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# Attenuating the bidirectional texture variation of satellite images of tropical forest canopies

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ABSTRACT

Quantifying and mapping dense tropical forest structure at region to country level have become pressing needs, notably but not exclusively for assessing carbon stocks as part of the Reducing Emission from Deforestation and forest Degradation (REDD+) process. Fourier texture features from very high spatial resolution passive optical data have shown good potential as non-saturating proxies for stand parameters, including above-ground biomass, within required standards of precision and accuracy. These proxies are, however, sensitive to acquisition geometry (sun–view angles), even for acquisition geometries usually in use in VHR sensors, hampering regional or multi-temporal studies combining multiple acquisitions. Our aim was to improve the understanding of this variation formalized in the bidirectional texture function (BTF), and find ways to mitigate it. We used simulated stands and the Discrete Anisotropic Radiative Transfer (DART) model, as well as a collection of Ikonos images over a forest site near Santarem (Para, Brazil). BTF proved dependent on forest structure and displayed strong anisotropy with respect to forward vs. backward scattering modes. But it remained approximately constant over a large range of angular configurations in forward mode, thereby allowing operational use without any correction. This range could be broadened by correcting bias using empirical BTF fitting or (more practically) by inter-calibrating Fourier spectra when some overlap area is available between images. Prediction of a forest structure parameter ($D_{max}$, the estimated maximum trunk diameter class) using images in varying configurations then remained unbiased and below 15% relative RMSE except in the vicinity ($\pm 10°$ in the principal bidirectional plane) of the hotspot direction. Near hotspot directions need to be proscribed, as the absence of visible shadows impedes textural description. These results, and the increasing availability of large swath VHR sensor constellations (e.g. SPOT 6–7), open the way to operational broad scale applications for forest characterization, above-ground biomass mapping and multitemporal degradation monitoring.



## 1. Introduction

In the context of a strong demand for precise and accurate proxies for monitoring the above-ground biomass (*AGB*) and degradation of tropical forests, very high resolution (VHR) optical imagery remains largely underused. This is in spite of the deployment of an impressive fleet of satellite-borne sensors (e.g. Ikonos, Quickbird, GeoEye, World-View, Pléiades, SPOT 6 & 7, Cartosat, etc.), and increasing availability and affordability of images. The temporal hindsight and spatial coverage allowed by this growing image archive, not to mention more than seventy years of airborne photography record, plead for pursuing efforts to develop reliable methodologies for their exploitation. Visual interpretation of air photos has long been used to infer forest structure. This interpretation relied heavily on the spatial information contained in the image (Curran, 2001), an information difficult to extract quantitatively. Approaches based on stereophotogrammetry (St-Onge, Jumelet, Cobello, & Vega, 2004; Vega & St-Onge, 2008) or crown segmentation (Culvenor, 2002; Clark, Castro, Alvarado, & Read, 2004, Palace, Keller, Asner, Hagen, & Braswell, 2008) were developed, but with limited success in tropical forest contexts. In parallel, it was shown that quantitative information on forest structure, such as aboveground biomass, stand density or basal area, could be inverted using canopy texture metrics such as variograms (Woodcock, Strahler, & Jupp, 1988; Cohen, Spies, & Bradshaw, 1990; St-Onge & Cavayas, 1997; Bruniquel-Pinel & Gastellu-Etchegorry, 1998), lacunarity (Frazer, Wulder, & Niemann, 2005; Malhi & Roman-Cuesta, 2008) or Haralick (GLCM) metrics (Kayitakire, Hamel, & Defourny, 2006). Among texture-based methods, the Fourier Transform Textural Ordination (FOTO) method has been put to test for about ten years in varied tropical contexts (Couteron, 2002; Couteron, Pelissier, Nicolini, & Paget, 2005; Proisy, Couteron, & Fromard, 2007; Barbier, Couteron, Proisy, Malhi, & Gastellu-Etchegorry, 2010; Ploton et al., 2012; Singh, Malhi, & Bhagwat, 2014, Bastin et al., 2014). Its principle is to extract

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unsupervisedly a small number (typically less than three) of quantitative texture features that can be readily interpreted in terms of fineness–coarseness gradients in the canopy, and that can serve for signal conversion into biophysical variables at stand level. An important advantage of this approach over variography is that it does not require choosing a particular fitting model prior to parameter estimation. A related issue with variograms of forest images is the presence of oscillations around the sill (Cohen et al., 1990), marking the presence of spatially periodic patterns for which spectral (e.g. Fourier) methods are better suited. Based on empirical models, the FOTO approach achieved satisfactory prediction of biomass in local case studies (typically 100–1000 $km^2$) dealing with closed canopy tropical forests observed via optical images having homogenous acquisition geometry that is with constant angles between the sun, scene and sensor (Couteron et al., 2005; Proisy et al., 2007; Ploton et al., 2012, 2013). For aboveground biomass, for instance, good agreements were found between predicted and observed biomass, with relative RMSE values below 15% and $R^2$ values above 0.75 even over biomass values above 500 Mg of dry matter per ha (Proisy et al., 2007; Ploton et al., 2012; Bastin et al., 2014). A problem remains however when it comes to large scale or multitemporal applications, since it is no longer possible to systematically ensure consistency in acquisition angles. Texture features are indeed sensitive to acquisition geometry, in a very similar way to reflectance. For reflectance, the bidirectional reflectance distribution function (BRDF), characterizing this angular variation, is widely studied (Nicodemus, 1965, 1970; Roujean, Leroy, & Deschamps, 1992). For texture, a similar concept exists, the bidirectional texture function (BTF), characterizing textural changes with acquisition geometry (Dana, Van Ginneken, Nayar, & Koenderink, 1999; Filip & Haindl, 2009). However, the application of this concept is generally limited to computer graphics and makes use of image data bases instead of a mathematical/statistical quantification of texture variation. The bidirectional variation of pixel variance was studied, notably by Ni, Woodcock, and Jupp (1999), but not in a spatially explicit way. Variograms have been used to characterize the sensitivity of texture to forest structure and acquisition configurations, using either geometric-optical models (Woodcock et al., 1988) or the Discrete Anisotropic Radiative Transfer (DART) model (Bruniquel-Pinel & Gastellu-Etchegorry, 1998). A major conclusion of these studies was that although forest biophysical parameters were very influential on, and could be inverted from the variogram parameters, changes in acquisition parameters could totally blur texture–structure relationships. A quantification of the variation of FOTO texture features with acquisition geometry in a tropical forest canopy context can be found in Barbier, Proisy, Véga, Sabatier, and Couteron (2011). In the latter study, image simulations were obtained using hillshade models on a digital surface model derived from airborne LiDAR in French Guiana.

