WIDE AREA FOREST HEIGHT MAPPING USING TANDEM-X STANDARD MODE DATA

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ABSTRACT

In this paper we report results of a study aimed at assessing the potential for using the standard mode of TanDEM-X (single polarization HH, single baseline and single-pass radar interferometry) to estimate forest canopy heights over two Canadian forest test sites, where supporting LIDAR data is available for validation. We first apply two coherence correction factors to TanDEM-X data, one for signal-to-noise ratio (SNR) based on noise statistics from TanDEM-X metadata and the other on a system correction based on bare surface reference scattering. We then use coherence amplitude of the interferogram and interferometric wavenumber k_z to estimate forest canopy heights. The radar heights are validated against a LIDAR CHM (Canopy Height Model) reference. A simple linear scaling of the TanDEM-X height products based on a relatively small LIDAR calibration patch is used to extend the canopy height products over a mosaic of multiple swaths for very wide area forest height mapping using radar coherence.

Index Terms — radar interferometry, forest canopy height, wide area mapping

1. INTRODUCTION

In our previous paper [1], we investigated the use of polarization diversity in single-pass dual co-polarization (copol) modes of TanDEM-X radar interferometry for forest canopy height estimation over two study sites of interest to the Canadian Forestry Service (CFS); namely Hinton, Alberta, and the Greater Victoria Water Supply Area (GVWSA) on Vancouver Island, British Columbia [1]. A key conclusion from that study was that it may be possible to obtain useful canopy height products even from TanDEM-X single-polarization co-registered single look slant range complex (CoSSC) data. In this paper we present a follow-on study of such ideas using the same two study sites and show results in two stages, firstly a validation against LIDAR reference data and then an example of the extension of the radar height product to regional scale coverage of Hinton.

In contrast to [1], we employ the 'standard mode' CoSSC interferometric data, provided courtesy of the German Aerospace Centre (DLR) from their satellite pair known as TanDEM-X. Unlike the dual copol mode used in [1], this standard mode has wide swath and global coverage and hence has great potential for large area forest canopy height mapping in Canada. A key element of our approach is therefore that we do not rely on any spatially limiting auxiliary data, (such as airborne LIDAR surface topography), which others employ in their phase center height based algorithms [2,3,4,5], but which is not available on the wide regional/continental scales to be considered in this study. Instead we developed a coherence-only based algorithm, free from the requirement of knowledge of true surface phase and requiring only access to any suitable DEM for local angle of incidence calculation.

We first describe the two study sites in Canada and the available data sets before summarizing the processing chain and then presenting results, which include LIDAR validation and an example of wider regional coverage in Hinton. We conclude with some comments about factors limiting the accuracy of the wide scale products and the potential for future forest applications.

2. STUDY SITES AND DATA

TanDEM-X is a dual radar satellite interferometer system, operating at X-band (3cm wavelength) and was launched on June 21, 2010 [6]. Although it has a dual- and quad-pol capability for scientific users, over the past few years it has been used to systematically collect data for global coverage in 'standard mode'; namely, the bistatic mode with single polarization [6]. The primary motive has been to use these data to generate a high resolution global DEM. Here we make use of these data to investigate a different application, the estimation of forest canopy heights from coherence. To this end, we use CoSSC data for two calibrated Canadian study sites as follows:

1) The first site is Hinton, Alberta, (center co-ordinates 53.2ºN, 117.37ºW). This site is heavily forested and has hyperspectral and LIDAR data available. The region's forest

cover is dominated by Lodgepole Pine (*Pinus contorta*) and White Spruce (*Picea glauca*) with low to medium crown cover and tree heights around 20-25m. It is typical of northern central forests in Canada. Figure 1 shows the TanDEM-X coherence product (August 29, 2011) over Google Earth of the Hinton area together with the LIDAR coverage shown as a red polygon.

