TANDEM-X AND GEDI DATA FUSION FOR A CONTINUOUS FOREST HEIGHT MAPPING AT LARGE SCALES

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ABSTRACT

The TerraSAR-X add on for Digital Elevation Measurement (TanDEM-X) mission provides Interferometric Synthetic Aperture Radar (InSAR) wall-to-wall data (not sparse) at high resolution and at global scale. In addition, the NASA Global Ecosystem Dynamics Investigation (GEDI) is a new spaceborne system that provides (from 51.6°N and 51.6°S) sparse measurements (not images) through LiDAR waveforms. Both systems are sensitivity to the canopy structure such as the forest height but with their own limitations. The TanDEM-X single polarization (HH) interferometric coherence magnitude at X-band provides a continuous mapping of the forest while GEDI provides accurate (but sparse) measurements of the forest. In this paper a methodology of how to combine both systems to estimated forest height is presented and applied to more than 900 TanDEM-X scenes over Gabon in Africa. The forest height results over an area of 1° by 1° are shown and compared respect to GEDI. Finally, a wall-to-wall forest map over the entire country of Gabon is presented as an example of large scale mapping towards a potential global (entire earth) forest height map.

***Index Terms*—** TanDEM-X, GEDI, Forest Height

1. INTRODUCTION

Forest height is an important forest parameters in forestry. It provides information about the development of the forest, it is an indicator for the timber production and it is frequently used to estimated forest biomass through allometric relations. The estimation of accurate forest height allows conclusions on the state of a forest, and can be used to constrain model estimates of above ground biomass, associated carbon flux components or detect logging activities where not all trees have been removed (i.e clear cuts) [1, 2].

Forest height is a standard parameter in forest inventories at local scales, but is hard to be measured on the ground as soon as the density and the area to be measured increase. In terms of remote sensing techniques, Light Detection and Ranging (LiDAR) have been established as the *reference* for measuring forest height on local and regional scales [3]. However, for large scale mapping from spaceborne configurations, LiDAR is limited by small and scattered footprints that do not allow wall-to-wall forest height measurements.

Synthetic Aperture Radar (SAR) systems are able to provide high-resolution and continuous measurements from spaceborne configurations [4]. Moreover, the use of more than one SAR image allows to have sensitivity in the vertical dimension by exploding the phase information between the two images. This technique is known as Interferometric Synthetic Aperture Radar (InSAR) and many studies have been demonstrated the potential of InSAR coherence to estimate forest height, but the performance is linked to the use of some specific SAR data (i.e. full polarimetric data) or external data (i.e. external digital terrain model) that are not available globally [5]. The TerraSAR-X add on for Digital Elevation Measurement (TanDEM-X) mission forms a space borne X-band single-pass interferometer that provides global acquisition of InSAR data at single-polarization [6]. Although the use of single-polarizations limits the performance of forest height depending for example in the forest type [7], the availability of a global data-set opens the door for large-scale (even the entire earth) forest height mapping.

The NASA Global Ecosystem Dynamics Investigation (GEDI) is a new spaceborne LiDAR instrument operating onboard the International Space Station (ISS) and has been collecting data (from 51.6°N and 51.6°S) since April 2019 [8]. GEDI is a full waveform LiDAR that provides the vegetation reflectivity profile at 25 m footprint allowing the accurate determination of ground topography, canopy height, and various relative height metrics. However, the GEDI beam pattern does not allow a continuous mapping as it provides scattered footprints with a distance of 60 m and 600 m in along- and across-track, respectively.

The combination of these two missions allows to overcome their individual limitations (i.e. not accurate forest height from TanDEM-X alone and sparse sampling for GEDI alone) by exploding the information of full reflectivity waveform provided by GEDI together with the single-polarization interferometric coherence [9, 10, 11]. In this paper, we show the last results and investigations to fusion the TanDEM-X and GEDI data in order to generate forest height wall-to-wall mosaics at large (i.e. country/continent) scale.

