LARGE-SCALE PRODUCT OF FOREST HEIGHT USING A NEW APPROACH FROM SPACBORNE REPEAT-PASS SAR INTERFEROMETRY AND LIDAR

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Spaceborne SAR interferometry (InSAR) has the potential of mapping the forest height on a global scale and a monthly/weekly basis under all weather conditions, which can improve our understanding of the global carbon dynamics. In previous work, repeat-pass SAR interferometry from spaceborne sensors is utilized to create large-scale forest height maps (that are particularly interested for large-scale ecological research) based on a newly developed approach. This paper thus serves as a summary paper and also sheds light on the future directions with improved results. In particular, it will be shown that repeat-pass SAR interferometry is able to create a large-scale forest height mosaic product with RMSE $\leq$ 4 m for forest stands on the order of 20 hectares through using the past spaceborne repeat-pass InSAR observations (i.e. JAXA's ALOS-1 and ALOS-2) combined with sparse airborne lidar training samples over the forested areas in New England, US. Moreover, the results and performance of this approach can be remarkably improved with several enhancement techniques that can be easily satisfied with use of future spaceborne repeat-pass InSAR and lidar missions (e.g. NASA-ISRO's NISAR and NASA's GEDI). The methodology described in this paper can be considered as a complimentary tool to the existing PolInSAR technique and also serves as an observing prototype for the future spaceborne missions of repeat-pass InSAR in fusion with lidar (e.g. NISAR and GEDI).

***Index Terms*—spaceborne, SAR, interferometry, repeat-pass, forest height, large-scale.**

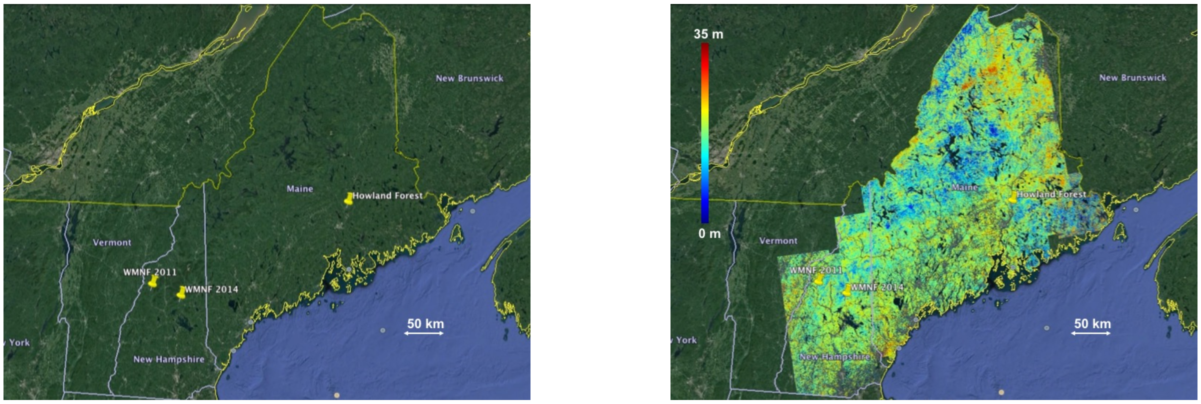
I. INTRODUCTION

Large-scale (e.g. state, continental, global) products of forest biomass and surrogates such as forest height are paramount to understanding how carbon is distributed across ecosystems. In order to obtain quantitative spatial data on forest height, a spaceborne InSAR system has the potential of mapping the forest height on a global scale and a monthly/weekly basis under all weather conditions. Generally, InSAR systems can be classified into two categories: single-pass and repeat-pass. A single-pass InSAR system usually has a pair of antennas mounted on the same platform (such as NASA's SRTM mission), or two synchronized satellites moving in a tandem manner (such as DLR's TanDEM-X mission). Since in either case the two separate antennas view the same ground target simultaneously, the interferometric information (both the InSAR phase and correlation magnitude) of the ground targets can be measured to a plausible accuracy without contamination by the atmosphere and/or the temporal change behavior of the targets. Therefore, successful forest height inversion along with estimation of other parameters (e.g. extinction coefficient characterizing forest density) can be achieved based on the Polarimetric InSAR (PolInSAR) techniques.