2) The second site is the Greater Victoria Water Supply Area (GVWSA) just north-west of Victoria City on Vancouver Island in British Columbia (center 48.52ºN, 123.64ºW). The GVWSA site is covered by temperate coastal rainforests with the forest stands composed of predominantly Douglas-fir (*Pseudotsuga menziesii*), Lodgepole Pine (*Pinus contorta*), Western Hemlock (*Tsuga heterophylla*) and Western White Pine (*Pinus monticola*). This study site has some very tall trees (> 50m) and rough topography and is supported by existing hyperspectral and LIDAR data sets.

Table I summarizes the TanDEM-X standard mode CoSSC products provided courtesy of DLR for use in this study. The height of ambiguity (hoa) and angle of incidence (aoi) can be obtained from DLR supplied metadata text files as part of their standard TanDEM-X product. The image size (ground range/azimuth) is about 40×55 km^2. All data was collected in a bistatic mode, with a single transmitter and two receivers and having the polarization HH.

Table I: TanDEM-X CoSSC data sets

Site	Date	aoi (θ_o)	|hoa|	Orbit
Hinton	13/06/11	36˚	46.6m	Asc
Hinton	05/07/11	38˚	45.2m	Asc
Hinton	29/08/11	36˚	45.5m	Asc
GVWSA	07/10/13	38˚	63.2m	Desc

Figure 1: A coherence product (black=0, white=1) from 29/08/11 for Hinton with LIDAR coverage in red (15×15km^2)

Of particular importance to this study is the availability of LIDAR derived digital elevation models (DEM) and canopy height models (CHM), which are used for TanDEM-X canopy height validation for both study sites. The LIDAR data for Hinton was collected by airborne LIDAR/ hyperspectral campaigns in the summer of 2009 with coverage approximately 15×15km^2 and a spatial resolution of 2m. Similar LIDAR/hyperspectral campaigns for GVWSA were concluded between 2008 and 2009.

3. SUMMARY OF PROCESSING CHAIN

In contrast to other approaches, our algorithm makes no use of phase centre height, but instead requires two parameters. One of them is the coherence amplitude of the single channel interferogram $\hat{\gamma}$, formed as shown in Equation 1,

$$\hat{\gamma} = \frac{\underline{w}^{*T}\Omega_{12}\underline{w}}{\sqrt{\underline{w}^{*T}T_{11}\underline{w}\,\underline{w}^{*T}T_{22}\underline{w}}} \qquad 0 \le |\hat{\gamma}| \le 1 \tag{1}$$

where T_{11} and T_{22} are the polarimetric coherency matrices for master and slave respectively, while the information from interferometry is contained in a complex matrix Ω_{12}. In our case the vector $\underline{w}$ is fixed by the radar hardware as HH polarization.

The other parameter required is the interferometric wavenumber k_z as shown in Equation 2, a function of the local angle of incidence (for which we need a supporting DEM) and the height of ambiguity (hoa) of the interferometer provided in the TanDEM-X metadata.

$$k_z = \frac{4\pi B_n}{\lambda}\frac{1}{R\sin\theta_i} = \frac{K}{\sin\theta_i} \Rightarrow K = \frac{2\pi\sin\theta_o}{hoa} \tag{2}$$

We then use these two parameters to estimate radar canopy heights directly from Equation 3 [1].

$$h_v \approx \frac{2\pi}{k_z}\left(1 - \frac{2}{\pi}\sin^{-1}|\gamma|^{0.8}\right) \tag{3}$$

This height relation was first derived in [7] as a part of a structure free height algorithm from polarimetric interferometry (POLInSAR). We expect it to underestimate in dense forests, but found in [1] that it is a reasonable stand-alone approximation for the type of forests found in northern central areas of Canada. In this paper, we apply Equation 3 for the first time to the TanDEM-X CoSSC standard mode data.