Given the paucity of the existing literature on quantitative BTF description, the closest reference we have in terms of concept and methods is to be found in BRDF studies. The most largely applied BRDF correction methods, which are for instance in use for the correction of MODIS products, use semi-empirical kernels to correct reflectance in each spectral band (Schaaf et al., 2002). Kernels form is usually derived from geometrical–optical models (Li & Strahler, 1992). Most of the model complexity is contained within these kernels, and simple linear fitting with two or three parameters are sufficient for model adjustment at the pixel level. Thanks to the high levels of repetitiveness allowed by the temporal resolution of these sensors, it is possible to derive fitting parameters on the basis of a few weeks record. The fitting of fully empirical (a priori non-linear) functions is of course much more demanding in terms of data. In the case of texture, we still lack the theoretical background to predict the form of the function, both for Fourier amplitudes and for the derived texture features (i.e. principal components). Moreover, given the existing trade-off between temporal and spatial resolution, and difficulty to obtain optical data over cloudy tropical areas, the data are often still insufficiently dense in space and time to adopt a comparable strategy for BTF correction as for BRDF.

Due to the above difficulties, statistical/empirical approaches have been used, such as multivariate regressions between texture features and acquisition angles (Barbier et al., 2010), partitioned standardization of Fourier spectra (Barbier, Proisy, et al., 2011) or frequency-wise regressions between r-spectra entries (Bastin et al., 2014), to remove unwanted illumination and scene geometry effects between different images. There is however a strong assumption that needs to be satisfied before canceling out all inter-image or inter-configuration variance, in that the distribution of the texture features and forest structure variables ought to be globally the same in each image or configuration class. This can be true for multi-temporal acquisition over a single area, but is not granted for spatially distinct areas. This assumption can be relaxed when (as in Bastin et al., 2014) a small overlap area exists between two images, allowing to compute correction parameters, in reference to a circumscribed set of forest structure types, that can then be applied to the rest of the image to be corrected.

A better knowledge of texture sensitivity to illumination effects is needed to move forward and let the forest observation domain benefit from the development of VHR optical imagery. To this end, we will here make use of two distinct approaches, a theoretical and an empirical one. The theoretical approach (Barbier, Couteron, Gastelly-Etchegorry, & Proisy, 2011), uses 3D forest mockups and a well-established radiative transfer model (Gastellu-Etchegorry, 2008) to systematically reproduce textural changes according to known forest structure gradients and their interactions with variations in acquisition geometry. Despite its apparent simplicity, this modeling approach is gaining widespread recognition in the forest observation community (Morton et al., 2014). Thanks to the improved physical realism of the radiation transfer (including multiple scattering) within tree foliage (Bruniquel-Pinel & Gastellu-Etchegorry, 1998), this approach allows a better representation of the spatial variability of observed reflectance values than geometrical–optical models. Our second approach aims at confirming and illustrating the usefulness of our findings using a dataset of multitemporal VHR (Ikonos) images over a large area of the Tapajos National Forest, near Santarem (Pará, Brazil). Our main focus will be to determine the ranges of acquisition configurations over which FOTO texture features, with or without statistical/empirical correction, remain stable in terms of accuracy and precision. If an in-depth study of texture–structure relationships is beyond the objective of this contribution, the consequences of the results for the application of texture features to forest structure retrieval from multi-temporal or spatial studies involving multiple acquisitions will be of particular concern.

## 2. Material & methods

### 2.1. Canopy image simulation

A total of 3969 canopy images were simulated using the combination of simple 3D forest stand mockups produced by the Allostand model, and the radiative transfer model DART, as explained by Barbier, Couteron, et al. (2011). In Allostand, generic forest stands were obtained using a power law approximations of tree density per one cm $D$ class and inter-tree distances provided by Enquist, West, and Brown (2009), $D$ referring to the trunk diameter at breast height. Stand structure was varied according to a single parameter, $D_{max}$, which is the largest $D$ class included in the simulation. In addition, general allometry rules were extracted from Muller-Landau et al. (2006) as to refer to tropical broadleaf forests and to produce trees with realistic bole length, total height and external crown spheroidal dimensions. The characteristic of simulated forest stands are summarized in Table A1. Although $D_{max}$ is not of common use in forestry, it has been shown to be a good predictor of forest structure and biomass (Bastin et al., 2015; Slik et al., 2013). A strong correlation (Table A2) was indeed found in our simulated dataset between $D_{max}$ and other relevant stand descriptors, such as above ground biomass, basal area, or higher percentiles of the distributions of tree heights or crown diameters. A range of 70 to 130 cm was taken