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 forests between the repeat interval of the satellite (usually on the order of months; e.g. 46 days for ALOS-1). Although airborne repeat-pass InSAR systems with short repeat interval (on the order of minutes, hours, or even a few days) have been shown to have minimal effects from the atmospheric phase delay and temporal decorrelation, thus making the single-pass InSAR/PolInSAR methods or their modified versions still valid, it is still cumbersome and thus much desirable to utilize and even interpret the accumulated large data volume of spaceborne repeat-pass InSAR observations (e.g. JAXA's JERS, ALOS-1, ALOS-2) for forest mapping.

For these reasons, spaceborne repeat-pass InSAR methods would not achieve the same accuracy of forest height estimation as the single-pass counterparts. However, if modeling of the temporal decorrelation effect can be properly addressed and also the target-dependence of this temporal change behavior can be tolerated/minimized by sacrificing the spatial resolution, it is possible to exploit these temporal decorrelation effects to generate a large-scale forest height metric out of these measurements. As long as the height estimation error is acceptable and robustly characterized (a potentially finer spatial resolution can be achieved with the techniques as will be detailed in this paper), large-scale forest height products are feasible and can help take an important step toward characterizing forest carbon storage and cycling.

Since the single-pass PolInSAR techniques have been widely reported in the literature, the goal of this research was to generate forest height product from spaceborne repeat-pass interferometry and lidar by utilizing the newly developed forest height inversion and mosaicking approach [1], [2]. This also serves as a complimentary tool to the single-pass PolInSAR techniques and is reviewed in Section II. Particularly, the extensive validation using the data from the past and current spaceborne repeat-pass InSAR missions (e.g.



(a) (b)

Fig. 1: *(a) Three airborne lidar sites ("Howland forest" , "WMNF 2011" and "WMNF 2014") overlaid on top of Google Earth optical image, (b) Two-state (Maine and New Hampshire) mosaic map of forest height created using ALOS-1 InSAR data from 2007 and 2010. Forest height estimate is color-coded from 0 to 35 m in all of these maps, i.e. "blue" means bare ground surface, "red" stands for 35 m tall canopy. A forest/non-forest mask (from NLCD 2011 data) has been applied to remove the non-forest areas in (b). The two-state mosaic map is at a spatial resolution of 20 m × 30 m.*

JAXA's ALOS-1 and ALOS-2) followed by the enhancement techniques that have been designed for the future spaceborne repeat-pass InSAR and lidar missions (e.g. NASA-ISRO's NISAR and NASA's GEDI) will be elaborated in Section III. In combination with the single-pass PolInSAR techniques, the presented methodology is important and efficient for large-scale forest characterization and monitoring.

II. Methodology

Since this paper serves as a summary paper with some improved procedure and results, it is thus useful to summarize the previous efforts. These include: 1) a physical scattering model was derived for spaceborne repeat-pass InSAR measurements of forests by accounting for the temporal decorrelation effects of wind-induced random motion and moisture-induced dielectric change [3]; 2) a forest height inversion approach [1] and an automatic mosaicking algorithm [2] were developed with a mosaic of forest height created for the US state of Maine using spaceborne repeat-pass L-band HV-pol InSAR correlation magnitude from ALOS-1 along with a small strip of airborne lidar data as "training samples"; 3) an improved procedure for forest height inversion under the condition of moderate disturbance was developed and validated in New Hampshire, US with a two-state mosaic map created for the US states of Maine and New Hampshire [4].

From the previous work [1], [4], the height estimation error of this new approach is $\leq$ 4 m with the spatial resolution on the order of 20 hectares. In this paper, we perform extensive investigation and validation of this approach by utilizing JAXA's ALOS-1 and ALOS-2 data over the US state of Maine and New Hampshire. Further, as will be seen in this paper, the spatial resolution can be enhanced remarkably with the observing strategy of the future spaceborne repeat-pass InSAR and lidar missions (e.g. NISAR and GEDI). These enhancement techniques will be correspondingly elaborated as the validation results are demonstrated below in Section III.