Note that before using γ for the canopy height calculation, two coherence corrections were performed in an effort to improve height estimation accuracy. One is a signal-to-noise ratio (SNR) correction based on noise statistics from the Tandem-X metadata shown in Equation 4, where S is the radar backscatter signal and the noise level N varies across the range swath due to antenna pattern variations.

$$\gamma_{SNR} = \frac{S}{S+N} \tag{4}$$

The other coherence correction is related to residual system errors and based on the bare surface reference scattering. It is assumed scene independent. For example, a bare surface should theoretically have a coherence of 1, but in practice may have a lower value (typically around 0.97) due to a combination of residual processing errors. By using a fixed correction factor g_{system}, the correct coherence level is obtained by Equation 5.

$$g_{correct} = \frac{g}{g_{SNR} \times g_{system}} \quad (5)$$

Any coherence values above the unit value are then set to 1 and modeled as clearcut or surface. This correction was applied to the coherence images.

4. VALIDATION OF RADAR HEIGHT PRODUCT

We first validated the radar canopy height products against reference LIDAR CHM data to find the best-fit straight line. Two factors needed to be considered. First, LIDAR CHM has 2m pixel spacing. The radar data is obtained from an average coherence over an effective pixel size around 20m. Hence, we can never retrieve forest heights with the same resolution as LIDAR. For this reason the LIDAR CHM was first filtered to generate an h_{100} estimate; i.e. an average of tallest trees in a given area [8]. The second factor is that the CoSSC data were acquired in 2011 for Hinton and 2013 for GVWSA, but LIDAR data were collected between 2008 and 2009. There were changes, such as forest clearcuts, occurring between the TanDEM-X and LIDAR acquisitions. These were excluded from the validation.

We started with the Hinton scene to find a least squares line fit between the two data sets. We selected a small test zone of the LIDAR data with wide variation of heights, as shown by the white box in Figure 2.

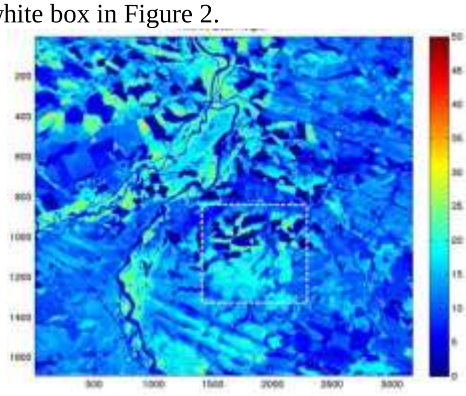

Figure 2: h_{100} LIDAR CHM showing box area used for linear fit

The best fit was found to be a slope of 1.01 and an offset intercept of 2.8m with the r^2 fit 0.85. In general we found fits with r^2 >0.8 for 100m scale averaging of the data and residual errors for this site are of the order of 3m rms. These figures are in line with those found for full POLInSAR of other sites [9] and reflect the real possibility of employing the TanDEM-X data for wide area forest height mapping. So to a first approximation we corrected the radar canopy heights at a spatial resolution 100m using Equation 6, where the two coefficients *m* and *c* as 1.01 and -2.8 respectively.

