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The global forest/non-forest map from TanDEM-X interferometric SAR data

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A B S T R A C T

In this paper we present the activities performed at the Microwaves and Radar Institute of the German Aerospace Center (DLR) to derive global forest/non-forest classification mosaics from interferometric synthetic aperture radar (InSAR) data acquired by the TanDEM-X mission. The data have been collected between 2011 and 2016 in bistatic stripmap single polarization (HH) mode, with the main goal of generating a consistent, timely, and highly accurate 3D representation of the global terrain's surface (digital elevation model, DEM). The global data set of quicklook images, which represent a spatially averaged version of the original full resolution data at a ground independent pixel spacing of 50 m × 50 m, was used as input, in order to limit the computational burden. For classification purposes, several observables, systematically provided by the TanDEM-X system, can be exploited, such as the calibrated amplitude, the digital elevation model (DEM), and the interferometric coherence. Among the several factors contributing to a coherence degradation in InSAR data, the so-called volume correlation factor quantifies the coherence loss due to volume scattering phenomena, which typically occur in presence of vegetation. This quantity is directly derived from the interferometric coherence and used as main indicator for the identification of vegetated areas. For this purpose, a fuzzy multi-clustering classification approach, which takes into account the geometry and acquisition configuration, is applied to each acquired scene separately. A certain variability of the interferometric coherence at X band was observed among different forest types, mainly due to changes in forest structure, density, and tree height, which led to an adjustment of the algorithm settings depending on the considered type of forest. The identification of additional information layers, such as urban settlements or water areas, is also discussed, and the procedure for mosaicking of overlapping acquisitions (two at global scale, up to ten over mountainous terrain, forests, and desert regions) to improve the classification accuracy is detailed. The resulting global forest/non-forest map was validated using external reference information as well as with other existing classification maps and an overall agreement was observed that often exceeds 90%. Finally, examples for high-resolution (at 12 m × 12 m) forest maps and potentials for deforestation monitoring over selected regions are presented as well, demonstrating the unique capabilities offered by the TanDEM-X bistatic system for a broad range of geoinformation services and scientific applications. The global TanDEM-X forest/non-forest map presented in this paper will be made available to the scientific community for free download and usage.

1. Introduction

Covering about 30% of the Earth's landmasses, forests represent the dominant terrestrial ecosystem and are of extreme importance for all living being on our planet. Indeed, forests act as Earth's lung, by continuously absorbing, storing, and converting carbon dioxide (CO_2) into oxygen which helps to reduce the concentration of atmospheric greenhouse gases and, ultimately, to control climate change. Plants and trees in forested areas catch rainwater and are natural watersheds preventing from flood events. Moreover, they mitigate soil erosion, which naturally happens due to the action of water and/or wind, or artificially because of irresponsible farming practices. They are an essential source of energy (such as biomass), food, jobs and livelihoods in general for a many populations on Earth and serve as natural habitat to a large variety of animal species, preserving the existence of biodiversities and healthy ecosystems.

However, this delicate balance is put in danger by the loss and degradation of forests, which is nowadays occurring at an alarming

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rate. Deforestation is a process which dates back to the dawning of human civilization. Over the past 10,000 years, more than 50% of the world's forests have been lost due to anthropogenic activities, such as the demand of energy (e.g. timber) and food (e.g. agriculture), and the realization of living spaces and of transportation infrastructure for a constantly increasing population. Such an age-old deforestation process was severely accelerated in the mid-twentieth century, and more sensitive environments have been irreversibly damaged, leading to a permanent loss of plants and animal habitats, a reduction in forest carbon stocks, and an accelerated soil erosion (Solomon et al., 2007).

For all these reasons, an up-to-date assessment and monitoring of forest resources becomes of crucial importance and, in this scenario, spaceborne remote sensing represents a unique instrument for providing consistent, timely, and high-resolution data at a global scale. In the last decades global forest classification maps have been produced by mainly optical and near-optical systems such as the Advanced Very High Resolution Radiometer (AVHRR (Hansen et al., 2000; Hansen and De Fries, 2004), at 1 km spatial resolution), the Moderate Resolution Imaging Spectroradiometer (MODIS (Hansen et al., 2003), 500 m resolution), or ENVISAT MERIS (CCI Land Cover (Hansen et al., 2003; Kirches et al., 2015), 300 m resolution) and its follow-on instrument on Sentinel-3. In 2013 a global forest tree cover map was produced from mosaics of Landsat sensor data at a spatial resolution of 30 m, including annual forest gain and loss (Hansen et al., 2013). In this frame, SAR sensors represent a very attractive solution for reliable mapping and monitoring of forest areas, thanks to their weather and daylight independence. The first global forest/non-forest classification map derived from SAR data, exploiting backscatter in HV polarization, has been provided by the L-band sensor ALOS PALSAR at a posting of 25 m (Shimada et al., 2014).

