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REVIEW

Digital elevation modeling through forests: the challenge of the Amazon

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ABSTRACT

Elevation mapping at ground level is challenging in forested areas like the Amazon region, which is mostly covered by dense rainforest. The most common techniques, i.e. photogrammetry and short wavelength radar, provide elevations at canopy level at best, while most applications require ground elevations. Even lidar and P-band radar, which can penetrate foliage and measure elevations at ground level, have some limitations which are analyzed in here. We address three research questions: To what extent can a terrain model be replaced by a more easily available canopy-level surface model for topography-based applications? How can the elevation be obtained at ground level through forest? Can *a priori* knowledge of general continental relief properties be used to compensate for the limits of measurement methods in the presence of forest?

KEYWORDS: tropical forest, digital terrain model, photogrammetry, lidar, radar

Modelagem digital de elevação através das florestas: o desafio da Amazônia

RESUMO

O mapeamento da elevação ao nível do solo é um desafio em áreas florestadas como a região amazônica, coberta principalmente por floresta tropical densa. As técnicas mais comuns, i.e., a fotogrametria e o radar de comprimento de onda curto, fornecem elevações ao nível do dossel na melhor das hipóteses, enquanto a maioria das aplicações requer a elevação do solo. Mesmo o lidar e o radar de banda P, que podem penetrar a folhagem e medir elevações ao nível do solo, têm algumas limitações que são analisadas aqui. Abordamos três questões: Até que ponto um modelo de terreno pode ser substituído por um modelo de superfície ao nível do dossel, mais facilmente disponível, para aplicações baseadas na topografia? Como a elevação ao nível do solo pode ser obtida através da floresta? O conhecimento *a priori* das propriedades gerais do relevo continental pode ser usado para compensar os limites dos métodos de medição na presença de floresta?

PALAVRAS-CHAVE: floresta tropical, modelo digital de terreno, fotogrametria, lidar, radar

INTRODUCTION

The Amazon is a vast forested plain that stretches between the Andes Mountains and the Atlantic Ocean over more than 5 million km², in the North of the South American continent. Beyond the strict perimeter of the Amazonas River watershed, the Amazon region extends to the coast of the Guianas to the north. The climate of the Amazon is hot and humid and there is a significant cloud cover for most of the year. The relief is very moderate and covered with dense forest. Landscape changes (urban growth, hydrography, deforestation, etc.) are rapid. Apart from the two Brazilian megacities Belém and Manaus, capitals of the states of Pará and Amazonas respectively, the population is mostly located in medium-sized urban centres and scattered village communities. For physiographic and economic reasons, relief mapping in the region is difficult. Until the end of the 20th century, the Amazonian relief was less known overall than that on the planet Venus, until some global reference DEMs (digital elevation models) such as SRTM (Van Zyl 2001) became available for Earth and environmental sciences (Mantelli *et al.* 2009; Hayakawa *et al.* 2010).

While two thirds of the Amazon region lie in Brazil, the remaining third is spread over Bolivia, Peru, Ecuador,

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Colombia, Venezuela, Guyana, Suriname and French Guiana, which hinders the development of a standardized cartographic product of homogeneous quality, especially since the different governmental mapping agencies have heterogeneous statutes and policies. Moreover, the Amazon is sometimes used as an experimentation site to demonstrate the feasibility of processing algorithms or satellite sensors to be launched, that do not necessarily seek to be integrated into national mapping programs, or even without the knowledge of public mapping agencies.

In this context, mapping efforts have never resulted in a fully satisfactory product, which is detrimental to development operations that require prior knowledge of the relief, such as the construction of structures (dams, roads, etc.) and the peaceful drawing of boundaries. It is also important to note that most DEMs are in fact DSMs (digital surface models, i.e., models of the elevation of the upper envelope, usually the canopy), while most applications are theoretically supposed to be based on a DTM (digital terrain model, i.e., a model of the elevation of the ground).

Our aim was to compare the characteristics of the Amazon with the needs of cartography and the limitations of existing elevation mapping techniques, and to provide an overview of the possibilities to overcome these limitations. We present the main characteristics of the Amazon region regarding elevation mapping requirements, review the main attempts at elevation mapping in the Amazon based on photogrammetry, lidar (light detecting and ranging), and radar, the most promising technique despite some limitations. Finally, we discuss the challenges and propose ways for improvement of elevation mapping in the Amazon.

ELEVATION MAPPING REQUIREMENTS IN THE AMAZON REGION

Due to the fact that the mapping of the Amazon region is the responsibility of nine countries, the cartography of the region is uneven. In each Amazonian country, the mapping of the territory is under the responsibility of a civil or military state agency: Instituto Geográfico Nacional (Peru), Instituto Geográfico Militar (Ecuador), Instituto Geográfico Agustín Codazzi (Colombia), Instituto Geográfico Militar (Bolivia), Instituto Geográfico Venezuela Simon Bolívar (Venezuela), Instituto Brasileiro de Geografia e Estatística (Brazil). In Guyana and Suriname, mapping is carried out by various national or foreign institutions, or by private organizations. As French Guiana is a French department, its cartography is part of the missions of IGN (Institut Géographique National). In Brazil, the army has its own prerogatives for the cartography of the Amazon region, as the only institution capable of geodetic expeditions into the heart of the Amazon forest, and for its strategic mission of territory occupation and defense. For these reasons, the Brazilian army defines its own needs and funds projects aimed to ensure security and sovereignty, such as *Sistema de Vigilância da Amazônia* (SIVAM - Silva 1998) and *Radiografia da Amazônia* (Correia 2011), which covers cartographic voids with new map products. In addition, the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais - INPE) is responsible for developing tools for territory mapping and monitoring, leading to new products such as the Topodata altimetric database (Valeriano and Rossetti 2012). Apart from the products offered by official mapping agencies, users increasingly rely on the private market for specific products or on worldwide free-access altimetric databases.