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2. FOREST HEIGHT INVERSION

2.1. TanDEM-X interferometric coherence

The interferometric coherence γ in one polarization channel can be expressed as:

$$\gamma = \gamma_{SNR}\gamma_B\gamma_{temp}\gamma_{vol} \tag{1}$$

where $\gamma_{SNR}\gamma_B\gamma_{temp}$ are the Signal to Noise Ratio (SNR), baseline and temporal decorrelation contributions, respectively. In the TanDEM-X case, $\gamma_{temp} = 1$. γ_{SNR} and γ_B can be predicted and compensated [12]. As a consequence, $\gamma \simeq \gamma_{vol}$ represents the decorrelation caused by volume scattering over vegetated areas and can be written as:

$$\gamma_{vol} = exp(ik_z z_0)\frac{\int_0^{h_v} f(z)exp(ik_z z)\, dz}{\int_0^{h_v} f(z)\, dz} \tag{2}$$

where k_z is the vertical wavenumber, z_0 is the reference height (ground level), h_v is the forest height and $f(z)$ is the radar reflectivity function (also referred as the vertical reflectivity profile) and expresses the vertical distribution of scatterers seen by the InSAR data at each pixel on the ground. In 2, there is only one complex measurement (γ_{vol}) and three unknown real parameters (z_0, h_v, $f(z)$). The magnitude of 2 is given by:

$$|\gamma_{vol}| = \left|\frac{\int_0^{h_v} f(z)exp(ik_z z)\, dz}{\int_0^{h_v} f(z)\, dz}\right| \tag{3}$$

In 3 there is no more dependency of z_0. However, to have a determined problem with one measurement (magnitude of the interference coherence $|\gamma_{vol}|$) and one unknown (forest height h_v), it is necessary to know (or assume by a model) the vertical reflectivity profile $f(z)$ [11].

2.2. Fusion TanDEM-X and GEDI waveforms

The GEDI space borne LiDAR instrument provides sparse waveforms that depend directly on the distribution of the different canopy elements inside the GEDI footprint. A first approach for the combination of GEDI and TanDEM-X is the use of GEDI waveforms as the reflectivity function $f(z)$ in 3 in order to estimate the forest height [11]. However, as previously mentioned, the GEDI mission only provides sparse measurements and therefore a wall-to wall forest height map over each pixel in the TanDEM-X scene is not possible.

Assuming that only m GEDI profiles $p(z)$ are available in a TanDEM-X scene, a covariance matrix can be formed as:

$$\mathbf{R} = \mathbf{P}\,\mathbf{P}^T \tag{4}$$

where $()^T$ represent the transpose operator and $\mathbf{P}$ represents a matrix whose columns are the m GEDI profiles normalized to unit height (i.e. only the shape of the pofile is considered). The matrix $\mathbf{R}$ can be decomposed in positive eigenvalues and orthogonal eigenvectors. Assuming that most of the profile energy is concentrated in the first eigenvalues, the use of the first eigenvector (or the combination of a few of them) as the vertical profile $f(z)$ for the whole scene represents a reasonable approximation for the whole TanDEM-X scene [11].

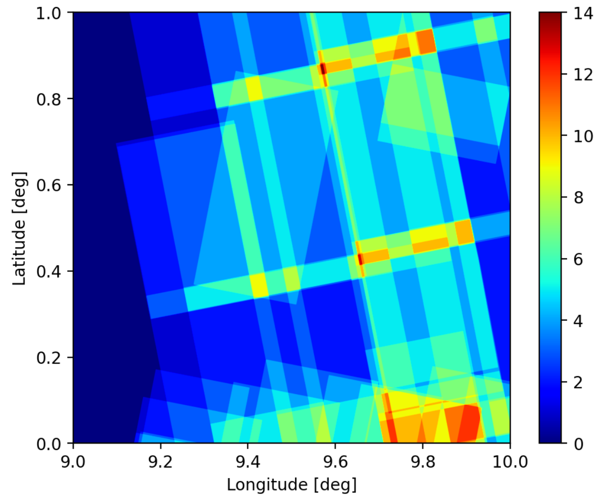

Fig. 1. Number of TanDEM-X acquisitions around the city of Libreville, Gabon.

