LARGE-SCALE FINE-RESOLUTION PRODUCTS OF FOREST DISTURBANCE USING NEW APPROACHES FROM SPACBORNE SAR INTERFEROMETRY

Yang Lei[1], Robert Treuhaft[1], Richard Lucas[2], Paul Siqueira[3], Michael Keller[1], and Michael Schmidt[4]
[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, 91109, USA
[2]University of New South Wales, NSW 2052, Australia
[3]University of Massachusetts, Amherst MA, 01003, USA
[4]Queensland Department of Science, Information Technology and Innovation, QLD 4102, Australia

Spaceborne SAR interferometry (InSAR) has the potential of detecting forest change on a global scale with fine (meter-level) spatial resolution as well as on a monthly/weekly basis under all weather conditions. This is significant to characterize the land-use change and its impact on climate change. In this paper, both single-pass and repeat-pass SAR interferometry from spaceborne sensors are combined in order to detect and quantify (with Normalized RMSE $\leq$ 30%) forest disturbance at a large scale (dozens of kilometers) however with a fine spatial resolution ($<$ 1 hectare) based on two newly developed approaches. The single-pass InSAR approach is not only able to detect forest disturbance but also capable of characterizing meter (or even sub-meter) level change of forest phase-center (mean) height due to forest growth and/or degradation. The methodology described in this paper can be considered as complimentary tools and thus can be combined with the existing PolInSAR technique (that has been widely used for retrieving forest height from single-pass SAR interferometry). These methods are extensively validated with the past and current spaceborne single-pass and repeat-pass InSAR missions (i.e. JAXA's ALOS-1, ALOS-2 and DLR's TanDEM-X) over subtropical forests in Australia as well as tropical forests in Brazil. Such techniques also serve as observing prototypes for the fusion of the future spaceborne InSAR missions (such as NASA-ISRO's NISAR and DLR's TanDEM-L).

***Index Terms*—spaceborne, SAR, interferometry, single-pass, repeat-pass, forest disturbance, large-scale, fine-resolution.**

I. INTRODUCTION

Large-scale products of forest disturbance events (such as selective logging, clearing, fire) at a fine (e.g. hectare-level) spatial resolution are paramount to understanding how carbon distribution is changing in response to human activities and natural events and processes. Such products provide information on the contributions of land use and cover change to overall greenhouse gas emissions, which is important for the United Nation's Reducing Emissions from Deforestation and forest Degradation (REDD) program. In order to obtain quantitative spatial data on the change of forest biomass and/or height, a spaceborne InSAR system has the potential of characterizing the forest change on a global scale with fine (meter-level) spatial resolution and a monthly/weekly basis under all weather conditions.

Generally, there are two types of spaceborne InSAR systems: single-pass and repeat-pass. A single-pass InSAR system (such as NASA's SRTM mission and DLR's TanDEM-X mission) is able to measure the interferometric phase information accurately without much contamination by the atmosphere and/or the temporal change behavior of the targets. Successful forest height inversion using techniques such as Polarimetric InSAR (PolInSAR) has been widely reported. However, due to the assumptions made for the PolInSAR scattering model, the error of the height estimates is usually on the order of several meters with a forest stand size of couple hectares. In this paper, the original InSAR phase is utilized without any model-based forest height inversion, and thus only the phase-center (mean) height can be achieved; nevertheless, the accuracy of the phase measurements is maintained without further degradation by the inversion models. It is this accurate measurement of phase-center height that enables the creation of Digital Elevation Model (DEM) products from spaceborne single-pass InSAR missions (e.g. SRTM and TanDEM-X). In the previous work [2], the same phase-center height has been utilized to monitor forest change at meter-level (or even sub-meter level) with the stand size of quarter hectares by developing a new approach based on a time series of spaceborne single-pass InSAR observations. Therefore, in this paper, this approach will be adapted and refined to monitor forest disturbance (Section III).