In this paper we present the first global forest/non-forest classification map from TanDEM-X interferometric SAR data at X band, based on the exploitation of the coherence-derived volume correlation factor, which quantifies the amount of interferometric decorrelation caused by volume scattering phenomena. The TanDEM-X mission comprises the two twin satellites TerraSAR-X and TanDEM-X, with the main goal of producing a global and consistent digital elevation model (DEM) with an unprecedented accuracy by exploiting single-pass SAR interferometry (Krieger et al., 2007). The potentials of TanDEM-X interferometric data for forest mapping have been successfully demonstrated e.g. in Schlund et al. (2014) and Martone et al. (2015a, 2016a).

The paper is organized as follows: the main aspects of the TanDEM-X mission and the available data set are summarized in Section 2, where the suitability of different observables for forest mapping at X band is also discussed. In Section 3 the volume correlation factor is introduced as main parameter used for the present classification approach, and a theoretical background for existing volume scattering models is shortly recalled. Section 4 introduces the set of external data sources that were used as support for the generation of the global forest/non-forest product. The developed method for forest/non-forest classification, based on fuzzy clustering, is introduced in Section 5, and in Section 6 the method for properly mosaicking all overlapping available observations is described. The procedure for the definition of a binary classification threshold as well as additional post-processing filtering is presented in Section 7. Section 8 focuses on the identification of additional information layers (such as areas affected by geometrical distortions, urban settlements, and water bodies) derived from TanDEM-X data as well as from the external data sources listed in Section 4. The resulting global forest/non-forest classification map at 50 m × 50 m spatial resolution is presented in Section 9, while the product validation with external reference data and comparisons with existing land cover maps is discussed in Section 10. Examples for high-resolution forest mapping (at a spatial resolution of 12 m or below), and the potentials for forest change monitoring are shown in Section 11, and in Section 12, conclusions are drawn.

2. The TanDEM-X mission and data set

TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) is the first operational spaceborne bistatic SAR system comprising the two twin satellites TerraSAR-X (launched in 2007) and TanDEM-X (launched in June 2010). After a first period of commissioning phase, the mission officially started in December 2010. Since then, the two satellites have been operationally acquiring interferometric SAR images in bistatic configuration, stripmap mode (HH polarization), with a typical resolution (azimuth and range) of about 3 m. Both satellites fly in a closely controlled orbit formation with the opportunity for flexible along- and across-track baseline selection with the primary objective of generating a global, consistent and high-precision digital elevation model (DEM) (Krieger et al., 2007) at a final independent posting of 12 m × 12 m. The global TanDEM-X DEM has been finalized and delivered in September 2016 (Rizzoli et al., 2017a). Such a high-demanding goal has been achieved by performing at least two global mappings of the Earth's land masses and multiple acquisitions over selected regions (such as mountainous terrain, forested areas, or sandy desert regions) to improve the overall product accuracy. Since the beginning of the mission, more than half a million high-resolution scenes have been acquired and processed, with incidence angles ranging between 30° and about 50°, and interferometric baselines $B_{\perp}$ in the range between 80 m and 500 m, which have been considered for the present work.

A fundamental acquisition parameter for the current investigation is the height of ambiguity h_{amb}, which represents the height difference corresponding to a complete 2π cycle of the interferometric phase, and gives information about the phase-to-height sensitivity in the interferogram. For the bistatic case, it is defined as

$$h_{\text{amb}} = \frac{\lambda r \sin(\theta_i)}{B_{\perp}}, \tag{1}$$

being λ the radar wavelength, r the slant range, and θ_i the incidence angle. For the first DEM global acquisition of TanDEM-X, the height of ambiguity was typically between 45 m and 60 m, ensuring good unwrapping quality over most land types. For the second one, larger baselines were considered (h_{amb} around 35 m), in order to increase the final DEM accuracy. The combination of at least two acquisitions by means of multi-baseline phase unwrapping algorithms allowed then to fully meet the mission requirements (Lachaise et al., 2012). A single bistatic scene typically extends over an area of about 30 km in range by 50 km in azimuth. From this, quicklook images, representing several SAR and InSAR quantities (like backscatter and coherence maps, or the roughly calibrated DEM (RawDEM)), are generated at a ground resolution of 50 m × 50 m by applying a spatial averaging process to the corresponding operational TanDEM-X interferometric data at full resolution. Working with such quicklook data allows for the exploitation of the TanDEM-X dataset on a global scale with a limited computational load: Indeed, a nominal TanDEM-X stripmap bistatic scene at full resolution comprises two raster images (master and slave), each with a size up to 2 GB, while the corresponding quicklook data have a size of only 1–2 MB each. Moreover, together with a reduction of about three orders of magnitude in terms of data volume, one should also point out that, when dealing with the original products at full resolution, the complete interferometric processing chain needs to be applied to generate, e.g., the coherence map or the DEM, which are used as input to the classification algorithm. This step requires additional processing time (and an increase in the memory usage), which becomes a critical bottleneck due to the large number of bistatic scenes (about half a million) used for the generation of the global classification product presented in this paper. On the other hand, the corresponding quicklook images are generated as a by-product of the full resolution data by the Integrated TanDEM-X Processor (Fritz et al., 2012), hence requiring no additional processing effort. Global mosaics from TanDEM-X quicklook data have already been produced in the last years (Rizzoli et al., 2014,