MULTICRITERIA EVALUATION OF THE POTENTIAL OF P-BAND AIRBORNE RADAR DEMs FOR 3D CHARACTERISATION OF HYDROGRAPHY IN TROPICAL FORESTS

L. Polidori[1,2], C.R.T. Caldeira[1], L. dos Reis[1], N. Eco[3], M. El Hage[4]
[1] PPGG, Instituto de Geociências, UFPA, Belém, Brazil – laurent.polidori@ufpa.br, caldeiracrt@gmail.com leo2reisgeo@gmail.com
[2] CESBIO, 18 av. Edouard Belin, bpi 2801, 31401 Toulouse cedex 9, France – laurent.polidori@ird.fr
[3] LASTIG, Institut Géographique National, Saint-Mandé, France – econejla@gmail.com
[4] Geospatial Studies Laboratory, Lebanese University, Tripoli, Lebanon – mhamad.elhage@ul.edu.lb

KEYWORDS: Amazon, hydrography, scale, P-band radar, digital elevation model, quality

ABSTRACT:

Relief mapping through dense tropical forest is a challenge, which can be met by processing P-band radar images. Digital terrain models (DTMs) obtained over three sites in the Amazon region (French Guiana and North Brazil) are evaluated according to two types of quality criteria: on the one hand, the accuracy of elevations and slopes, calculated by comparison with lidar surveys used as reference data; on the other hand, the hydrographic coherence of the DTM, revealed by its compliance to some universal rules like "all rivers flow downhill", or the fact that landforms shaped by water have a fractal behaviour. The results depend on the scale, the effect of which is addressed. Overall, the results confirm the potential of P-band airborne radar for 3D characterisation of hydrography in tropical forested areas.

1. INTRODUCTION

The suitability of a digital elevation model (DEM) for hydrological modelling, and in particular for watershed delineation and drainage network extraction, must be evaluated according to multiple quality criteria, because the DEM must be close to the topographic surface (i.e., minimize elevation error) and at the same time respect the shapes (i.e., minimize slope error due to random variations of elevation error), among other requirements (Polidori and El Hage, 2020). This evaluation can be based on the comparison of the DEM with a more accurate local DEM or a set of ground control points (GCPs). However, even when no GCPs are available, a detection of geomorphological inconsistencies can contribute to DEM quality assessment (Polidori et al., 2014).

In the case of tropical forest regions, such as the Amazon, these requirements are more difficult to meet. Indeed, in addition to difficult field access and to the cloud cover, the presence of forests, with an average height of about 30 m and a very irregular texture, makes it impossible to observe the ground with optical techniques (such as photogrammetry) and even with short wavelength radar interferometry (Polidori *et al.* 2022). Therefore, those methods provide a model of the canopy elevation, which turns very uncertain the description of hydrography due to important elevation and slope errors, especially in areas with moderate relief. This is the case, for example, of the widely used SRTM model (Bamler, 1999).

To overcome this limitation, airborne lidar is commonly considered as the most accurate method to measure topographic points through dense forest foliage (Kraus and Pfeifer, 1998), which can be interpolated to generate a digital terrain model (DTM). However, this method is only accurate at the cost of a low and slow flight, which makes it very expensive and time consuming for large areas.

Another solution is P-band airborne radar, which has a wavelength close to 70 cm that can penetrate the forest cover and reach the ground. The backscattered signal can be processed by interferometry (InSAR) or tomography (TomoSAR) depending on the acquisition configuration, offering the possibility to model the relief through the forest. Acquisitions have taken place in several states of the Brazilian Amazon as part of the *Radiografia da Amazônia* project to update deficient mapping (Correia 2011), and more recently in the state of Amapá, bordering French Guiana (Guimarães Filho and Borba, 2020). In addition, P-band airborne radar data were acquired in a similar ecosystem in Paracou (French Guiana) as part of the TropiSAR project (Dubois-Fernandez et al., 2010), for the calibration-validation activities of the European Space Agency's Biomass space mission, which will carry onboard a P-band imaging radar for the first time (Le Toan et al., 2011). As one of the foreseen products of the Biomass mission is a quasi-global digital terrain model, data from the TropiSAR project have been used to evaluate the potential of P-band radar tomography for this application (Mariotti D'Alessandro and Tebaldini, 2019, El Hage et al. 2022).