Unlike single-pass SAR interferometry, however, a spaceborne repeat-pass InSAR system is subject to the atmospheric phase delay effect as well as the so-called temporal decorrelation effect among a distributed target such as forest between the repeat interval of the satellite (usually on the order of months; e.g. 46 days for ALOS-1). In response to these problems, a set of efforts [1] have been made recently to interpret and utilize the accumulated large data volume of spaceborne repeat-pass InSAR observations (e.g. JAXA's ALOS-1, ALOS-2) for forest mapping. More importantly, as will be demonstrated later in this paper, a repeat-pass InSAR system is not only sensitive to the vertical dimension of the targets (like single-pass InSAR), but also most suitable to measure the temporal changes among the targets, such as the human activity-induced and/or natural disturbance events. Through separation of forest disturbance from effects of the scene-wide mean temporal decorrelation and forest structure in the apparent repeat-pass InSAR coherence, a forest disturbance detection method has been developed and validated with JAXA's ALOS-1 and ALOS-2 data (Section II and Section III).

In combination with the single-pass PolInSAR techniques, the presented approaches are important and efficient for large-scale forest monitoring through the fusion of the future spaceborne single-pass and repeat-pass InSAR missions (e.g. DLR's TanDEM-L and NASA-ISRO's NISAR).

II. LARGE-SCALE FOREST DISTURBANCE PRODUCT FROM SPACEBORNE REPEAT-PASS SAR INTERFEROMETRY

As mentioned, a set of efforts have been recently made for utilizing the spaceborne repeat-pass InSAR observations. For example, a physical scattering model was derived for spaceborne repeat-pass InSAR measurements of forest by accounting for the normal temporal decorrelation effects of wind-induced random motion and moisture-induced dielectric change [1]. Since a spaceborne repeat-pass InSAR system (with temporal baseline on the order of months) is particularly sensitive to the temporal changes among the targets, such as wind-induced position change, moisture-induced dielectric change as well as human activity-induced and/or natural disturbance events, all of these information will be lumped together in the apparent InSAR correlation magnitude. However, if the normal temporal change effects (a.k.a wind-induced position change, moisture-induced dielectric change) can be appropriately determined and then compensated for the mean forest height in the study area, it is also possible to retrieve the information that only indicates forest disturbance.

The derived repeat-pass InSAR scattering model [1] of the repeat-pass InSAR correlation, $\gamma_{v\&t}$, can be written as below,

$$\gamma_{v\&t} = \mathbf{M} \begin{pmatrix} \text{vertical structural information} \\ \text{moisture-induced dielectric change} \\ \text{wind-induced random motion} \end{pmatrix} \quad (1)$$

where the "vertical structural information" consists of the tree height and the vertical profile (relates to the extinction coefficient), "moisture-induced dielectric change" introduces a decorrelation factor (dependent on the moisture change of the tree components) during the repeat period of the two SAR acquisitions, while "wind-induced random motion" represents another decorrelation component that depends on the random motion level of the tree components due to wind effect. In order to isolate the forest disturbance information from the apparent repeat-pass InSAR correlation, the mean behavior of the normal temporal decorrelation effect (dielectric change and random motion) on the average forest vertical structure can be captured, i.e.

$$\gamma_{dist} = |\gamma_{v\&t}| \,/\, |\overline{\gamma_{v\&t}}| \quad (2)$$

where the mean-behavior term $|\overline{\gamma_{v\&t}}|$ can be estimated from observations by first applying a forest/non-forest mask to remove the non-forest areas and then taking the mode value from the histogram of the forest-covered InSAR correlation magnitude. The correlation component due to disturbance (γ_{dist}) goes from 0 to 1, i.e., 0 means complete disturbance and 1 represents no disturbance. The InSAR disturbance index ($0 \leq I \leq 1$) can thus be defined as follows,

$$I = 1 - \gamma_{dist} \quad (3)$$

which characterizes the degree of the forest disturbance event. The physical meaning of the disturbance index is the percentage of the damaged forest within each image pixel area.