A variety of applications justify the need for digital elevation modeling , such as geological mapping, hydrological modeling, natural resource monitoring or military operations, based either on absolute elevation, slope and other derivatives, hydrographic networks, etc. In all countries, the choice of a DEM production technique and product specifications must be made according to the characteristics of the Amazon region, including existing geodetic infrastructure, and to the general user requirements. However, the demand for suitable DEMs in the region is still hampered by technical, physiographic, socio-economic and geopolitical constraints.

The area to be covered is immense. It is impossible to measure the terrain point by point, so that space technology is essential. In this context, global DEM projects are particularly relevant, even if their specifications do not necessarily take the specific needs of the Amazon into account. As the region is sparsely populated and little urbanised, it is often considered less prioritary and of low economic stake, which contributes to the cartographic voids.

The constant cloud cover during most of the year is a major obstacle to the implementation of most cartographic techniques (Elmiro *et al.* 2006), particularly those based on optical remote sensing imagery, which require preprocessing for atmospheric correction and cloud removal (Sanchez *et al.* 2020), both in 2D for land-use monitoring and in 3D for the implementation of photogrammetric methods. Therefore, radar methods are more indicated, even if their independence from meteorological conditions is relative, as the shortest radar waves may be sensitive to the presence of rain (Jameson *et al.* 1997).

The dense forest masks the ground for most remote sensing techniques, so that the small hydrographic features are not visible. Tree height often reaches 30-40 m, which is significant in view of the limited altimetric topographic variations, making micro-relief mapping difficult. Floodplain hydrography is particularly unstable and the coast of the Guiana Shield from the Brazilian state of Amapá to Venezuela is changing so rapidly that any conventional cartographic product is quickly outdated after its publication (Anthony *et al.* 2008).

Finally, structural constraints such as limited road infrastructure limit the possibility of placing control points for aerotriangulation or for map product quality control. Furthermore, geodetic networks are generally less dense and less accurate in continental forested areas than in coastal and urbanised regions (Figure 1), which limits the accuracy of the derived cartographic products (Blitzkow *et al.* 2016; Castro Júnior *et al.* 2018). The region also features orphaned branches in unconnected areas (Figure 1), as is the case of the Papaichton-Maripasoula path in French Guiana. In Brazil, the existing altimetric network in the state of Amapá cannot be connected to the Imbituba tide gauge in the south coast of Brazil, due to the impossibility of transporting altitude over the lower Amazonas River, so that another tide gauge located in the port of Santana is used as a level reference for this region.

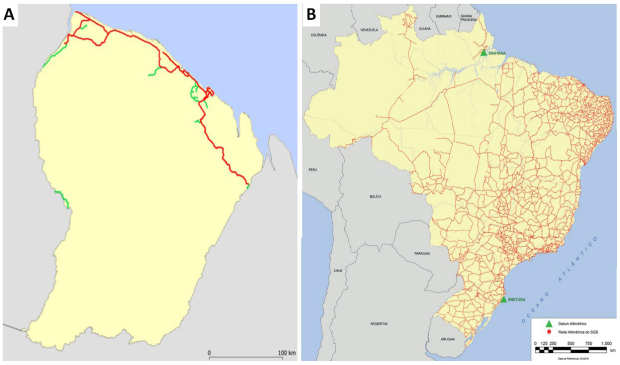

Figure 1. Leveling networks in French Guiana (A), and Brazil (B). Source: IGN (A); IBGE (B). This figure is in color in the electronic version.

ATTEMPTS AT ELEVATION MAPPING IN THE AMAZON

Despite the difficulties listed above, the Amazon has been the subject of numerous attempts at elevation mapping in different contexts:

(a) map production commissioned by the official authorities in charge of cartography in each country;

(b) extraction of a regional DEM over the Amazon region from a global altimetric database;

(c) experimental mapping programs aiming to validate future space missions or mapping methods.

All elevation mapping techniques addressed in here (photogrammetry, lidar and radar) (Table 1) consist in computing a dense set of topographic points and to resample it into a predefined grid structure. They must meet some specifications defined according to common user needs and technical limitations (Polidori and El Hage 2021). The most important are the definition of the physical surface to be modeled (terrain or upper surface of trees and/or roofs) and the characteristics of the elevation grid, like the mesh shape (square or triangle) and the mesh size, which is an indicator of scale or information density. DEM quality is meaningless if these specifications are not considered.