However, the potential of these data for scientific exploitation remains poorly understood. DTMs obtained from P-band radar in three areas located in French Guiana and Amapá have been analysed in recent experimental studies, most of which are reported in El Hage et al. (2022), Ećo (2022), Reis (2023). They are compared to aerial lidar data, which are considered as more accurate in forested areas and therefore taken as reference data, and to other more widely used models, leading to preliminary results about DTM quality. This paper brings together some of these results to evaluate the suitability of P-band radar DTMs for 3D characterisation of hydrography in tropical forest environments like the Amazon region.

2. MATERIALS AND METHODS

2.1. Study areas and data

P-band airborne radar data were acquired in 3 areas of the North coast of South America (figure 1): Paracou in French Guiana (A), a steep relief area along the Oiapoque border river (B) and a floodplain in the lower Amazon in the Amapá state, Brazil (C). Areas A and B are covered by dense forest, while area C is a partially flooded plain with low vegetation and some woodland. In area (A), the DTM was obtained by tomographic processing of SETHI radar data from ONERA (Dubois-Fernandez et al., 2010) as part of a calibration-validation experiment for the ESA Biomass space mission. The data from areas B and C are part of the *Base Cartográfica Digital e Contínua do Amapá* (BCDCA) of the Amapá state. The images acquired in P and X bands were processed by interferometry to produce a DTM (digital terrain model) and a DSM (digital surface model, which describes the upper envelope of the canopy) respectively, at 5 meter ground sampling (Guimarães Filho and Borba, 2020). In areas A and B, high resolution DTMs obtained from airborne lidar are used as reference data. The SRTM product, derived from interferometric processing of C-band radar data at 30 m resolution (Bamler, 1999), and the Topodata model obtained by densifying the initial version of SRTM from 90 to 30 m over the entire Brazilian territory (Valeriano and Rossetti, 2012), are also used in areas B and C. In area C, several other open access DEMs are used, including ASTER GDEM v3, obtained by spatial photogrammetry at 30 m (Abrams et al. 2020).

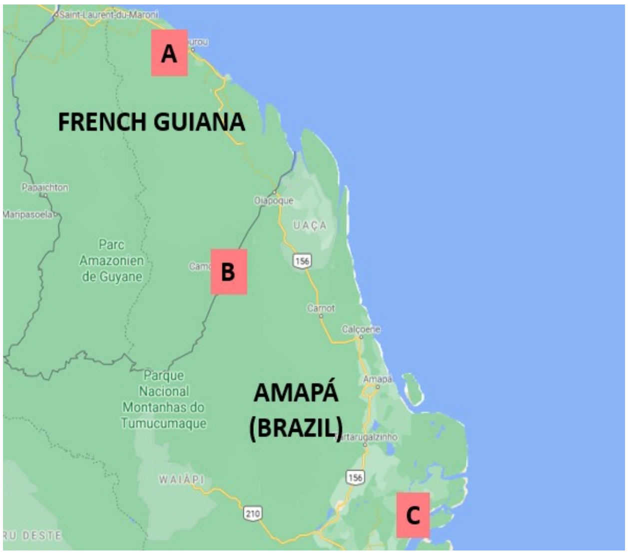

Figure 1. Location of study areas in French Guiana and Amapá

2.2. Absolute accuracy assessment

A visual comparison of the DTM obtained from P-band radar with the lidar reference DTM and other DEMs along a river in area B provides a preliminary evaluation of the ability of this DTM to describe hydrographic shapes.

In more quantitative terms, the ability of a DTM to describe a hydrographic system is conditioned by the accuracy of elevations and slopes, which may be degraded in forested areas. The aerial lidar survey is used as a reference in areas A and B to assess the DTM accuracy based on a statistical analysis of the discrepancies between the two DTMs. The bias and the random error of the DTM produced by P-band radar interferometry are calculated in terms of both elevation and slope. The effects of the local terrain shape (i.e., slope and orientation) and of the incidence angle (i.e., the angle between the radar line of sight and the perpendicular to the ground surface) are studied for both elevation and slope errors. Finally, the statistical distribution of slope, which is generally Gaussian over most continental surfaces, is analysed for the P- and X-band radar DEMs at the same scale (5 m pixel).

