MONITORING FOREST DEGRADATION IN THE AMAZON BASIN WITH TANDEM-X HIGH-RESOLUTION IMAGES AND DEEP LEARNING TECHNIQUES

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ABSTRACT

The TanDEM-X Forest/Non-Forest map, derived from the volume decorrelation factor using a supervised fuzzy clustering algorithm, represents the baseline approach for forest mapping with TanDEM-X data at global scale. Deep learning (DL) methods have been demonstrated to be also suitable for mapping forests at large scale with TanDEM-X interferometric data. In this work, we investigate the capabilities of using a U-Net-like architecture with TanDEM-X interferometric data for forest mapping at 6 m resolution. With such high-resolution data, we aim at improving the forest mapping accuracy and to be able to detect forest degradation over the Amazon rainforest caused e.g. by selective logging, fires and natural hazards. The classification improvements already observed applying DL methods on TanDEM-X data allow for the generation of large scale time-tagged mosaics. The explotation of such mosaics over extended areas is a key aspect for the detection and monitoring of forest dynamics worldwide.

Index Terms— Synthetic Aperture Radar, TanDEM-X, rainforest, tropical forest, forest mapping, deforestation monitoring, deep learning, convolutional neural network, U-Net

1. INTRODUCTION

The Amazon rainforest is the largest moist broadleaf tropical forest on the planet and plays a key role for regulating environmental processes on Earth, playing a crucial role in the carbon and water cycles and acting as climate regulator, e.g. by producing about 20% of the Earth's oxygen and contrasting global warming. The monitoring of changes in such forested areas characterized by a unique biome is of paramount importance. Synthetic Aperture Radar (SAR) systems, thanks to their capability to acquire images independently of the weather and day/light illumination, are an attractive alternative to optical sensors for remote sensing applications over such areas, which are covered by clouds for most of the year.

In this context, the TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) mission maps the Earth's surface providing single images at high resolution from the recorded backscattered signal as well as high accurate unique interferometric SAR (InSAR) products acquired in bistatic mode [1]. The advantage of flying two satellites in close formation, constituting a single-pass InSAR system, adds valuable information to the amplitude data, such as the the interferometric phase and coherence.

The interferometric coherence, defined as the normalized complex correlation coefficient between the two InSAR acquisitions, gives information about the amount of noise in the interferograms and is sensitive to different decorrelation sources, such as the signal-to-noise ratio losses and volume scattering mechanisms. This last aspect is quantified by the volume decorrelation factor (γ_{Vol}) [2], which was the main input feature for the generation of the global TanDEM-X Forest/Non-Forest (FNF) map, provided at a resolution of 50 m x 50 m and generated using a machine learning (ML) fuzzy clustering algorithm [3].

For information extraction and forest mapping in the context of TanDEM-X SAR images, the potential of deep learning has been demonstrated in [5]. A U-Net architecture [6] demonstrated to be the most effective one and was the starting point for a DL approach with further model generalization capabilities [7]. An ad-hoc training strategy has been developed to distinguish forest on TanDEM-X images acquired with different acquisition geometries over the Amazon rainforest. The reached classification improvements applying DL methods on TanDEM-X data have allowed for the generation of time-tagged mosaics at 50 m resolution over the tropical forests by utilizing the nominal TanDEM-X acquisitions between 2011 and 2017, skipping the weighted mosaicking of overlapping images used in the clustering approach for achieving a good final accuracy. Furthermore, the trained U-Net over the Amazon rainforest has been used to extend the forest mapping to other tropical forests over Africa and Asia, also showing a high accuracy and a good agreement with other land cover maps [7].