$$h_{correct} = mh_{radar} + c \quad (6)$$

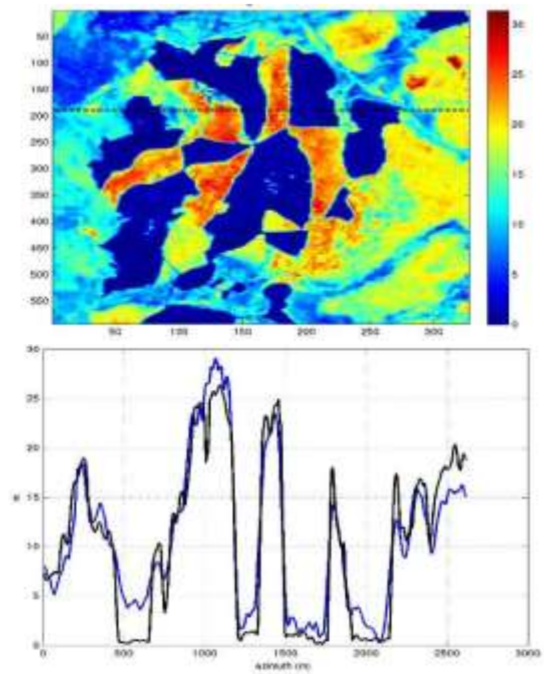

Figure 3: h_{100} (top) and transect (bottom), showing LIDAR height (black) and corrected radar height (blue)

The result of the corrected radar canopy heights was then compared with LIDAR CHM again. We see a good agreement. Figure 3 (top) is the LIDAR h_{100} reference data with a dashed transect line and Figure 3 (bottom) shows the LIDAR and best-fit radar estimates plotted along the dashed transect line. For GVWSA, this study site contrasts with Hinton in two important ways. First it has more severe topographic variations than observed at Hinton, causing problems for radar in some strongly sloped areas. Secondly, the tree heights and stem densities are much higher than Hinton and so the simple uniform vertical profile model (Equation 3) used in Hinton can be expected to be less valid at the X-band wavelength of TanDEM-X.

Our validation results in general showed that the radar canopy height over GVWSA has a larger offset than Hinton (around -8m) while the slope is also greater than unity, implying that the radar estimation (after offset correction) is still slightly too small. Some areas of GVWSA have better correlations with LIDAR, with r^2 of 0.8 or more at the 100m scale, but others have poorer correlations with LIDAR, typically r^2 of 0.5 at the 100m scale. This may be due to the high density of trees in some areas leading to higher X-band wave extinction in the canopy and hence less wave penetration. The problem is likely about the challenging combination of tall trees, dense forest and severe slopes that characterize this type of temperate rain forest for X-band interferometry. We conclude therefore that the radar model is much better for the Hinton site, where we now consider its extension to wider area mapping.

5. EXTENSION TO WIDE AREA MAPPING

One key potential advantage of using radar coherence for height estimation is the ability to apply it outside of the reference LIDAR coverage area. In our approach, we need just the radar coherence data and a reference DEM for topography compensation. In particular we do not need to know the true underlying surface topography to generate height and so can extend it over regional or larger scales, where such information may not be available. We used three CoSSC data sets over Hinton (Table I) for this demonstration.

We applied the best fit correction using the same regression from our LIDAR data to all three TanDEM-X CoSSC scenes. Figure 4 shows the final mosaic of radar canopy height product as greyscale in range 0-30m and embedded in Google Earth. Now the total spatial coverage is around $50\times100km^2$. We note good contrast between forest stands of different heights across the entire scene and see no obvious beam shaping effects at the edges. This product was generated using SRTM 3-arcsecond DEM to estimate k_z. For size comparison, the LIDAR region is shown in red in Figure 4. Here we can view regional scale variations in forest height. Only radar interferometry currently has the potential to provide this level of continuous information on such large spatial scales.

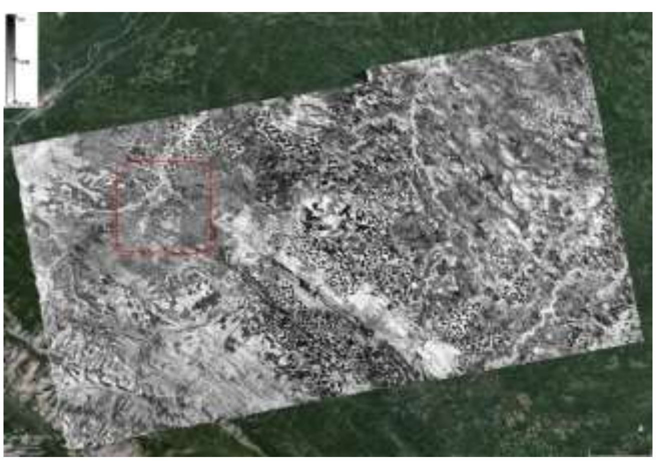

Figure 4: Wide area radar canopy height product over Hinton by using three TanDEM-X overlapping swaths (LIDAR in red)