Table 1. Characteristics of the main techniques for elevation mapping.

Technique	Typical scale range		Modeled surface	Spaceborne missions
	Airborne	Spaceborne		
Photogrammetry	0.1 – 1 m	1 – 10 m	DSM	SPOT-5, ASTER, Pleiades
Lidar	0.1 – 1 m	10 - 100 m (along track) 600 - 3000 m (across track)	DSM/ DTM	GEDI, ICESAT-2
SAR interferometry (short wavelength radar)	1 – 10 m	10 – 30 m	DSM	TDX, SRTM
PolInSAR, SAR tomography (long wavelength radar)	1 – 10 m	50 - 100 m	DTM	Biomass (scheduled 2023)

PHOTOGRAMMETRIC SURVEYS

Three-dimensional mapping has been mainly carried out by aerial photogrammetry over all continents since the second half of the twentieth century. In the 1970s, the traditional analog stereoplotters, in which the image acquisition geometry was modeled by optical and mechanical devices, were progressively replaced by analytical ones, in which the geometric modeling was performed by a computer. More recently, the extensive use of digital photography has stimulated the development of image processing algorithms for automated production of orthorectified image mosaics and digital elevation models using high resolution aerial or satellite imagery (Kasser and Egels 2002).

For large continental expanses, photogrammetry can also be advantageously implemented with spatial data from spaceborne sensors that offer medium resolution imagery with stereoscopic configurations, like SPOT and ASTER. For smaller areas, when aerial photographs are not available, high resolution satellite imagery can be used with the same method for local on-demand DEM production. Photogrammetry, however, is subject to severe limitations in the Amazon.

Cloud cover limits the period suitable for optical acquisitions in 2D cartographic applications. To update land-use mapping, it is necessary to work with mosaics of images acquired at different dates, which limits interpretation relevance. In the case of stereoscopic acquisitions, this difficulty is even more critical, because the two images of the stereopair must be acquired with an appropriate geometric configuration (related to the orbit and to the viewing angles) and with a time interval as short as possible. The first space systems which offered stereoscopic observation possibilities (like SPOT-1, launched in 1986) had to observe the same area from two different orbits (across-track acquisitions), i.e., in different dates, sometimes several months apart, requiring dry weather on two different dates, which was very unlikely. This difficulty has been eased with the possibility of along track acquisitions (made possible, for example, by the HRS sensor of SPOT-5 launched in 2002). In this case, the same zone is observed twice from the same orbit, a few seconds apart, and in the event of dry weather, the two images are acceptable. In addition to cloud cover, frequent fires in the Amazon create large plumes of smoke, which contribute to further restricting the availability of optical data.

A further difficulty lies in the ability of the automatic correlation algorithms used for the mapping, which consist in matching similar features in pairs of stereoscopic images. Indeed, they can have difficulties to identify recognizable features within areas characterized by homogeneous radiometries or textures.

Finally, in forest, when the production of a DEM has not been hampered by cloud cover, the output surface model does not represent the ground itself but the canopy. In this case, it is necessary to subtract from the DEM the estimated height of the trees, which is generally not known accurately and spatially variable, resulting in a degraded model quality. Moreover, for high resolution DEMs, which are supposed to describe the micro-relief, the texture of the tree crowns remains in the corrected model and creates ghost shapes in the ground surface model.

For the above reasons, particularly the effect of cloud cover, the scale and updating frequency of mapping programs for the Amazon are limited compared to coastal or higher latitude regions. Moreover, the inability to see the ground through the forest in optical images is a major limitation of photogrammetry for Amazon landscapes, encouraging the use of lidar surveys.

Lidar surveys

Lidar uses a scanning laser on board an aerial platform together with a GNSS/INS type navigation instrumentation for measuring position and orientation. It measures a point cloud of the surveyed area, as with photogrammetry, but without the step of image acquisition. It has the same limitations as photogrammetry regarding meteorological conditions, i.e., the laser beam is attenuated by the atmosphere and stopped by clouds. However, flight conditions are more flexible for lidar surveys than for photogrammetry and it is possible to fly under the clouds with airplane or helicopter if the clouds are not too low. Since the 2000s, airborne lidar has proved to be a powerful tool for forest mapping and monitoring. The lidar point cloud may be used to study the forest structure and estimate parameters such as tree height (Simard *et al.* 2011; Fayad *et al.* 2014) or above-ground biomass (Næsset 1997; Asner *et al.* 2012; Kankare *et al.* 2013). It has also become the most efficient and accurate method of producing DTMs in forested environments due to the greatly increased scanning frequency, enabling the acquisition of very dense point clouds on the ground (typically several points per square meter). Indeed, a very small part of the laser pulses reach the ground through openings in the foliage, which is sufficient to build a lower envelope by interpolating the lowest points and to create a DTM (Kraus and Pfeifer 1998; Sithole and Vosselman 2004; Guo *et al.* 2010; Montealegre *et al.* 2015) (Figure 2). The potential of this method for elevation mapping in tropical forested areas has been demonstrated (e.g., Andrade *et al.* 2018), but the density of ground points depends on the foliage density and an acceptable DTM can only be derived under specific flight conditions, typically slow and low flights, close to the canopy. Thus, even if airborne laser altimetry is currently the most efficient method for elevation mapping in wooded regions, its operational constraints limit its economic viability for very large areas.