The objective of the present study is to extend the previous work by exploiting the full-resolution TanDEM-X InSAR dataset. Preliminary promising results were presented in [5] and [8], both based on a limited set of single TanDEM-X full-resolution images over a temperate forest in Pennsylvania (USA). In [8], the TanDEM-X interferometric acqui-

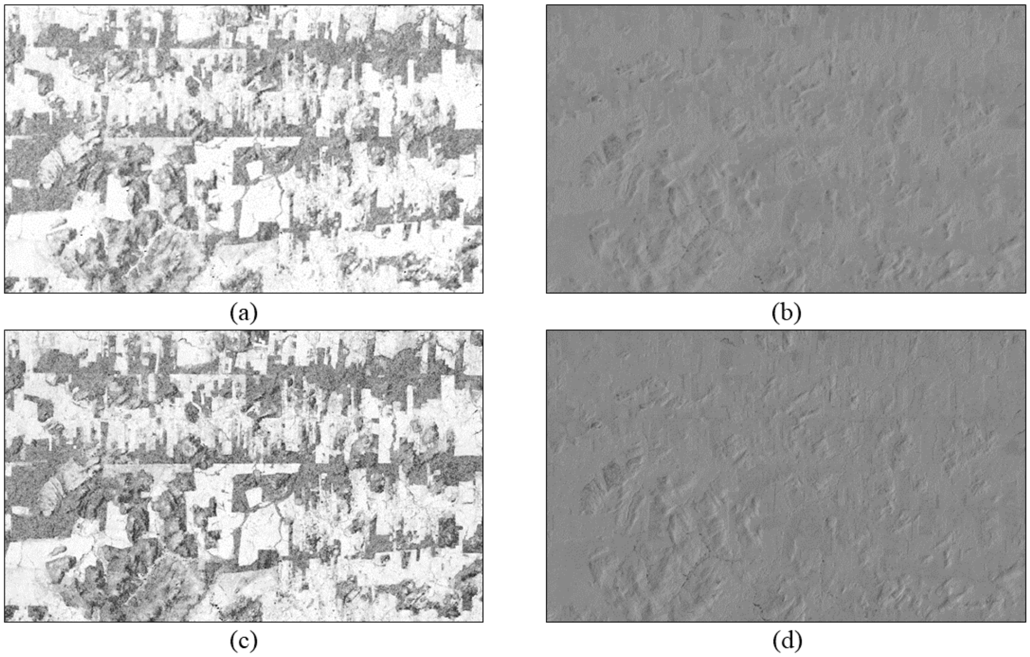


Fig. 1. Comparison of the TanDEM-X bistatic InSAR data set processed at different resolutions. Details of an image acquired over the Amazon rainforest in 2011. (a) volume correlation factor at 50 m resolution, (b) amplitude image at 50 m resolution, (c) volume correlation factor at 6 m resolution by applying state-of-the-art interferometric processing techniques [4], (d) corresponding amplitude image at 6 m resolution.

sitions were processed with a non-local filtering technique and they were classified using a similar clustering approach as the one used for the global TanDEM-X FNF map [3]. By applying further sophisticated InSAR processing techniques [4], it is possible to process the TanDEM-X single-look slant-range complex images acquired at 3 m resolution (stripmap single-polarization mode) to an independent pixel spacing of 6 m. With such high-resolution data, we aim at improving the forest mapping accuracy and to detect forest degradation phenomena over the Amazon rainforest caused by selective logging, fires and natural hazards. Deforestation paths in the middle of dense forested areas, which were not visible at 50 m resolution, can be successfully detected using 6 m resolution images. Moreover, a finer contour delimitation of the deforested areas is possible, as depicted in Figure 1. The image shows typical deforestation patterns occurring over the Amazon rainforest.

The paper is organized as follows: in Section 2, current state-of-the-art approaches for forest mapping with TanDEM-X, including preliminary investigations with deep learning methods, are summarized. Further developments currently under investigation for the exploitation of the full-resolution TanDEM-X bistatic data set, including first results, are presented in Section 3. Finally, in Section 4 the conclusions are drawn.

