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TOPOGRAPHIC MODELING OF MARAJÓ ISLAND WITH SRTM DATA[1]

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Abstract

This work presents the application of SRTM-90m in topographic modeling of Marajó Island, with special reference to the processing of the data in low terrain. This research pointed out the demand for extreme precision of elevation data due to very low topography, and SRTM data sensitivity to non-topographic features. The island was shown to present abundant paleochannels since first examinations of the data, motivating attempts to model these features under a parametric approach through morphometric derivations. The terrain conditions of the study site, combined with the predominance of canopy effect, caused morphometric maps to be highly affected by terrain-vegetation interactions. Though parametric approach was found to be inadequate for the study of this site, digital processing techniques were considered to improve the data capabilities for visual analyses, allowing a uniform enhancement of the paleochannels' height, regardless of their actual elevation.

Keywords: Digital Elevation Model (DEM), paleochannels, canopy effect.

Resumo

Este trabalho apresenta a aplicação dos dados SRTM na modelagem da topográfica da Ilha do Marajó, com ênfase no processamento dos dados em relevo baixo. Esta pesquisa apontou a demanda de extrema precisão altimétrica devida ao relevo baixo e à sensibilidade dos dados SRTM a feições não-topográficas. A primeira apreciação dos dados revela que a Ilha apresenta numerosos paleocanais, o que motivou um esforço de modelar estas feições sob uma abordagem paramétrica, através de derivações geomorfométricas. Das condições do terreno das áreas de estudo, aliadas à predominância dos efeitos de dossel vegetal, resulta que os mapas geoorfométricos se apresentem fortemente afetado pelas interações entre a vegetação e o terreno. Apesar de a abordagem paramétrica não se mostrar adequada para as condições vigentes na área de estudo, as técnicas de processamento digital foram consideradas capazes de aumentar o potencial dos dados para análises visuais, permitindo um realce uniforme da altura dos paleocanais, independente de sua altitude.

Palavras-chave: Modelo Digital de Elevação (MDE), paleocanais, efeito de dossel.

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Introduction

Positive impacts on the understanding of Brazilian environments are expected since the availability of data from the Shuttle Radar Topography Mission (SRTM). This mission successfully recorded the first near global (from 60º N to 57º S) elevation dataset by single-pass interferometric synthetic aperture radar (InSAR) in February 2000, in C- and X-bands at 1 arc sec resolution (Rabus et al. 2003). For South America, C-band data, processed by NASA-JPL, were released in the form of a seamless digital elevation model at a resolution of 3 arc sec (~90m), available on-line since 2003. In the particular case of the Brazilian Amazonia, where dense canopies and frequent cloud coverage deprives the mapping potentials of optical remote sensing, SRTM data are about to support the first descriptions of many landscape features. Exploring this type of data is particularly important considering that existing topographic maps of lowland areas in Amazonia exhibit low descriptive power, as the contour lines are vertically spaced at ranges that match or exceed the local relief amplitude, generally of only tens of meters. Furthermore, considering the large size and difficult access, the use of SRTM data is essential to create a set of information concerning to characterization of Amazonian physical environments, which might serve as key elements to undertake studies aiming at the understanding of their dynamics in both geographic and temporal scales.

However, C-band wavelength 5.6cm beams are able to penetrate dense forest canopies, although not reaching the ground (Le Toan et al. 1992). The number and height of individuals along with closeness of the canopy are determinants of the radiation penetration into the canopies. For the radiation that penetrates the canopy, the typical sources of scattering at C band are branches and leaves and volumetric scattering is the main scattering mechanism for this band in tropical dense canopies (Leckie and Ranson 1998). Exploring these interactions, Kellndorfer et al. (2004) used SRTM data as a source for canopy height estimates, by establishing a regression model as a function of the SRTM surface height, or phase center height, relative to ground altitude, or "bald-Earth", referenced from the National Elevation Dataset – NED (Gesch et al., 2002). Though there is not a Brazilian NED and canopy height estimates are not the scope of this research, the interaction mechanisms between SRTM data and canopy structure have to be accounted for in studies on Amazonia.

Our ongoing studies in the Marajó Island reveal that this area has experienced many changes in landscape through its evolution, as a result of a combination of factors, including mostly tectonics, as well as climatic and sea level fluctuations. Because these changes appear to have taken place even during the Quaternary, past environments can be still reconstructed through the geomorphological analysis. Existing topographic maps of the island, available in the scales of 1:1,000,000 or 1:250,000 (contours spaced respectively 100 m and 50 m), show no contour lines, only quoted points, thus not contributing for this kind of analysis. Taking into account the very low topographic nature of the Marajó Island, characterization of the many features related to its physical environments can benefit from adequate processing of SRTM data in order to enhance their resolution.