The test area for validating this approach is located at the Injune Landscape Collaborative Project (ILCP; $25°32'$ S, $147°32'$ E) from the central southeast Queensland, Australia. There was a clearing event in mid-2007 through mid-2008 as verified with the Statewide Landcover and Trees Study (SLATS) data. Concurrently, one Fine Beam Dual-polarization (FBD) InSAR pair (20070716–20071016; with temporal baseline of 92 days) from ALOS-1 captured the selective logging event at the beginning of the clearing process. This InSAR pair has a small perpendicular baseline of 434 m (interferometric wavenumber of 0.0419) with a relatively and uniformly high InSAR correlation magnitude of 0.75 (scene-wide). The pair of ALOS-1 raw data were processed using GAMMA Remote Sensing software with the window size of 30 m $\times$ 30 m for correlation estimation, and the geometric and thermal noise decorrelation were corrected respectively. The multi-looked image was then projected onto the SRTM DEM at a spatial resolution of 30 m $\times$ 30 m. The SAR backscatter power measurements from the master image (July 16 2007) along with a threshold serves as the forest/non-forest mask. The mean-behavior term is thus estimated as $|\overline{\gamma_{v\&t}}| = 0.79$ for HH-pol and $|\overline{\gamma_{v\&t}}| = 0.69$ for HV-pol. The image of the fused (average of HH-pol and HV-pol) InSAR disturbance index is illustrated in Fig. 1. The blowup of the selective logging region is also shown for the InSAR disturbance index and the optical disturbance index (derived from Landsat dense time series; serves as the ground truth for this study), respectively. The quantitative comparison between the two disturbance indices is illustrated in Fig. 2 with the Normalized RMSE (NRMSE) of 13.68% and the statistical R measure of 0.76 at a spatial resolution of 0.81 hectare, which validates that the repeat-pass approach has the capability to detect and quantify forest disturbance at a large scale (the InSAR imagery is 84 km $\times$ 72 km) with fine spatial resolution (0.81 hectare).

III. LARGE-SCALE FOREST DISTURBANCE PRODUCT FROM SPACEBORNE SINGLE-PASS SAR INTERFEROMETRY

Since spaceborne single-pass SAR interferometry has the capability of measuring the interferometric phase (and thus phase-center height) accurately, it is possible to monitor the change of phase-center height as a function of time. In previous work [2], the phase-center height from TanDEM-X data was utilized to monitor forest growth or degradation at meter-level (or even sub-meter level) with the stand size of quarter hectares by developing a new approach based on a time series of spaceborne single-pass InSAR observations. In the current paper, this method is adapted to examining forest disturbance by refining and automating some of the processing steps.

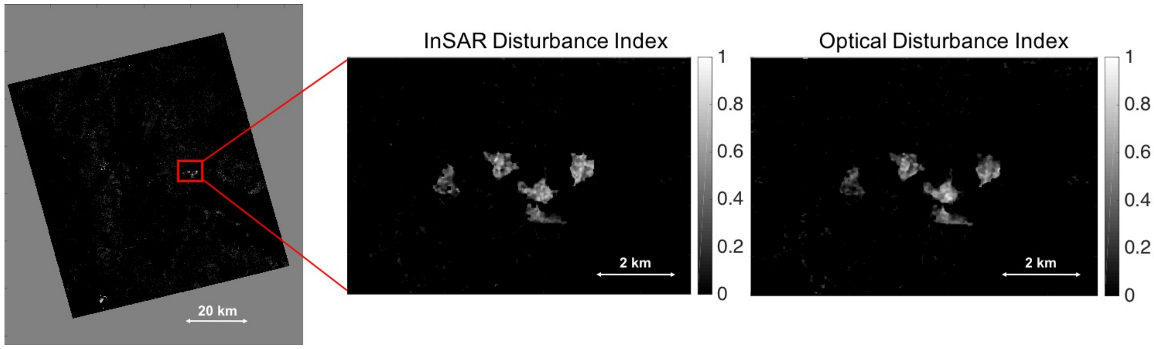

Fig. 1. (left) InSAR-derived disturbance index for the entire ALOS-1 InSAR image (84 km × 72 km) over the ILCP site in Australia; (middle) blowup of the selective logging site for the InSAR disturbance index; (right) blowup for the optical disturbance index (derived from Landsat dense time series). 3×3 median filter was applied in order to suppress the correlation sampling noise.

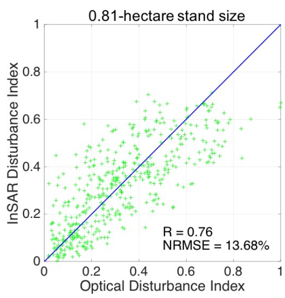

Fig. 2. Scatterplot of ALOS-1 InSAR disturbance index and Landsat optical disturbance index over ILCP, Australia. Both the Normalized RMSE and the statistical R measure are shown with the stand size of 0.81 hectare.