2. FOREST MAPPING WITH TANDEM-X

2.1. The Global Forest/Non-Forest Map

In a bistatic SAR system such as TanDEM-X, with the absence of temporal decorrelation, the volume decorrelation factor γ_{Vol} adds valuable information for discriminating between forested and non-forested areas, thanks to its sensitivity to the presence of vegetated areas. The γ_{Vol} was selected as main feature for the generation of the global TanDEM-X FNF map, based on a supervised geometry-dependent fuzzy clustering classification approach as explained in [3]. This approach represents the baseline approach for forest mapping with TanDEM-X . In the generation of the global TanDEM-X FNF map, only acquisitions with a height of ambiguity ($\mathrm{h}_{\mathrm{amb}} < 100\mathrm{m}$) were classified. On images acquired with higher $\mathrm{h}_{\mathrm{amb}}$, the forest classification was too ambiguous due to the acquisition geometry characterized by smaller perpendicular baselines between the satellites, which reduces the sensitivity of the γ_{Vol} to vegetated areas. The classified images were mosaicked in a final single forest map following a weighted mosaicking process. The mosaicking of the overlapping images was necessary to improve the accuracy of the generated TanDEM-X global FNF. On this map, external references were necessary to filter out water surfaces as well as urban areas [3].

2.2. Deep Learning-Based Approaches

The potential of deep learning for forest mapping in the context of TanDEM-X bistatic SAR images was demonstrated in [5], where three different state-of-the-art convolutional neural network (CNN) architectures were utilized, namely ResNet, DenseNet and U-Net, while training and testing were performed on a limited data set of TanDEM-X full resolution images acquired over Pennsylvania, USA. Overall, the U-Net [6] demonstrated to be the most effective solution for such a task, achieving the best performance among all investigated architectures. For model generalization, an ad-hoc training strategy on all different acquisition geometries has been developed and the number of considered input features of the U-Net has been extended in [7]. The acquisition incidence angle and the height of ambiguity ($\mathrm{h_{amb}}$), which quantifies the phase-to-height sensitivity of an interferogram in a bistatic acquisition, have been added as major descriptors of the variability in the TanDEM-X acquisition geometries. The trained CNN has been first tested on a separate set of images over the Amazon rainforest, which are representative for the considered acquisition geometries. In general, thanks to its capabilities in understanding two-dimensional patterns, the CNN performs much better with respect to the clustering approach, it is able to generate forest maps with closed forested areas and non-forest regions which are less noisy. The trained CNN has been used to classify more than 50,000 TanDEM-X images acquired over the tropical forests between the end of 2010 and the middle of 2017. The improvement in the classification accuracy of the TanDEM-X images has allowed for skipping the weighted mosaicking process of overlapping acquisitions used for the generation of the TanDEM-X FNF map. Up to three time-tagged mosaics over the Amazon rainforest have been generated and two over the other tropical forest areas located in Africa and South-East Asia, respectively [7].

3. TOWARDS HIGH-RESOLUTION FOREST MONITORING WITH TANDEM-X

The high accuracy shown by the obtained mosaics represents a good starting point to estimate the deforestation occurred over the tropical areas in the last decade. Unfortunately, the classified images with the U-Net suffer from the mid spatial resolution of 50 m x 50 m when detecting details such as narrow deforestation patterns. In some circumstances, also areas close to rivers, where the vegetation presents different characteristics with respect dense rainforest, as well as areas with secondary forest, are seen at X band as non-forest areas, leading to possible misclassification errors.

To overcome these limitations, the aim of the present study is to extend the previous work to high-resolution, by combining improved interferometric processing approaches of the TanDEM-X bistatic acquisitions together with DL techniques for accurate classification of forested areas.

3.1. TanDEM-X Interferometric Processing

As demonstrated in [8], the estimation of the complex interferogram is a fundamental step for InSAR applications, as it impacts any further high-level processing. A critical task is the unbiased estimation of the interferometric coherence. Non-local filtering techniques represent an effective approach to improve such an estimation and res, since they allow for the achievement of a better noise suppression, a finer resolution preservation and, at the same time, a reduction of the coherence estimation bias. As a drawback, they require a high computational effort and are therefore inadequate for large-scale deployment. In [8] a non-local filtering technique was used to interferometrically process TanDEM-X images acquired in 2011 over Pennsylvania (USA). Afterwards they were classified using a similar clustering approach as the one used for the global TanDEM-X FNF map [3].

In the current study we use an improved InSAR processing technique aiming to push the output resolution down to only 6 m. The interferometric coherence is estimated by the Φ-Net, a deep residual CNN which allows for achieving a state-of-the-art denoising performance by maintaining the resolution [4]. The improvement in details, thanks to the InSAR processing technique, can be seen in Figure 1.