3. RESULTS

The methodology presented in Section 2 have been applied to more than 900 TanDEM-X scenes acquired between 2011 and 2015 for the generation of the Global Digital Elevation Model (DEM). All images have been acquired at single polarization channel HH with vertical wavenumbers k_z between 0.05 and 0.15 rad/m. Figure 1 shows the footprint of each TanDEM-X acquisition over an area of 1° by 1° around the city of Libreville in Gabon. As it can be observed in Figure 1, the area is not uniformly covered and each pixel is *observed* by a different number of images, which gives the opportunity to get a different forest height result for the same pixel depending on the scene characteristics (e.g. acquisition time or vertical wavenumber).

Each of the TanDEM-X acquisitions is processed independently, this includes the whole interferometric processing starting from the Single Look Complex (SLC) images and the generation of the vertical reflectivity profile $f(z)$ from the GEDI data inside the scene. Then, with the interferometric coherence, the vertical wavenumber and the profile $f(z)$ from the GEDI data, the forest height can be estimated for each pixel in the image as indicated in 3.

Figure 2 shows the mosaic of the forest height result using all TanDEM-X scenes shown in Figure 1. As indicated

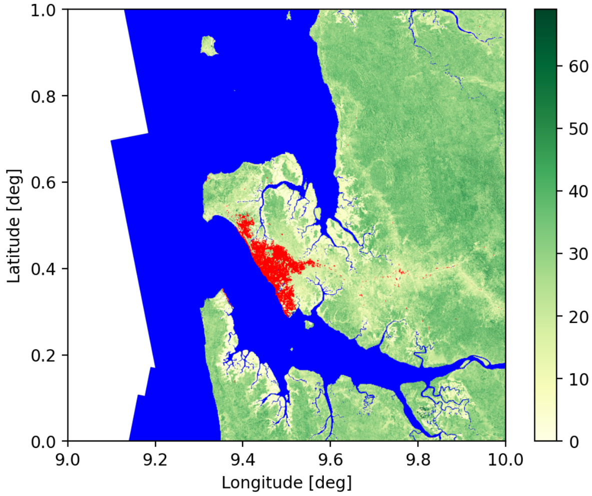

Fig. 2. Forest height TanDEM-X GEDI fusion around the city of Libreville, Gabon. Red represents the settlements and blue the water bodies.

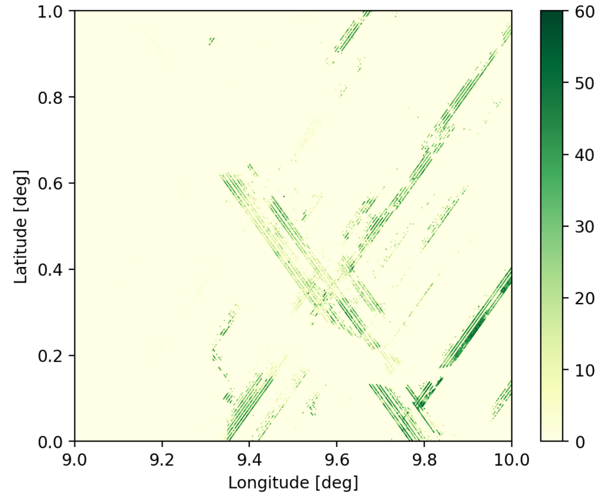

Fig. 3. GEDI RH95 forest height metric around the city of Libreville, Gabon. The size of each GEDI sample have been increased to 250 m in the figure for visualization purpose.

before, each pixel is *estimated* by different images and therefore many solutions can be selected for the final mosaic. Here, we first exclude images with a priori *bad* forest height performance, for example due to low values of interferometric coherence or non-desired values of vertical wavenumnber (e.g ambiguity problems). Then, with the remaining images, the final result is obtained by selecting the image with the most common (and valid) k_z of the area. this allows to ensure a continuous mapping with a (prior) accepted range of vertical wavenumnber. Figure 2 shows the final forest height mosaic.