6. CONCLUSIONS

In this paper we have presented an initial analysis of using TanDEM-X COSSC data for wide area forest height mapping using a coherence-only algorithm approach. Our LIDAR validations showed that there is variable accuracy of the radar height product across different forest types. In Hinton the fit was very good, in Victoria moderate to poor. One way to deal with such variations is to employ discrete height classes rather than the continuous height product itself. In this way, areas with poor r^2 would have fewer classes than those with high r^2. Such a variable classification product could still be useful for forest management and biomass estimation based on radar forest canopy height estimation. In this study we also demonstrated successful extension to a wide area of the forest canopy mapping over Hinton using three frames of the TanDEM-X CoSSC data.

7. ACKNOWLEDGEMENTS

We thank The German Aerospace Center for provision of the Tandem-X data used in this project. We acknowledge the support of Natural Resources Canada, the Canadian Space Agency and the University of Victoria (UVic). Thanks also to radar image processing support from intern students, Kaileen McCulloch and Philip Snead of UVic.

8. REFERENCES

[1] Cloude S.R., Chen H. and Goodenough D.G., "*Forest Height Estimation and Validation using Tandem-X POLInSAR data*", Proc. IEEE Geoscience and Remote Sensing Symposium, IGARSS 2013, Melbourne, Australia, July 2013

[2] Sadeghi Y., St-Onge B., Leblon B., Simard M. and Papathanssiou K., "*Mapping Forest Canopy height Using tandem-X DSM and Airborne Lidar DTM*", Proc. IEEE Geoscience and Remote Sensing Symposium, IGARSS 2014, Quebec, Canada, July 2014

[3] Kellndorfer J., Bishop J., Cartus O., Walker W., Rosenqvist A. and Shimada M., "*High Resolution Pan-Tropical Vegetation Height Estimation from Satellite Radar and Lidar Observations*", Proc. IEEE Geoscience and Remote Sensing Symposium, IGARSS 2014, Quebec, Canada, July 2014

[4] Toraño Caicoya A., Kugler F., Pardini M., Hajnsek I. and Papathanassiou K., "*Vertical Forest Structure Characterisation for the Estimation of Above Ground Biomass: First experimental results using SAR vertical reflectivity profiles*", Proc. IEEE Geoscience and Remote Sensing Symposium, IGARSS 2014, Quebec, Canada, July 2014

[5] Soja M., Persson H. and Ulander L., "*Estimation of Boreal Forest Biomass from Two-level model inversion of interferometric Tandem-X data*", Proc. IEEE Geoscience and Remote Sensing Symposium, IGARSS 2014, Quebec, Canada, July 2014

[6] Krieger G., Moreira A., Fiedler H., Hajnsek I., Werner M., Younis M. and Zink M., "*TanDEM-X: A Satellite Formation for High-Resolution SAR Interferometry*", IEEE Trans. Geoscience and Remote Sensing, Vol. 45, November 2007

[7] Cloude S.R., "*Polarisation: Applications in Remote Sensing*", Oxford University Press, 978-0-19-956973-1, 2009

[8] van Laar A. and Akca A., "*Forest Mensuration (Managing Forest Ecosystems)*", Dordrecht, The Netherlands: Springer-Verlag, pp. 118–121, 2007

[9] Hajnsek I., Kugler F., Lee S.K. and Papathanassiou K.P., "*Tropical Forest Parameter Estimation by means of Pol-InSAR: The INDREX II Campaign*", IEEE Transactions on Geoscience and Remote Sensing, Vol 47, No. 2, pp. 481-493, 2009