First, the apparent InSAR phase must be flattened (flat-earth removal) in order to reveal the signatures due to topography and forest structure as well as its change. However, it is recommended in this study to flatten the InSAR phase measurement with use of an external DEM (with the topography removed), which will simplify the following analysis and processing. Second, it is observed that at each epoch the flattened InSAR phase have a random offset. In order to bring the phases measured at various epochs onto a common reference so that they can be most comparable to each other however not overwhelming the disturbance signature, the InSAR phase measurements with high-coherence are thus utilized. In particular, for each epoch, by setting up a threshold of the InSAR coherence (selected as the scene-wide mean value plus the standard deviation), each multi-looked pixel with coherence larger than that threshold is identified as a *high-coherence point*. Then, the average of the InSAR phases at these high-coherence points will be subtracted from the entire InSAR image so that the phase center of the high-coherence points corresponds to zero height on average. This treatment is convenient and useful since the high-coherence points mostly correspond to bare ground surfaces, buildings, roads, and other persistent scatterers, which are considered to be constant topographically. In this sense, a dense time series of InSAR phase-center height can be achieved, i.e.

$$h_i = -\frac{\phi_i - \phi_i^{high}}{\kappa_{z_i}} \tag{4}$$

where h_i is the phase-center height, ϕ_i is the flattened interferometric phase, ϕ_i^{high} is the average InSAR phase for the high-coherence points (thus constant for the entire image), and κ_{z_i} is the interferometric wavenumber (i.e., phase to height conversion factor). All of the parameters above correspond to the i^{th} epoch. A disturbance index I can thus be defined as

$$I = \frac{\Delta h}{h_0} \tag{5}$$

where Δh is the change of the phase-center height due to the disturbance event, and h_0 is the absolute phase-center height before the disturbance. In order to have a robust estimate of the height change term Δh, it is suggested to use a logistic function (or any other step-like function) to fit into the time-series data with the fitted step size parameter considered as Δh. This single-pass InSAR disturbance index has the same physical meaning as the repeat-pass counterpart, i.e., $I = 1$ means complete removal of the forest, $I = 0$ means no disturbance.

The study area for testing this approach is located at the Brazilian Amazon forest in Tapajos ($3°22'$ S, $55°00'$ W). A selective logging event was scheduled in October 2015 through mid-January 2016 over 32 50 m × 50 m plots in Tapajos. Tree-by-tree field inventory data were recorded before and after the logging event, which indicates some of the 32 plots were not disturbed, while most plots have several up to twenty trees (out of a hundred or so) logged. There are six TanDEM-X InSAR pairs available over this logging period, i.e., three of ascending mode (20151030, 20151121, 20151202) and three of descending mode (20151129, 20151210, 20160123). The Height of Ambiguity (HoA) is between 60 m and 70 m. Concurrently, there are four ALOS-2 InSAR pairs available with relatively high scene-wide coherence (as low as 0.1). Both of the TanDEM-X and ALOS-2 data were processed using NASA JPL's ISCE software and projected onto the SRTM DEM with a spatial resolution of 30 m × 30 m. The correlation estimation window occupies 50 m × 50 m for TanDEM-X, and 40 m × 40 m for ALOS-2. The resulting InSAR phase was flattened through the use of SRTM DEM. Since SRTM DEM is not a perfect DEM (i.e., C-band phase-center height