Area C is used to assess the ability of the P-band radar DTM to model the relief of a floodplain, assumed horizontal, where vegetation potentially forms shapes that can be misinterpreted as relief. In this case, the reference is implicit, since the surface is assumed to be horizontal. The DTM is also compared to other available models.

2.3. Requirements related to hydrography

The quality of a DTM has an impact on the extracted hydrographic information, such as the 2D drainage network, so that the network extracted automatically from the DTM may be used as an indicator of DTM quality, as illustrated in figure 2. Indeed, the terrestrial reliefs shaped by water do not have a random behaviour. They respect some universal rules. The non-compliance of these rules may reveal errors in the DTM (Polidori *et al*. 2014). It may be noted in figure 2 that the detection or unrealistic shapes or impossible topology does not require reference data, while an absolute location error or a wrong topology can only be revealed by comparison with a reference drainage network.

One of the rules is the fact that all rivers flow downhill. The respect of this rule is verified by assessing the number and depth of the sinks detected along the drainages. A reasonable requirement is that the mean depth is statistically lower that the overall accuracy of the DTM, ensuring that the longitudinal profile of the rivers is well preserved despite the limitation of the DTM accuracy.

Another rule most often verified in terrestrial relief is that landforms shaped by water have a fractal behaviour (Rodriguez-Iturbe and Rinaldo, 2001). In this study, the DTMs are analysed to verify that they respect Horton's law, according to which the logarithm of the number of drainage sections with Strahler order N decreases linearly when N increases.

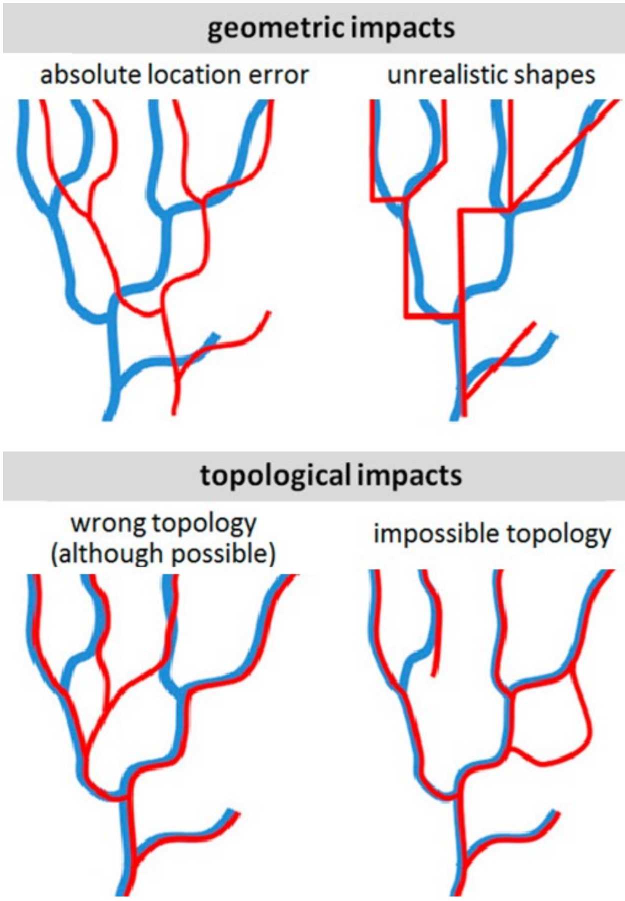

Figure 2. Effects of main DTM error behaviours on extracted drainage errors, with ground truth in blue and extracted network in red (adapted from Polidori and El Hage, 2020)

2.4. Influence of scale

The resampling period, i.e., the scale at which the relief is modelled, has an impact on slope accuracy (Polidori and Simonetto, 2014) and therefore on the respect of hydrographic shapes. Therefore, the hydrographic indicators based on slope are unstable when the scale is changed (Santos et al., 2017).