Ground truth data included NASA's LVIS lidar data (acquired in 2011) over Howland forest in central Maine [1], and University of New Hampshire's GRANIT lidar data collected at two different sites over White Mountain National Forest (WMNF) in New Hampshire in 2011 and 2014, respectively [4]. These airborne lidar height maps are illustrated in Fig. 1a and overlaid on top of the Google Earth optical image.

As mentioned in [4], a Python-based forest height inversion and mosaicking software was developed at the University of Massachusetts Amherst in collaboration with the company Applied GeoSolutions. The software is implemented based on the forest height inversion method [1] and the automatic mosaicking algorithm [2], and has been designed and automated to seamlessly work with the spaceborne repeat-pass HV-pol InSAR correlation magnitude (e.g. from ALOS-1 and ALOS-2) produced by NASA JPL's ROI_PAC and ISCE softwares.

III. Results

A. Validation with ALOS-1 data

A two-state mosaic map [4] has been generated for the US states of Maine and New Hampshire (total area of 11.6 million hectares) and is illustrated in Fig. 1b. It was created by mosaicking 41 ALOS-1 HV-pol InSAR correlation magnitude images with 61 overlapping areas between adjacent images, and only requires limited airborne lidar data (about 44,000 hectares) at the Howland forest in central Maine as "training samples". The ALOS-1 raw (Level 1.0) data were processed into InSAR correlation magnitude using NASA JPL's ROI_PAC software package. The validation results at the three ground validation sites are shown in Fig. 2, and both the height estimation RMSE and the statistical R measure are included in Table I. As a reference, the single-scene height estimation metrics are also demonstrated in Table I for the three ground validation sites respectively. The single-scene height estimate was generated using each corresponding airborne lidar data as "training samples" in combination with the single InSAR scene that overlaps the lidar data. The height estimation metrics from the two-state mosaic are generally better compared to those from the single-scene height maps. This is because at each overlapped location, there are either

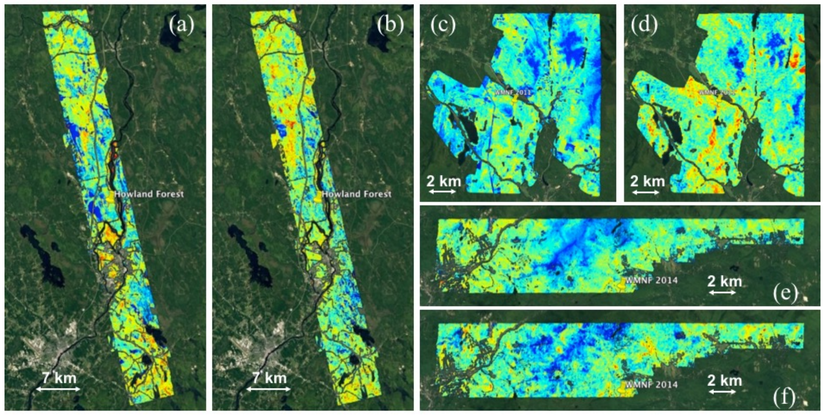


Fig. 2: *Validation of the ALOS-1 two-state mosaic at the three airborne lidar sites as illustrated in Fig. 1a. In particular, (a) and (b), (c) and (d), (e) and (f) show the lidar and radar-inverted height over "Howland forest", "WMNF 2011", "WMNF 2014", respectively. Forest height estimate is color-coded from 0 to 35 m in all of these maps, i.e. "blue" means bare ground surface, "red" stands for 35 m tall canopy. A forest/non-forest mask (generated from NLCD 2011 data) has been applied to remove the non-forest areas in all of the maps.*

2 or 4 InSAR scenes mosaicked together with the height estimates averaged. It is as expected that through statistical averaging, the height estimation RMSE tend to become smaller while the R measure tend to increase. Therefore, as for the future NISAR mission with 12-day repeat interval instead of the 46-day interval of ALOS-1, there will be around 30 SAR images each year, and thus around 30 InSAR pairs with 12-day temporal baseline. Provided that most of the InSAR scenes have stable temporal (weather) change behaviors, the statistical averaging at each location would be performed upon ($\sim 30 \times 2$ or 4) overlapped InSAR scenes, which will considerably reduce the estimation uncertainty (defined as *Enhancement technique #1*).

