. However, as discussed above, the absolute unwrapping ambiguity cannot be determined. There are two cases of absolute ambiguity errors. For case 1, the unwrapped phase of the high differs by $N2\pi$ from the unwrapped phase of the low. This causes an unreasonably large ionospheric phase that can be corrected by shifting either the high or low by $N2\pi$. For case 2 both the high and low have the same $N2\pi$ ambiguity. Similar to the common phase error discussed in [10] and [13], the resulting ionospheric correction $\Delta \phi_{\text{iono}}$ will be shifted by

$$\frac{N2\pi f_H f_L}{f_0 (f_H + f_L)} = \frac{N2\pi (f_0 + \Delta f) (f_0 - \Delta f)}{f_0 (2f_0)} = N\pi \left(1 - \frac{|\Delta f|^2}{f_0^2}\right) \quad (8)$$

which is roughly $N\pi$ since $\Delta f = (f_H - f_L)/2 \ll f_0$. When removing the ionospheric phase from the original interferogram, this term will contaminate the interferogram (Fig. 7), and thus, further affect the later InSAR time-series analysis. Below we discuss two approaches for correcting these $N\pi$ ambiguities in InSAR time series.

V. AMBIGUITY CORRECTION/TIME SERIES ALGORITHMS

The current generation of SAR satellites has narrow bandwidths that are not well suited for ionospheric corrections.
VI. DISCUSSION AND CONCLUSION

We demonstrate the adverse effects of phase ambiguities from solid earth tide and split-spectrum ionospheric correction on InSAR time-series. The 12-day repeat sampling of the current generation of InSAR satellites results in aliasing of the diurnal and semidiurnal tidal much longer periods. The absolute tide variations across an SAR scene will be wrapped so only the fractional part of the correction is important. This fractional tide will bias an L-band time series by up to 60 mm over 3 years while the effect is smaller at C-band (∼10 mm). The relative tide variations across and along an unwrapped interferogram are typically 20–30 mm (same for C- and L-bands) due to the geographic variations in the tide but more importantly the change in look angle across the SAR swath. These tide errors map directly into the phase, and thus, have aliases of 64, 365.25, and 77 days caused by the 12-day exact repeat sampling of Sentinel-1 and NISAR. After the time series analysis, these relative tide errors can introduce large (+/− 20 mm) apparent deformation at a period of ∼1 year that is easily confused with true seasonal deformation signals. The ocean loading tide will introduce a similar signal but over a shorter spatial scale [16]. There are studies that show that tide may also affect ranging accuracy [32], and thus, further affect SAR co-registration. Both the absolute and relative solid earth tide errors are easily corrected in the SLC, and we have implemented this correction in GMTSAR [33]. The ocean loading tidal correction can also be implemented, although it is less accurate. The standard split-spectrum ionospheric correction methods can also introduce ambiguities, but they are at half the rate of phase unwrapping ambiguities (Nπ instead of the usual 2π). We have refined the standard loop-closure method to identify and correct for both types of ambiguities by solving for the minimum number (L1-norm) of interferogram ambiguities that will result in loop closure. The algorithm performs well when the number of nonclosing loops is less than about 60%. A higher percentage of loop closures usually reflects decorrelated areas where the time series will be unreliable. The large bandwidth available for NISAR will facilitate the split-spectrum ionospheric correction, and we propose two algorithms to correct the ambiguities in InSAR time series, which will result in the absolute phase connection from the first to the last InSAR acquisitions.

ACKNOWLEDGMENT

The authors would like to thank ESA for the open policy on all the data sets and ASF and UNAVCO for archiving the data and orbital products. They would also like to thank JAXA for providing the ALOS-2 data. They would also like to thank D. Milbert for sharing his solid earth tide code on-line and M. Grant and S. Boyd for the convex optimization tool CVX.

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Xiaohua Xu received the B.S. degree in geophysics from the University of Science and Technology of China, Hefei, China, in 2012, and the Ph.D. degree in geophysics from the Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA, USA, in 2017. He is currently a Post-Doctoral Researcher with Scripps Institution of Oceanography, where he is studying on InSAR technique and its application to geophysical problems. His research interests include developing InSAR processing techniques, studying crustal deformation related to interseismic tectonic processes and anthropogenic activities, imaging earthquake and volcanic sources, and monitoring reservoir depletion.

David T. Sandwell received the B.S. degree in physics from the University of Connecticut, Storrs, CT, USA, in 1975, and the Ph.D. degree in geophysics and space physics from the University of California at Los Angeles, Los Angeles, CA, USA, in 1981. Since 1994, he has been a Professor of geophysics with the Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA, USA. His research interests include satellite geodesy crustal deformation and marine geophysics.

Prof. Sandwell is a member of the U.S. National Academy of Sciences and a fellow of the American Geophysical Union.