Figure 3 shows the RH95 forest height metric obtained from the GEDI waveform at each of the footprints over the same area. As already mentioned, although GEDI provides an accurate measurement of the forest height, the sparse measurement does not allow a wall-to-wall mapping. The procedure indicated in Section 2 includes only the information about the shape of the vertical profile and not forest height extracted from GEDI. Therefore, the forest height shown in Figure 3 can be used to have a first evaluation of the forest height fusion approach. Figure 4 shows the 1D and 2D histograms comparing the forest height obtained from the combination procedure and the RH metric of GEDI. The histograms show a similar distribution of heights for both systems with a RMSE of 12 m. Although there is an (expected) underestimation of the forest height obtained from TanDEM-X, due to the low penetration of TanDEM-x over dense tropical forests, the results are reasonable taking into account that the approach only uses the absolute value of the interferometric cohrence and it assumes one profile for the whole TanDEM-X scene.

As an example of the final product at country scale, Figure 5 shows the final results over the entire Gabon in Africa.

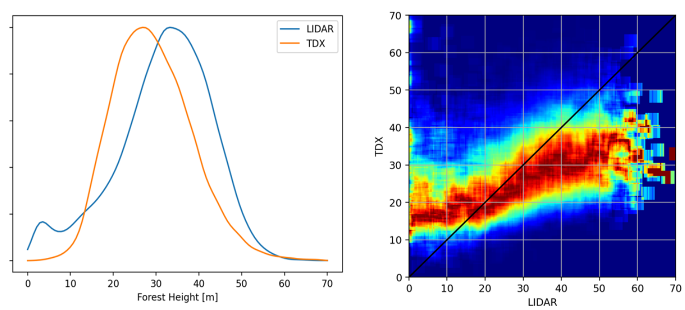

Fig. 4. Comparison of forest height fusion and RH95 forest height gedi metric in the form of 1D Histrogram of height (left) and 2D histogram (right).

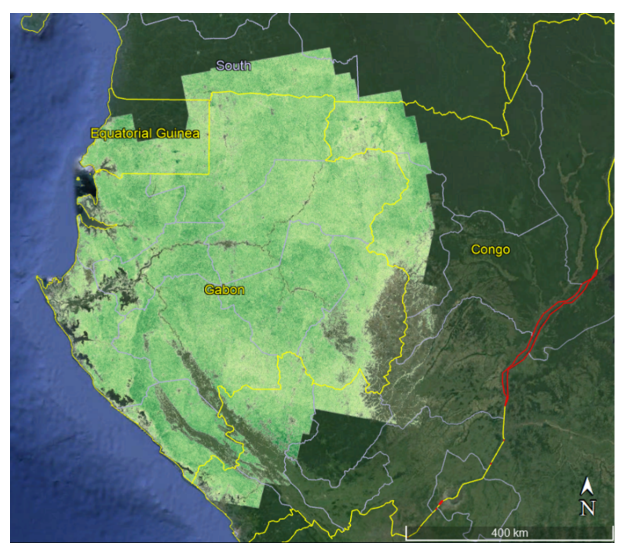

Fig. 5. Forest heigtht over Gabon.

4. CONCLUSIONS

The experiments in this work confirm that TanDEM-X coherence magnitudes can be used together with GEDI sparse waveforms to estimate forest height wall-to-wall maps with a reasonable accuracy range. The mismatch between the profile obtained from GEDI (i.e the one used to estimate the forest height) and the actual reflectivity at each pixel affects the performance of the estimated height. From one side, in shorter forest areas there is an overestimation due to the fact that the profile used in the model predicts a coherence higher than the observed one. This occurs due to the fact that a significant amount of scattering contribution close to the ground are missed. From another side, in dense and higher stands, the limited penetration leads to underestimated forest heights due to a saturation of the coherence magnitude. Note that for this paper one single profile is used to *represent* the whole scene, which could potentially lead to inaccurate estimations of height depending on the homogeneity of scene. In the near future, as soon as more GEDI data will be available, more accurate profiles for different regions of one TanDEM-X scene could improve the performance of the final forest heights. Moreover, different methods to mosaic individual acquisitions over the same pixel can be further investigated. For example, the use of the mean value of different acquisitions or the selection of the final image for the mosaic based on certain constrains such as the geometry or the acquisitions date. In any case, and taking into account the limitations of the method, the global coverage of TanDEM-X data at single-polarization together with (almost) global sampling of GEDI give a unique opportunity to generate forest height maps at large (or even global) scales.

5. REFERENCES

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