Lidar Site	ALOS-1 single-scene	ALOS-1 mosaic	ALOS-2 single-scene
Howland Forest	0.51, 4.06	0.53, 3.91	0.54, 3.88
WMNF 2011	0.46, 3.30	0.50, 3.98	0.59, 2.64
WMNF 2014	0.54, 2.93	0.67, 2.48	0.52, 3.03

TABLE I: *Error metrics (denoted as "R, RMSE (m)") of the forest height inversion and mosaicking approach at the three airborne lidar sites ("Howland forest", "WMNF 2011" and "WMNF 2014") using 1) ALOS-1 single-scene inverted height, 2) ALOS-1 two-state mosaic height, and 3) ALOS-2 single-scene inverted height. All of the error metrics are calculated at a spatial resolution of 25 hectares.*

In Fig. 1a, the two GRANIT lidar sites in New Hampshire are almost 300 km away from the training samples of LVIS lidar site in central Maine. However, from Table I, it can be seen that the error metrics are indeed comparable to each other, i.e. RMSE $\leq$ 4 m on the order of 20 hectares and R measure $>$ 0.5 (that is consistent with the previously-reported numbers [1], [4]). Although the automatic mosaicking algorithm is efficient and successful in mitigating the error propagation problem, there is still a potential weakness of this approach, which causes the height estimation RMSE of the two-state mosaic to be worse than that of the single-scene map at the "WMNF 2011" lidar site. This is because the assumption [1] that the temporal (weather) change behaviors are considered constant in each InSAR scene (thus with the mean behavior captured) might not be valid. For example, over the "WMNF 2011" lidar site, the overlapping InSAR scene has uniform temporal change behavior; however, the adjacent InSAR scenes have some distortion of temporal changes, which in turn makes the mosaicked (averaged) height after mosaicking biased to a bigger value (around 0.6 m bias). In other words, the Enhancement technique #1 indeed reduces the estimation uncertainty at the "WMNF 2011" lidar site, as can be seen from the bigger R measure in Table I; however, the failure in the assumption of constant temporal change behavior will introduce systematic bias in the mosaicked forest height. A simple and intuitive solution is 1) to partition the InSAR scene into several pieces with each piece has its own high-resolution lidar "training samples", then 2) to apply the forest height inversion approach to each piece of InSAR scene, and finally 3) to mosaic the pieces of inverted forest height together. This solution is not practical for the test case here since there are only three airborne lidar sites available as illustrated in Fig. 1a. However, a separate spaceborne lidar mission (i.e., GEDI), that is going to be launched around the same timeframe as NISAR, will acquire a large data volume of high-resolution (both horizontal and vertical) sparse lidar samples with the revisit time of 1.5 hours. Therefore, through the partition of each InSAR scene based on a large amount of sparsely-distributed lidar data, the mosaicked forest height will be tuned to the local optimum according to each set of lidar samples, which gives a data fusion prototype for NISAR and GEDI (defined as *Enhancement technique #2*).

B. Validation with ALOS-2 data

In 2014, JAXA launched the upgrade version of ALOS-1, a.k.a ALOS-2 mission, with 14-day repeat period, which is most suitable to compare with the future NISAR mission's 12-day repeat period. However, due to the data acquisition mode and the observing geometry, most of the ALOS-2 stripmap SAR imageries that are separated by 14 days do not align correspondingly in the Northeast US, e.g. 1) one image may be from descending mode and the other from ascending