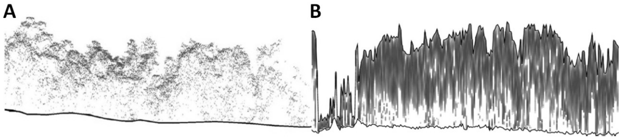

Figure 2. Typical airborne (A) and spaceborne (B) lidar profiles over forest with interpolated topographic profile. Source : ALTOA (A), GEDI (B).

The potential of airborne laser altimetry for mapping has inspired space missions. Radar altimetry had already proved its ability to measure the topography of the oceans – an essential information for monitoring sea level rise. On the contrary, lidar is more suitable for continental surfaces, where profiles can be obtained with high vertical accuracy. In 1995, the SLA (Shuttle Laser Altimeter) flew over tropical regions on board of the Endeavor space shuttle for three days to produce elevation profiles over desert and forest landscapes (Bufton *et al.* 1995). This experimental mission enabled the validation of a promising concept and in 2003, NASA launched the GLAS sensor (Geoscience Laser Altimeter System) on board ICESat (Ice, Cloud and land Elevation Satellite). Although ICESat was mainly designed to measure changes in the elevation of polar ice caps, it has been successfully applied to the characterization of forest vertical structure and to the estimation of canopy height and above ground biomass (Lefsky *et al.* 2005).

In 2018, NASA launched two laser altimetry space missions for geophysical measurements to monitor climate change: ICESat-2, successor to ICESat with increased precision and resolution (Neuenschwaner and Magruder 2019), and GEDI (Global Ecosystem Dynamics Investigation) designed to provide a 3D survey of forests using a laser altimeter on board the International Space Station (Dubayah *et al.* 2020). Their ability to describe the structure of forest ecosystems is expected to improve the estimation of forest biomass, which is an important part of carbon stocks.

However, even if the ground can be detected through the forest cover in satellite lidar profiles, their acquisition is incompatible with the classic requirements of topographic mapping in terms of scale and spatial continuity. Indeed, what is feasible from an aircraft or a helicopter is not necessarily from a satellite at an altitude of 300 to 500 km.

At such a distance the laser footprint has a diameter of several tens of meters, and the vertical profiles are generally too far apart to provide a spatially continuous description of the topographic surface. For instance, the GEDI profiles, which consist of laser dots representing 25-m footprints with a sampling interval of 60 m along track, are 600 m apart. This spacing is even larger in the Amazon because the distance between orbits is maximum in the tropics. For these reasons, spaceborne lidar is a powerful geophysical sensor rather than a mapping tool, at least when used alone. Nevertheless, lidar profiles can be used to provide accurate ground control points to assess or improve other DEMs, which often have a lower vertical accuracy (Liu *et al.* 2020).

Radar surveys

Radar imaging techniques are interesting for regions of frequent cloud cover, because microwaves are very little affected by atmospheric conditions. As early as the 1970s, several mapping programs were launched by Amazonian countries, such as RADAM in Brazil (Azevedo 1971; Van Roessel and Godoy 1974; Escobar *et al.* 2005) and similar initiatives in some neighboring countries. These acquisitions were carried out by short wavelength airborne radars, not in 3D but allowing a 2D hydrographic mapping and a qualitative description of the geomorphology through the interpretation of the radar images, which are very sensitive to landforms due to the side-looking acquisition. Experimental mapping programs have also been implemented with spaceborne radars, to assess the potential of a new satellite under the specific conditions of the Amazon. For example, the project *Guyana Through the Clouds* led to the elaboration of a mosaic of ERS-1 images over the whole French Guiana (Rudant 1994). Similarly, the SAREX-92 project aimed to evaluate the potential of radar data for tropical forest environments (Wooding *et al.* 1994), and the GlobeSAR project aimed to test the data from the Radarsat satellite over several countries in Latin America (Brown *et al.* 1996). These experiments have confirmed the potential of radar imagery as a valuable information source for a variety of applications in geoscience and environmental management, such as geology, ecology, flood monitoring, among others. However, they have also highlighted the limitations of these data in Amazonian environments. For example, short wavelengths (e.g., C band, which is the most common) provide little contrast on hydrographic features and cannot detect the ground or the water through the forest. In addition, radar is not as "all weather" as often said: (a) bright spots may appear in Ku/X-band images in the event of heavy rain (Figure 3); (b) refraction index variations may create phase errors in interferometric products (Ramos *et al.* 2012); and (c) moisture reduces the contrast between forest and low vegetation, resulting in increased difficulty to detect deforestation in the rainy season (Le Toan *et al.* 2017).

Figure 3. Effect of a rainstorm on a SIR-C radar image in X band over Pará state, Brazil. Source: NASA.