This paper aims to describe techniques that can be adapted for processing SRTM data in order to enhance topographic features of the Marajó Island, and which can be extended to analyze the morphology of other areas with similar low topography. This study area is characterized by an abundance of morphological features attributed to a complex history of channel abandonment as a response to tectonic activity, whose adequate reconstruction might be the key to substantially improve our understanding on the evolution of the low Amazon drainage system through time.

Material and Methods

The Marajó Island, the largest fluvial island in the world, is located to the northwest of the town of Belém in the State of Pará, being limited by the Amazonas River to the west, Pará River to the south, Tocantins River to the east, and the Equatorial Atlantic Ocean to the north. (Figure 1). This is a region of tropical climate characterized by a mean annual temperature of 28ºC and precipitation of 2500 to 3000 mm/year, 90% of which concentrated between January and July. In Koeppen classification, the southern part of the island is described as Af (forest tropical climate) and the remaining areas as Amw' (relatively drier than Af, with dry winters). Vegetation cover is variable from west to east, ranging from dense ombrophyla forests to *cerrados*, grasslands, and savanna woodlands.

The Marajó Island is inserted in the Marajó Graben System, a tectonic depression formed as a result of the extension related to the opening of the Equatorial South Atlantic Ocean during the late Jurassic/early Cretaceous (Azevedo, 1991; Galvão, 1991; Villegas, 1994). Although sediments started to accumulate since the Cretaceous in this basin, the Marajó Island consists in surface of a belt of Miocene rocks represented by the Barreiras Formation in its extreme eastern margin, Plio-Pleistocene deposits of the Pos-Barreiras sediments in the western margin (Rossetti et al., 1989, 1990; Rossetti & Truckenbrodt 1997; Rossetti, 2004; Rossetti & Santos Jr., 2004), and a variety of deposits displaying Holocene ages in its central and eastern parts (Simões, 1981; Costa et al., 1997; Behling & Costa, 2000; Behling et al., 2001).

This work was based on the analysis of SRTM-90m radar data provided by NASA (National Aeronautics and Space Administration), NIMA (National Imagery and

Mapping Agency), DLR (German Space Agency) and ASIA (Italian Space Agency). The data used here corresponds to the version 1 data, downloaded by August 2003 from The National Map Seamless Data Distribution System, provided by the United States Geolgical Survey at http://seamless.usgs.gov. The data is unprojected, with geographic coordinates as reference units and WGS84 as reference ellipsoid and datum. Elevation is expressed in meters (integer).

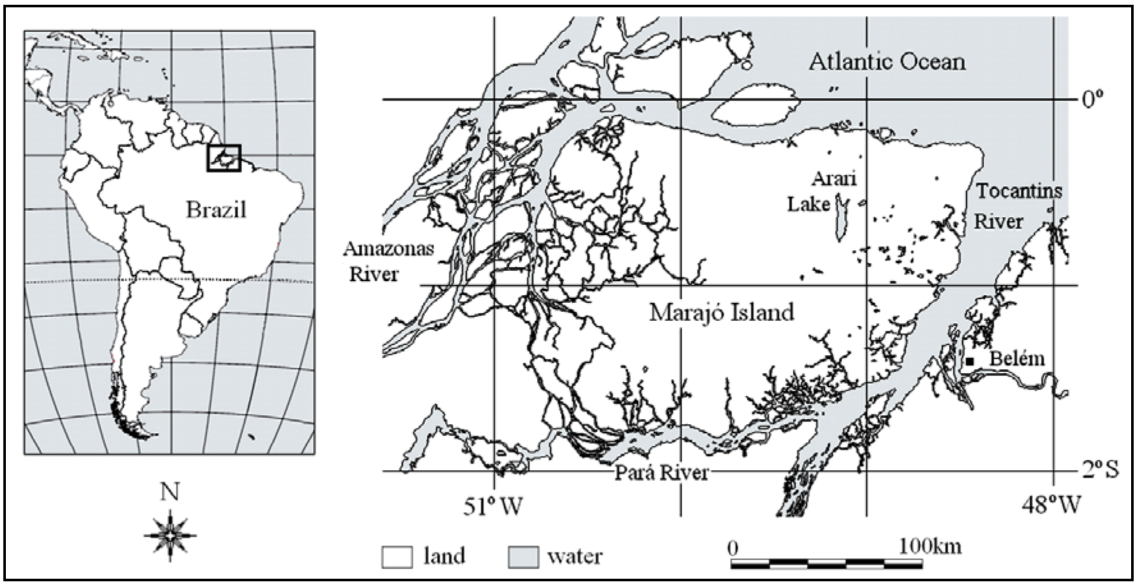

Figure 1 - Location of Marajó Island in northern Brazil (left) and extracted detail from IBGE 1:1 000 000 map series (right).