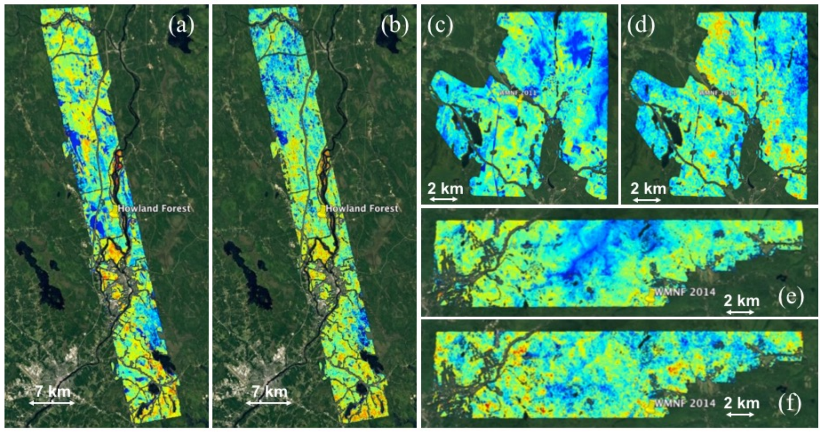


Fig. 3: *Validation of the ALOS-2 single-scene forest height maps over the three airborne lidar sites as illustrated in Fig. 1a. In particular, (a) and (b), (c) and (d), (e) and (f) show the lidar and radar-inverted height over "Howland forest", "WMNF 2011", "WMNF 2014", respectively. Forest height estimate is color-coded from 0 to 35 m in all of these maps, i.e. "blue" means bare ground surface, "red" stands for 35 m tall canopy. A forest/non-forest mask (generated from NLCD 2011 data) has been applied to remove the non-forest areas in all of the maps.*

mode (thus completely different viewing geometry), or 2) the two images only overlap by a small portion of each other, etc. In this sense, there are not many ALOS-2 InSAR pairs available in the current archives. In fact, in 2014 through 2016, there is only one Fine Beam Dual-polarization (FBD) ALOS-2 InSAR pair (descending mode; 20150422–20150506) covering the two GRANIT lidar sites in New Hampshire, and another pair (ascending mode; 20160613–20160627) covering the LVIS lidar strip in Maine. The ALOS-2 Level 1.1 data were processed using NASA JPL's ISCE software for these two InSAR pairs. The inverted forest height estimates using the above technique are shown in Fig. 3, with the height estimation RMSE and the R measure also demonstrated in Table I. Although there are few choices of ALOS-2 InSAR pairs, it can be seen from Fig. 3 and Table I, the height estimates from ALOS-2 with 14-day repeat interval indeed improves compared to the single-scene forest height estimates from ALOS-1 with (at least) 46-day repeat period. Moreover, each ALOS-1 pair (utilized for creating the single-scene results and the two-state mosaic) was selected as the "best" InSAR pair with the highest InSAR correlation magnitude in 2007 through 2010 from dozens of ALOS-1 InSAR pairs available. However, each ALOS-2 pair here is the only choice that is usable at the airborne lidar site for this study. Therefore, it is as expected that the shorter temporal baseline (or repeat period), the stabler temporal (weather) change behavior, and thus the better performance of the forest height inversion approach (defined as *Enhancement technique #3*).

IV. Conclusions

This paper serves as a review of the newly-developed forest height inversion and mosaicking approach using spaceborne repeat-pass SAR interferometry in fusion with lidar. This simple and efficient approach only requires single-baseline, cross-polarized (HV-pol) InSAR data, and the performance is still plausible at mountainous areas with large topographic slopes (e.g. over WMNF). Therefore, this method can be considered as a complimentary tool to the PolInSAR methods for using spaceborne single-pass SAR interferometry. Through validation with use of ALOS-1 and ALOS-2 InSAR data over the three airborne lidar sites in the Northeast of US, it is shown that the height estimation error is manageable (RMSE $\leq$ 4 m on the order of 20 hectares). More importantly, three enhancement techniques have been designed to further improve the robustness of the performance as well as to reduce the estimation uncertainty. These techniques are specifically designed for the fusion of the future spaceborne repeat-pass InSAR and lidar missions (such as NISAR and GEDI).

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