Methods have also been developed for the 3D mapping of the relief from aerial, and later from satellite radar images. Three techniques that take advantage of the sensitivity of radar images to relief, have been proposed to develop DEMs from these data: radargrammetry, radarclinometry and interferometry. Radargrammetry extends the principle of photogrammetry to radar geometry, by calculating altitudes from the parallaxes between the images of a stereoscopic pair. Although geometrically rigorous, the technique is limited by the fact that automatic image matching does not work well with images from an active sensor. Indeed, the radiometry depends on the position of the sensor, which necessarily varies between the two acquisitions of a stereoscopic pair (Leberl 1990). Radarclinometry applies the principle of "shape from shading" to estimate the terrain orientation from the radiometry of the radar image. This technique, which consists in identifying intensity variation as a consequence of slope variation, has the advantage of being able to work with a single image, but it is not very accurate, in particular because the spatial variations of the image intensity can be linked to land cover heterogeneity and not only to slope changes (Leberl 1990). However, in the Amazon region, which is mainly covered by forest, it can be reasonably assumed that the landscape is uniform and therefore radiometric gradients can be attributed to slope changes.

Radar interferometry is by far the most efficient of the three techniques despite some limitations. It consists in determining the terrain elevation from the phase difference between two radar echoes acquired from two very close positions of the radar antenna. The potential of this technique for elevation mapping from spaceborne radar was demonstrated in the 1980s (Zebker and Goldstein 1986), then more thoroughly after the launch of ERS-1 in 1991 (Massonnet and Rabaute 1993). Ideally the two images should be obtained from two antennas in a single pass, however, most space radar systems have only one antenna so that they must fly over the same area twice to produce an interferometric pair, leading to two main constraints:

(a) the elevation accuracy depends on the interferometric baseline (i.e., across-track antenna spacing), which cannot be predicted accurately before the second flight, so that it is impossible to know beforehand the expected DEM accuracy;

(b) in the case of short wavelength radar, variations in atmospheric conditions, which are often significant in the Amazon, can cause a significant phase shift and therefore an altitude error (which confirms that radar is not exactly an "all weather" technique), and the random movement of the vegetation (mainly the foliage) can cause a decorrelation of the phase which limits the altimetric precision, and even the feasibility of the method.

Dual-antenna interferometry, which culminated in the SRTM mission (Van Zyl 2001), overcomes all these obstacles for elevation mapping. The SRTM mission made it possible to develop a DEM with 30 m grid spacing, first published with a degraded resolution (90 m) and then at full resolution over all tropical and temperate continental regions. Despite a theoretical specification of 16 m (Bamler 1999), the altimetric accuracy of SRTM is generally of the order of 10 m. Rodriguez *et al.* (2006) found a bias of 1.7 m and a standard deviation of 4.1 m for whole South America, which, based on ground-control points selected manually in favorable sectors (in particular by avoiding buildings and trees) probably is an overestimation of the product's quality. To meet the demand for higher resolution altimetric maps in Brazil, INPE created the Topodata altimetric database at 30 m, resulting from the densification of the 90 m SRTM product by kriging with an empirical adjustment of the parameters on the basis of a geomorphological expertise (Valeriano and Rossetti 2012).

Although SRTM (and Topodata in Brazil) have provided an unprecedently complete and accurate map of the Amazonian topography, these products and other DEMs obtained by "spaceborne radar are not actually digital terrain models. Indeed, they are obtained from X/C-band radar acquisitions, which penetrate very little into the foliage. Therefore, the surface model is located within the canopy, close to the upper surface, rather than on the ground (Kellndorfer *et al.* 2004). Deforested areas appear as dark "holes" in a SRTM DEM due to their lower elevation (confirmed by an optical image acquired in the same year), forming a local effect superimposed to the general rendering of the relief, with light grey levels on the highest hills (Figure 4).

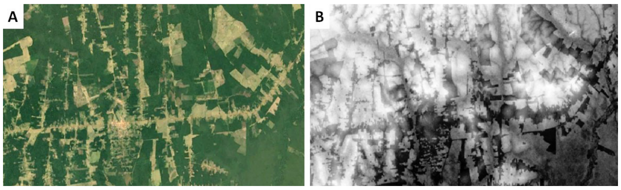

Figure 4. Vegetation effect on the SRTM model in an agricultural area in southern Pará state (Brazil). A – Optical Landsat image; B – SRTM DEM displayed in hypsometric grey levels . Both images acquired in 2000. Source: Google Earth (A), USGS (B). This figure is in color in the electronic version.

Due to this limitation of short-wavelength radar methods, the potential of longer wavelengths has been explored for elevation mapping in wooded regions. L-band (15-30 cm) and P-band (30-100 cm) radar signals have a deeper penetration into the forest volume. The potential of simultaneous X-band and P-band image acquisition in the Amazon was demonstrated by Moreira *et al.* (2001), inspiring the mapping program *Radiografia da Amazônia* for the Brazilian Amazon. The product of interferometric processing consists of a terrain model obtained from P band and a surface model obtained at canopy level from X band (Correia 2011). Figure 5 shows a 25-km long profile extracted from these two products in the Negro River basin. The use of a P-band imaging radar on a satellite has been considered since the 1990s (Chandra and Hounam 1998). The first P-band radar space mission will be ESA's Biomass (Le Toan *et al.* 2011), designed for the mapping of above-ground biomass, and "secondary products", including a quasi-global DTM even in forested areas.