For example, the Gravelius index, which characterises the shape of a watershed in terms of compactness, depends on both the area (which remains almost stable when changing scale) and the perimeter (which increases and may diverge when the scale becomes more detailed) :

$$K_G = \frac{P}{2\sqrt{\pi A}} = 0.28\frac{P}{\sqrt{A}} \quad (1)$$

where P is the perimeter and A is the area. Consequently, the Gravelius index is expected to be unstable with regards to scale. The distribution of Gravelius indices obtained at two different scales (5 and 30 m) are compared in order to analyse the effect of scale, for both X- and P-bands.

3. RESULTS

A preliminary visual analysis shows the similarity of the DTM obtained from P-band radar with regards to the reference lidar DTM, though with less hydrographic details due a coarser resolution. It is clearly a DTM, as compared with the X-band radar DSM extracted from the same data base, and with SRTM, which both describe the upper surface of the canopy as can be observed in figure 3.

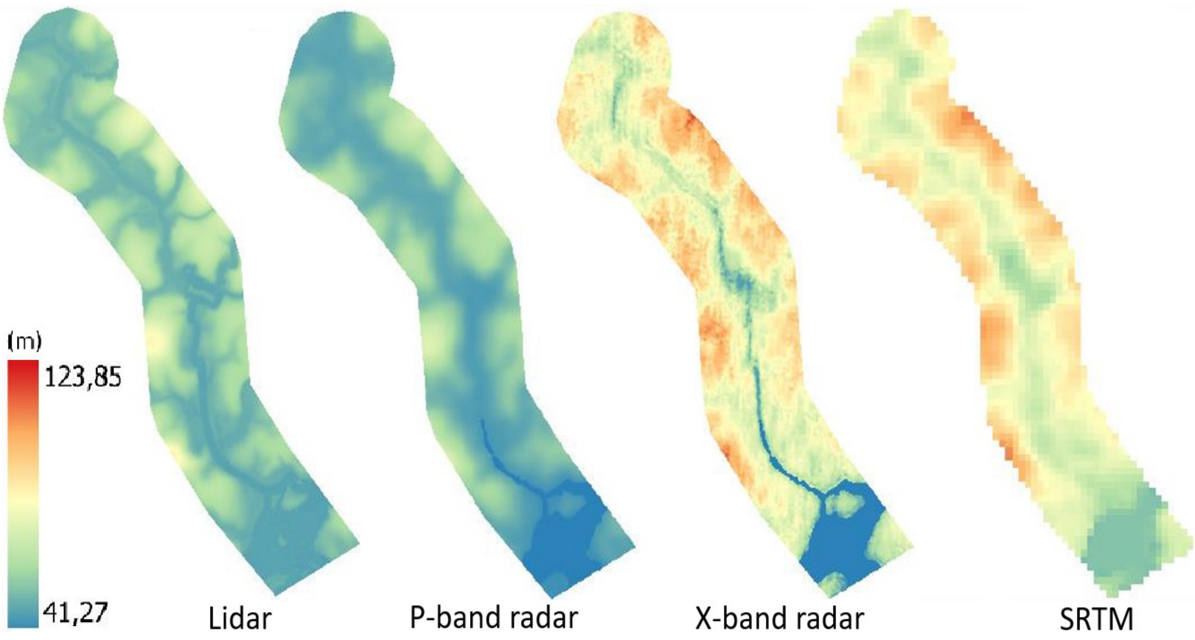

Figure 3. Comparison of the P-band radar DTM with the reference lidar DTM and other DEMs in color hypsometry

In terms of absolute accuracy, ongoing studies carried out in areas A and B show that the RMS error ranges from 2 to 3 m for elevations, with no significant bias, and from 7 to 15 degrees for slopes. However, this error is not homogeneous, and results obtained in area A show that it is a function of the local slope, the surface orientation with regards to the radar viewing direction, and the incidence angle. Indeed, both elevation and slope RMS errors increase as the local slope increases, they are more important on slopes facing away from the radar, and they increase when the incidence angle decreases (El Hage et al., 2022).