3.2. First Results

Fully supervised DL approaches rely on high-accurate reference data. At 6 m resolution and at a large-scale, the availability of such reference data is limited. To overcome this limitation, we first used the Lidar-Optic (LO) forest/non-forest reference map, provided by the University of Maryland at a ground resolution of 1 m x 1 m over Pennsylvania [9], for training a CNN at high resolution. The data were acquired before 2010. Figure 2 shows the available number of images which overlap with the area of the LO reference map. They are indicated for each range of $\mathrm{h_{amb}}$ (2 m steps) and for three different incidence angles. Following the training strategy presented in [7], it was necessary to include images acquired in 2012 and 2013 as well. Acquisitions over this region in 2011 were acquired with $\mathrm{h_{amb}}$ between 40 m and 50 m [8]. Acquisitions affected by snow and ice were filtered out. We ended up with a data set of 450 TanDEM-X images processed at 6 m resolution for end-to-end training, validation, and testing of the CNN proposed in [7]. First results are shown in Figure 3, were details of a classified image at 6 m resolution are compared with the reference data at 1 m resolution. Most of the details are visible. Further investigations are necessary for a more robust model generalization. Fine-tuning of the CNN over the Amazon basin, where a limited set of reference data is available, is an on-going activity. We expect the CNN to be able to catch the differences between temperate and tropical forest. Furthermore, to overcome the lack of high-resolution reference data for fully-supervised training methods, self-supervised learning approaches are currently under

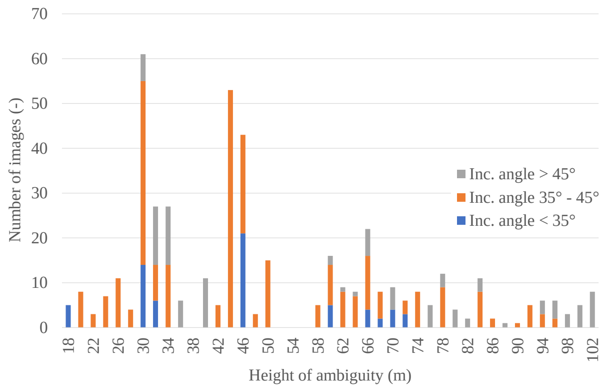
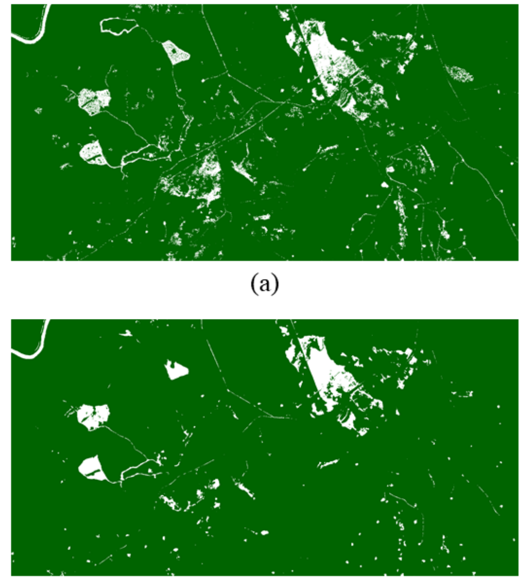


Fig. 2. Images acquired between 2011 and 2013 over Pennsylvania and available for fully supervised training of a CNN.

investigation as well.

4. CONCLUSIONS AND OUTLOOK

In this paper we presented first results obtained for forest discrimination with TanDEM-X data at 6 m resolution. Previous works dealing with CNN approaches for forest mapping with TanDEM-X have been extended to exploit such high-resolution SAR images. By applying sophisticated interferometric processing techniques, which preserve the original resolution of the acquired image, more features are observed in the TanDEM-X interferometric data set. By comparing the detected forest over the years, deforestation areas can be detected, showing the capabilities of TanDEM-X for forest monitoring based on deep learning approaches.



(a)

(b)

Fig. 3. First classification results of a high-resolution TanDEM-X image. (a) Reference data at 1 m resolution, (b) TanDEM-X forest/non-forest map at 6 m resolution.

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