Although the physical properties of P-band radar waves favor the reception of an echo from the ground, the ability to locate the ground in the echo depends on the processing technique used. Conventional interferometric processing exploits phase measurement to extract geometric information, but the use of polarimetry (PolSAR) allows to consider the different components of the forest structure, typically discriminating the ground, the internal volume and the top of canopy to characterize the 3D organization of the forest. The PolInSAR technique implemented combines the possibilities of polarimetry and interferometry, allowing to estimate the elevations of both the ground and the canopy even when there is a mixture of volume and surface backscattering effects (Papathanassiou and Cloude 2001). Tomography goes further, it extends the synthetic aperture principle in the across-track direction by processing several co-registered and phase calibrated images taken over the same area from slightly different flight paths, in order to discriminate the backscattering effects that occurred at different levels of the forest structure, from the ground to the top of the canopy (Reigber and Moreira 2000). This technique has been applied to P-band airborne images acquired over Paracou (typical Amazonian ecosystem in French Guiana) for the validation of the ESA Biomass mission (Dubois-Fernandez *et al.* 2009),

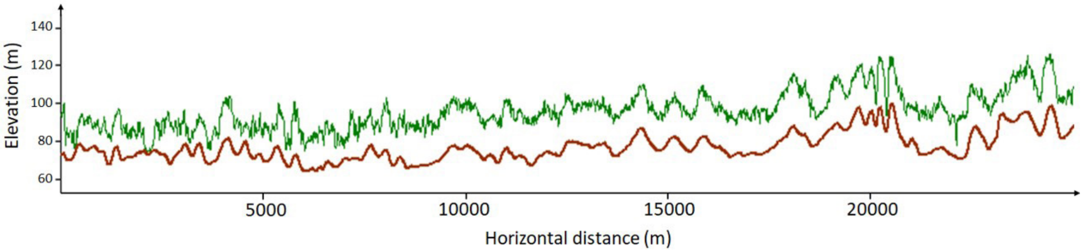

Figure 5. Altimetric profiles obtained along a 25-km track with the P band (DTM, bottom line) and X band (DSM, top profile) for the *Radiografia da Amazonia* project. This figure is in color in the electronic version.

with promising results (Mariotti d'Alessandro and Tebaldini 2019; Smessaert *et al.* 2021).

CHALLENGES FOR ELEVATION MAPPING IN THE AMAZON

The previous sections have highlighted the variety of elevation mapping methods applied more or less successfully to the Amazon, either to improve the knowledge of the territory, or to test sensors and algorithms being developed in this particularly difficult environment. In a densely forested plain like the Amazon, the most usual methods result in a DEM that is a canopy model rather than a terrain model, implying an elevation error of around 30 m if the model is used as a DTM (Asner *et al.* 2006; Helmer and Lefsky 2006). The improvement possibilities that have been conceived to improve the production of a real terrain model remain little explored. Sensors that can detect the ground through the forest, such as lidar and P-band radar are efficient in aerial, but less so in spaceborne acquisition, which limits their employability for a large region like the Amazon. However, the terrain lies under the canopy at a roughly known distance (the typical height of trees in a tropical forest). In addition, the geometry of the Earth surface is not totally random and the available geomorphological expertise is far from being fully used for creating, improving or validating DEMs (Polidori and El Hage 2020). In this context, three relevant research questions regarding elevation mapping in the Amazon remain open: To what extent can a terrain model be replaced by a more easily available canopy-level DEM for topography-based hydrological or geomorphological applications? How can the elevation be obtained at ground level through forest? Can a general *a priori* knowledge of continental relief properties be used to compensate for the limits of measurement methods in the presence of forest?

Terrain morphology analysis in digital canopy models

Most DEM applications require a model describing the ground rather than the upper surface. However, most topographic mapping methods provide a DSM rather than a DTM. For example, the SRTM model, which is widely used in all temperate and tropical regions, particularly in the Amazon, is approximately a DSM, i.e., a canopy model in the case of forests, although it is not explicitly specified as such. Since SRTM and similar products which represent the geometry of the canopy are often used instead of unavailable DTMs, one can wonder to what extent a digital canopy model can be used to characterize the relief for hydrological and geomorphological applications. The consequences of such a substitution can be evaluated by comparing a DSM to the corresponding DTM, according to the criteria defined by the requirements of the application. The altimetric profiles acquired in the Amazon region by airborne X and P-band radar for the *Radiografia da Amazônia* project allow to compare the behavior of the two surfaces in terms of elevation, slope, aspect, curvature and more complex features such as the hydrographic network, which is not necessarily truthfully represented in a DSM.

If the desired magnitude is ground elevation, we can reasonably assume that the error made by using the DSM instead of the DTM behaves like a constant bias equal to average tree height, which can be subtracted from the DSM to bring the surface model down to the ground level. This method is commonly used in traditional medium-scale map production based on photogrammetry.