In area B, it can be observed that in the DSM obtained from X-band radar, besides the elevation bias due to the fact that short wavelengths do not penetrate the vegetation, the slopes have a very different statistical distribution as compared with the DTM obtained from P-band radar (figure 4). They have a much higher mean and standard deviation, because of the irregular geometry of the trees at this resolution (5 m), as confirmed by the profile shown in figure 6. This difference disappears when the resolution is significantly degraded, as shown in a previous study (Polidori and Simonetto 2014), suggesting that it is at high resolution that the superiority of the P-band radar DTM is more obvious.

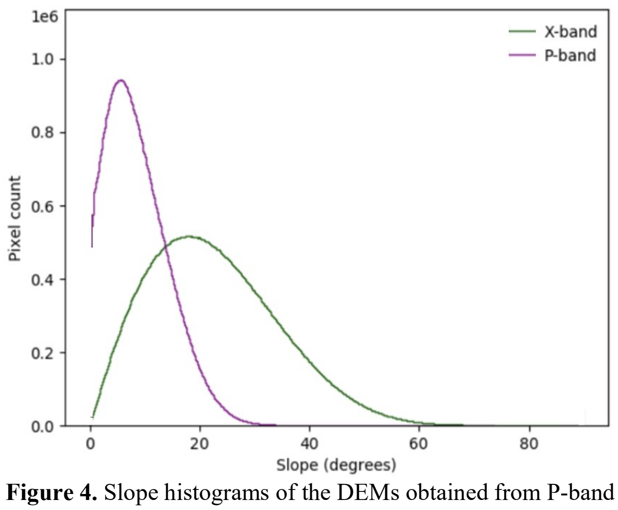

Figure 4. Slope histograms of the DEMs obtained from P-band and X-band radar in area B (adapted from Ećo 2022)

Floodplain areas present an additional difficulty, since non-topographic objects (like vegetation) and various error sources have a much larger impact on elevation measurements than the natural variations in ground and water elevation. In area C, figure 5 shows that the P-band radar DTM – profile A – clearly describes the flat horizontal shape of the floodplain, as well as a small hill on the right side. It is very close to the ground and water surface since it is almost not affected by the presence of vegetation. Indeed, the vegetation identified in optical imagery has no impact on the elevation in the P-band radar DTM. On the contrary, all other models create ghost shapes due to vegetation, with errors around 5-10 m in the case of shrub vegetation and 20-25 m in the case of dense forest (with the exceptions of the X-band radar DEM – profile B – which is explicitly designed to provide a DSM), while ASTER GDEM – profile D – exhibits gross altimetric errors whatever the land cover.

Figure 6 compares several DEMs with the reference lidar DTM along a tributary of the Oiapoque River (area B), showing that the P-band radar DTM meets two essential quality requirements for hydrological modelling. On the one hand, the similarity of this model with the reference. On the other hand, the fact that the river flows downhill, the presence of depressions being indicative of local elevation errors. Similarly, a quantitative analysis performed in area A showed that depressions affect only 2% of the DTM with a mean of 0.38 m and a standard deviation of 0.60 m, much below the DTM elevation error.

Figure 6 also shows that SRTM and Topodata, with a 30 m resolution and based on a short radar wavelength which is unable to penetrate through the vegetation layer, only describe the upper surface of the trees. The X-band radar DSM has the same behaviour in the case of dense forest due to its short wavelength, but the higher resolution allows the radar signal to reach the water surface when it is not obscured by trees, resulting in the same elevation as in the P-band radar DTM.

Horton's law is verified in the data of area A with an almost perfect linearity (R^2 = 0,99832), which means that the hydrographic network extracted from this DTM has a fractal behaviour. Similar results are found in other areas. This confirms the hydrographic coherence of the DTM obtained by P-band radar.