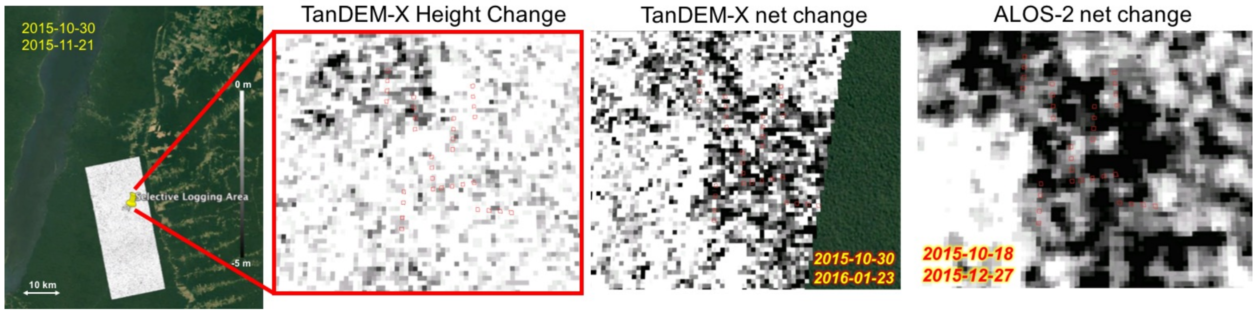

Fig. 3. (leftmost) phase-center height change between 20151030 and 20151121 for the entire TanDEM-X InSAR image (40 km × 16 km) over the Tapajos site in Brazil with the blowup of the selective logging site to the right; (second from the right) TanDEM-X phase-center height change between 20151030 and 20160123 (difference between before and after the disturbance event); (rightmost) ALOS-2 InSAR coherence component due to disturbance γ_{dist} (20151018–20151227). 3×3 median filter was applied in all of the subfigures in order to suppress the correlation sampling noise. The greyscale is from -5 m ("black") to 0 m ("white") for all of the subfigures except the rightmost one, i.e., from 0 ("black") to 1 ("white").

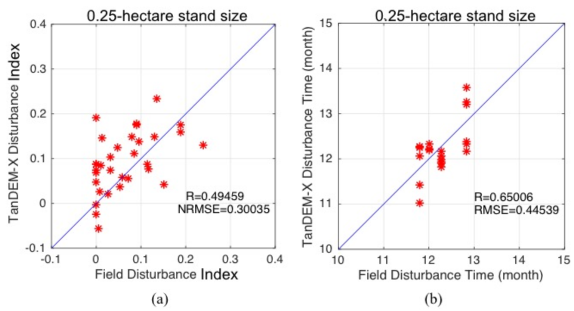

Fig. 4. (a) Scatterplot of TanDEM-X InSAR disturbance index and field disturbance index over Tapajos, Brazil. (b) Scatterplot of TanDEM-X InSAR disturbance time and field disturbance time over Tapajos, Brazil. Both the RMSE/NRMSE and the statistical R measure are shown with the stand size of 0.25 hectare.

is not zero for forest), the calculated h_i is only a relative phase-center height (i.e., X-band phase-center height minus C-band phase-center height). The random phase offset was then removed by using the high-coherence points. One example of the change in the phase-center height (20151030–20151121; at the beginning of the logging process) is shown in Fig. 3, where the blowup of the selective logging plots is shown to the right. The overall change of phase-center height (20151030–20160123; the entire logging process) is also shown on the right of Fig. 3 in comparison with the repeat-pass γ_{dist} from ALOS-2 InSAR correlation observations (20151018–20151227), which indicates that both TanDEM-X and ALOS-2 consistently detected when and where the disturbance event happened. The quantitative comparison between the single-pass InSAR disturbance index and the field-measured disturbance index is illustrated in Fig. 4a with the NRMSE of 30% and the statistical R measure of 0.49 at a spatial resolution of $1/4$ hectare, while the scatterplot between the single-pass InSAR-derived logging date (when a change is induced in the time series of phase-center height) and the field-recorded logging date is shown in Fig. 4b with the RMSE of 0.45 month (13.5 days) and the statistical R measure of 0.65. These results conclude that the single-pass approach has the capability to detect and quantify the forest disturbance at large scale (the InSAR imagery is 40 km $\times$ 16 km) with fine spatial resolution (0.25 hectare).

IV. Conclusion

Two new forest disturbance characterization approaches using spaceborne single-pass and repeat-pass SAR interferometry have been developed and validated by using the past and current spaceborne InSAR missions (JAXA's ALOS-1, ALOS-2 and DLR's TanDEM-X) against with optical data and field inventory data. These methods are simple and efficient (thus have been automated), which only requires single-baseline, single-polarization InSAR data. More importantly, these methods can detect and quantify (with NRMSE $\leq$ 30%) forest disturbance at a large scale (dozens of kilometers) with fine spatial resolution ($<$ 1 hectare). These techniques are specifically designed for the fusion of the future spaceborne single-pass and repeat-pass InSAR missions (such as NISAR and TanDEM-L).

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