The profiles in Figure 5 show an elevation difference of the order of 20-25m (Polidori and Simonetto 2014), slightly less than the typical Amazonian canopy height which is most often around 30 m (Asner *et al.* 2006; Helmer and Lefsky 2006). These data suggest that the hypothesis "the P band describes the soil and the X band describes the canopy roof" may be too simple, and that, depending on the angle of incidence of the radar wave and the characteristics of the forest cover (density, structure, moisture, etc.), the P-band model can represent a surface above the ground and the X-band model a surface located inside the foliage.

If the desired magnitude is the ground slope or any variable related to terrain shape, the potential of the canopy model to provide topographic information is not so clear. The DTM and DSM shown in Figure 6a,b are represented with a hypsometric grey scale, i.e., each grey level corresponds to an elevation interval. Except along the main river course, the DSM is expectedly higher than the DTM due to the forest height. The DSM offers a good rendering of the inselbergs

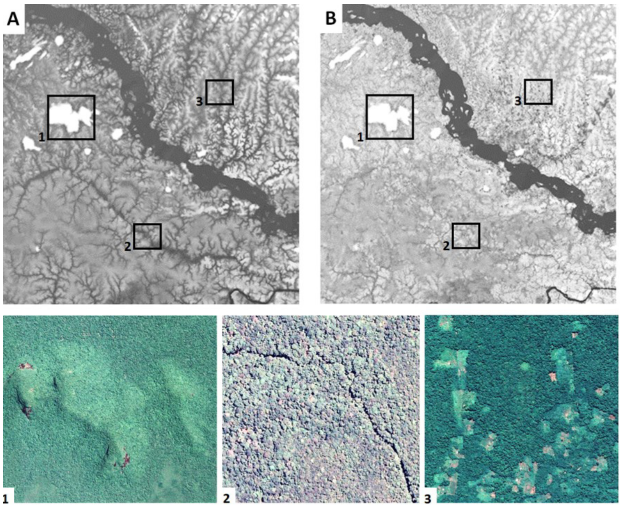

Figure 6. Comparison of a digital terrain model (DTM) and digital surface model (DSM) for land surface modeling in the upper Negro River region (Amazonas, Brazil) for the *Radiografia da Amazônia* program. A – DTM obtained by P-band SAR interferometry; B – DSM obtained by X-band SAR interferometry.The boxes 1, 2 and 3 indicate the small landscape portions. 1 – an inselberg; 2 – a small river partially covered by trees; 3 – deforested plots. Source: DSG, Brazilian Army (A, B) and Google Earth (1, 2, 3). This figure is in color in the electronic version.

(steep hills in the northwestern quadrant) and the main rivers, as well as deforested plots represented by dark spots, that are lower than the surrounding forest. Yet, the description of the terrain shape under the intact forest is very poor. The smallest drainages, though clearly identified in the P-band DTM, are mostly invisible in the X-band DSM. This example illustrates the limitations of X-band SAR interferometry to provide information on ground geomorphometry.

Polidori and Simonetto (2014) compared the DTM and DSM data of the Figure 6 models and found a scale effect. The ground and canopy slopes are increasingly correlated as the sampling interval increases, i.e., the two surfaces become almost parallel at low resolution. The relative slope error made by using the DSM instead of the DTM is of the order of 5° over 30 m (SRTM 1"), but only 2° over 90 m (SRTM 3").

In this context, the idea of the INPE's Topodata product mentioned above is particularly interesting. It is based on the SRTM DEM which was initially subsampled to 90 m, therefore little influenced by the canopy elevation undulation. Oversampling SRTM to 30 m based exclusively on geomorphological criteria leads to a DEM that is free from the textural effects linked to the geometry of the canopy, which would have degraded the precision of the slopes. This makes Topodata a valuable product, though initially based on a DSM, for all applications in which the quality requirements are based on slope accuracy or other geomorphological criteria (Polidori *et al.* 2014a).

Digital elevation mapping at ground level

To obtain a true DTM through the forest, i.e., a surface model describing the ground (or the water in case of permanent flooding) rather than the canopy, two approaches can be considered, namely, removing the tree height in a DSM, or explicitly measuring the ground elevation to generate a true DTM.

Removing tree height from a DSM can be done by subtracting a tree height estimation, preferably at medium or low resolution, so that an average height can be considered to avoid preserving the shapes of tree crowns which are present in the DSM instead of the micro-relief (Valeriano *et al.* 2006). When the forest is discontinuous due to deforestation or landscape heterogeneities, landcover can be considered to locally improve the DEM. Indeed, if the forest patches have been identified and located, tree height removal is implemented in the presence of forest only. This removal can be achieved assuming a constant tree height, through empirical methods based on tree height estimation at forest edges (Gallant *et al.* 2012), or using ancillary data such as ICESat profiles (Yamazaki *et al.* 2017). Near-infrared observation may help to identify the trees so that their removal can be achieved even during the photogrammetric process (Skarlatos and Vlachos 2018).

Measuring the ground elevation through the forest requires a suitable survey method. Airborne lidar is by far the most robust and accurate method. However, as recalled above, achieving high accuracy and high point density requires low flight height and therefore a narrow scanning swath, compromising the economic viability for very large areas. As far as spaceborne laser altimeters are concerned, the specifications of existing missions like ICESat-2 and GEDI produce dense vertical profiles with high altimetric accuracy and reasonable along-track resolution, but without any across-track scanning mechanism, so that adjacent profiles are too far apart. Therefore, spaceborne lidar is not compatible with the requirements of topographic mapping in terms of spatial continuity.