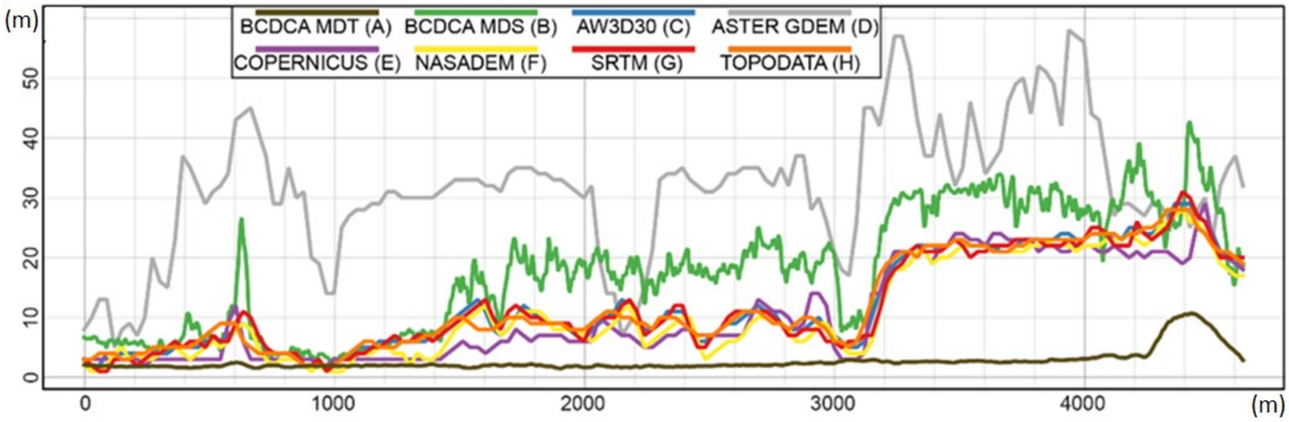

Figure 5. Elevation profiles of different DEMs in a floodplain in area C. The black profile (A) representing the P-band radar DTM analysed in this study is compared with the X-band radar DSM (B), the ALOS WORLD 3D DEM (C), ASTER GDEM v3 (D), the Copernicus DEM (E), The NASADEM (F), SRTM (G) and Topodata (H)

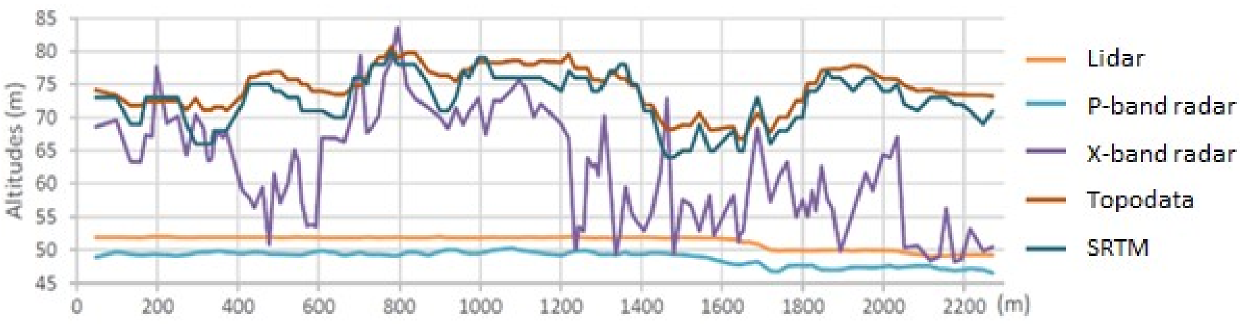

Figure 6. Elevation profiles of DEMs along a river in area B.

The comparison of Gravelius compactness indices computed in the P-band radar DTM and in the X-band radar DSM shows that watersheds are statistically more compact in the DTM, as shown in figure 7. This difference is due to the fact that for a given area, the perimeter is longer in the DSM, as a consequence of the small ghost shapes created by the trees at 5 meters. This leads to a smaller value of K_G in the P-band radar DTM according to equation (1).

This difference between X and P-band is reduced when the two models are subsampled fron 5 to 30 meters, as the smallest shapes tend to disappear. Consequently, the calculated perimeter becomes shorter in both DEMs, leading to more compact basins. This confirms that the scale of the model influences the description of hydrography and therefore should be specified carefully.

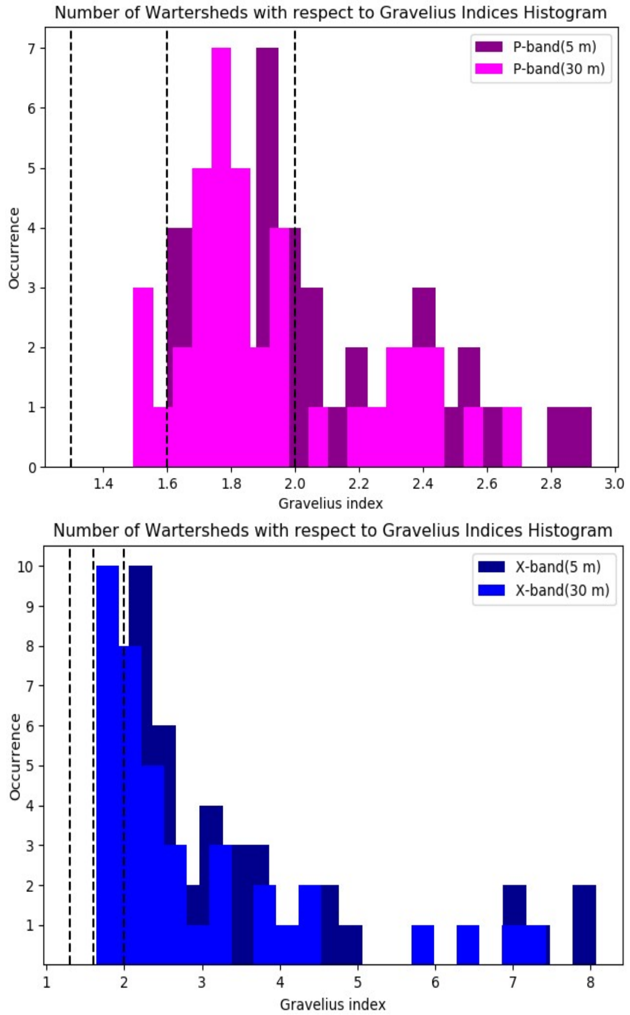

Figure 7. Histograms of the Gravelius compactness indices of drainage basins extracted from P-band radar DTM (top) and X-band radar DSM (bottom) in area B at 5 and 30 m.

CONCLUSION

The results of this multi-criteria analysis confirm the potential of DTMs obtained by interferometric or tomographic processing of P-band airborne radar data for the 3D characterisation of hydrography in tropical forests. On the one hand, their accuracy is around 2-3 meters with no significant biais, which is much better than that of most available DEMs, produced by photogrammetry or by short wavelength radar interferometry, which in fact describe the canopy. On the other hand, they account for the geometric characteristics of continental hydrography, such as the longitudinal profile of rivers and the fractal behaviour of the drainage network. This assessment is made possible by the fact that the landforms shaped by water obey certain rules that can be easily checked, thus allowing the hydrographic consistency of DTMs to be controlled.

Beyond this overall assessment of the quality of P-band radar DTMs, ongoing studies ae revealing that the error is not homogeneous, with local variations depending on the slope, azituth and local incidence angle. Further work should also consider the possibility to improve a raw DTM by taking into account the known properties of the terrestrial hydrography.

These satisfactory results are due to both the physical properties of P-band radar waves, which penetrate through dense forest cover and reach the ground, and the availability of rigorous algorithms for interferometric and tomographic processing of radar images. This makes DTMs obtained from P-band airborne radar suitable for hydrology.

The studies that contributed to this paper are ongoing, and are expected to contribute both to improving the data used in hydrology, and to using the known behaviour of water on continental surfaces to improve the production and validation of digital terrain models.

ACKNOWLEDGEMENTS

The work carried out on area A was funded by CNES (France) as part of the TOSCA programme within the framework of the CALVAL experiments of the ESA Biomass mission. The work carried out on zones B and C benefited from study grants awarded by IGN (France) and CAPES (Brazil), respectively, and benefited from radar data made available by SEMA-AP (Macapá, Brazil) and lidar data made available by CTG (Cayenne, French Guiana), respectively.

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