We have also seen that P-band radar offers the possibility to reach the ground. This requires knowing the behavior of the radar signal as it crosses the forest cover and separating the effects of the ground and other components of the vertical column crossed by the radar signal, based on radar signal processing techniques like PolInSAR or tomography. Preparatory studies of the Biomass space mission should enable the refinement of relief extraction methods under the forest cover and the assessment of their uncertainty (Mariotti D'Alessandro and Tebaldini 2019). The performance should be expected to depend on the environmental conditions (which may affect the moisture in the canopy) and on the terrain slope. In the case of two-pass interferometry, it should also depend on the orbital period, since the time delay between the two acquisitions is likely to increase the phase decorrelation, leading to noisy results, although it remains limited in P band.

Although the potential of lidar and long wavelength radar has clearly been demonstrated, some relevant research issues remain regarding operational implementation. They concern both the understanding of physical phenomena (effect of wavelength, polarization and incidence angle in the case of radar, and effect of footprint and incidence angle in the case of lidar), and the improvement of processing algorithms to isolate the ground contribution or to interpolate the lower envelope.

The two approaches that allow to derive a DTM through forest (tree height removal from DSM and direct ground survey) can lead to gross local errors, not significant in the statistical quality assessment, but not acceptable in terms of cartographic requirements. Such errors may be corrected by considering the neighboring point, which consists in making assumptions about the shape of the terrain. The feasibility of using an *a priori* knowledge of the general properties of the Earth's relief to improve the terrain description is addressed below.

Potential of geomorphologic knowledge injection in the elevation mapping process

The previous two sections addressed the possibility of an accurate altimetric measurement but actually describing the geometry of the canopy and risking being misused as a description of the ground topography ; and an explicit altimetric measurement of the ground but necessarily inaccurate due to the presence of the forest mask. In both cases, the knowledge of the geometry of the land is very degraded. However, this data is often obtained without considering the general properties of the Earth's relief, which suggests possibilities for further DEM quality improvement based on a geomorphological expertise. Considering these properties allows the inclusion of other quality criteria linked to realistic geomorphological description, in addition to the usual elevation accuracy assessment (El Hage 2012). The failure to respect these properties can result in impossible reliefs (e.g., a drainage profile with uphill sections) or improbable reliefs (e.g., abundance of very steep slopes, inconsistency of the hydrographic network, unexplained anisotropies, etc.). This extends the possibilities for quality control (Polidori *et al.* 2014a), at least for landforms shaped by water runoff and therefore structured into watersheds, as is the case of most continental landscapes. These geomorphological landscapes have scale invariances based on their fractal properties (Rodriguez-Iturbe and Rinaldo 2001) which can be verified with simple mathematical tools. Compliance with these rules allows the definition of quality criteria based on geomorphological realism that complement the traditional criteria of altimetric precision like mean error, standard deviation and root mean square error (Polidori and El Hage 2020). On the other hand, the possibility of injecting these properties during the DEM generation process to constrain the computation and the resampling of elevation values remains a little advanced field of research. This has already been done to guide resampling i.e., to improve an existing DEM using geomorphological quality criteria. This is the case of drainage burning to improve hydrographic coherence (Polidori *et al.* 2014b; Lindsay 2016), surface densification by kriging (Valeriano and Rossetti 2012) or by fractional Brownian motion (Polidori and Chorowicz 1993) and, at least implicitly, interpolation of the lower envelope of a lidar point cloud (Dong and Chen 2017).

This approach may be considered more upstream in the processing chain, as soon as the ground altitudes are being calculated. Indeed, the calculation of a topographic point aims to locate the interaction of a wave with the illuminated surface (terrain or canopy), and this is generally done without considering the result obtained for its neighbors. Constraining the computation of each individual point by imposing conditions of realism taking into account the neighboring points can improve the algorithms of interferometry and tomography in the case of long wavelength radar (Smessaert *et al.* 2021). These constraints can even be injected more upstream to optimize the choice of processing parameters, for instance to adjust the size of the matching template depending on land cover in the photogrammetric processing chain (El Hage 2012), so that several neighboring points are determined together using criteria related to slope, roughness or other geomorphometric attributes. This implies that the knowledge of the Amazonian geomorphology must be updated and expressed in more quantitative terms.

CONCLUSIONS

The overview given in this article has presented the methods to generate DEMs and their limitations in the Amazon region. In order to support the efforts of mapping agencies and to best meet the needs of the operational and scientific user community, the criteria for the choice of sensors and processing algorithms must be adjusted, and improvements of the elevation mapping process must be adapted to the characteristics of the Amazon environment. Three prioritary lines of research have been identified to (a) limit the risks when using a canopy model to characterize ground geometry; (b) ensure that the DEM is a true ground surface model; and (c) constrain elevation mapping by imposing rules based on geomorphological properties of the relief. Beyond the possibility of improving elevation mapping, the approach based on the search for invariants should contribute to geophysical research for a better understanding of land surface processes in the Amazon in particular, and on continental surfaces in general.

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