SRTM-90m data were pre-processed to improve its information potential and to allow for morphometric analyses. The applied modifications were pixel thinning (from 3” to 1”) after removal of the data failures, with a slight smoothing directed to a reduction of artifacts (unrealistic presentation due to pixel size and abrupt variations between height-contrasting objects and canopy) and distribution of the spatial randomness, as depicted below. This pre-processing was considered a key procedure to assure a better performance of the algorithms for morphometric analyses (Valeriano et al., 2006). The procedure was an adaptation of a geostatistical approach originally designed to construct DEM (Digital Elevation Models) from contour lines (Valeriano, 2002). The method was adapted to SRTM-90m data structure through the selection and detachment of squared sample areas (30x30 pixels) for the geostatistical analyses. The method also includes a trend analysis to assure geo-stationarity of the data set submitted to the geostatistical analysis, by feeding variogram calculations with the linear trend residues. Theoretical semivariogram models present three main coefficients that scales the fit to experimental semivariograms, namely range, sill and nugget effect. Variograms of trend residues showed adequate fits with classical semivariogram types, as Gaussian, Spherical and Exponential models (Isaaks & Srivastava, 1989), which present a clear defined sill. The resulting geostatistical coefficients were applied in kriging interpolation of the original SRTM elevation data set.

The analyses of 12 sample sets taken from the study site led to the identification of three similar sets of semivariogram coefficients which were applied in interpolation tests. The interpolation results were visually evaluated under shaded relief presentation, which implicitly resumes the vertical and horizontal angular characteristics (respectively slope and aspect) of the observed surface. After applying this method in the main different relief conditions of the whole area, the coefficients of an exponential model were selected to interpolate data for the whole studied region. The computational programs used for pre-processing were: ENVI (Research Systems Incorporation, 2002) for failure correction, sampling and ASCII data export; MINITAB® (MINITAB Incorporation, 2000) for trend analysis and calculation of residues; VarioWin (Pannatier, 1996) for geostatistical analysis and Surfer (Golden Software, 1995) for kriging interpolation.

After this pre-processing of the elevation data, a suite of algorithms programmed with GIS (Geographical Information System) functions was applied to produce digital images of slope angle (steepness), aspect, plan curvature, profile curvature and thalweg-divide delineation. All morphometric analyses were programmed in Idrisi (Eastman, 1995) macro language. Slope angle images were calculated through the vector sum of slope orthogonal components (Valeriano, 2002b), as quantified through moving windows in “x” and “+” orientation systems, taking the maximum height in each windowed direction and the maximum resultants between the orientations. The method to map profile curvature (Valeriano, 2003) is based on local 3x3 pixel windows designed to perform geometrically the second order derivative through the slope profile. Curvature calculations required the DEM spatial resolution as one of the inputs, so as to calculate a comparable absolute value, with the slope change rate per horizontal distance as unit, in degrees per meter (°/m). The classification of aspect in octants was used to control the overlapping derivation results, calculated towards the eight neighbor pixels of each windowed position. Plan curvature was mapped through a similar application of moving windows, on the slope direction image instead, providing the slope direction change rate per horizontal distance (°/m) (Valeriano & Carvalho Júnior, 2003). Slope direction maps were directly obtained through the aspect function of the used GIS.

These algorithms were originally designed to be used as an analytical parameter, but the former interpretation of their results was conducted by visual approach. Special palettes were developed to code the morphometric images according to their histograms so as to enhance the delicate features of the local geomorphology. Slope angle was codified into a reverse grey scale (the lowest the brightest) to render a "vertical" perception of the terrain. Otherwise, a circular gray scale (darker the southern directions) was adopted for slope direction, producing another 3-dimensional presentation that enhances surface hydrology of the modeled relief. The thalweg-divide delineation was overlaid on a synthetic hill shading image, enhancing the watershed structure, channels and divides, in a process here called "ADD" (Azimuth, Drainage and Divide).

In an attempt to isolate the individual heights of the paleochannels from bulk elevation, a "floor" elevation model (bald Earth) was constructed by interpolating points selected through morphometry and subtracting its height from the actual DEM. Since there is not a reliable elevations data source in appropriate scales in Brazil, like the National Elevation Model – NED (Gesch et al., 2002) DEM used by Kellndorfer et al. (2004) for this task, bald Earth DEM has to be extracted from the same SRTM data, by indirect means. The whole processing of SRTM data, from original DEM until the calculation of the height model is presented in Figure 2.

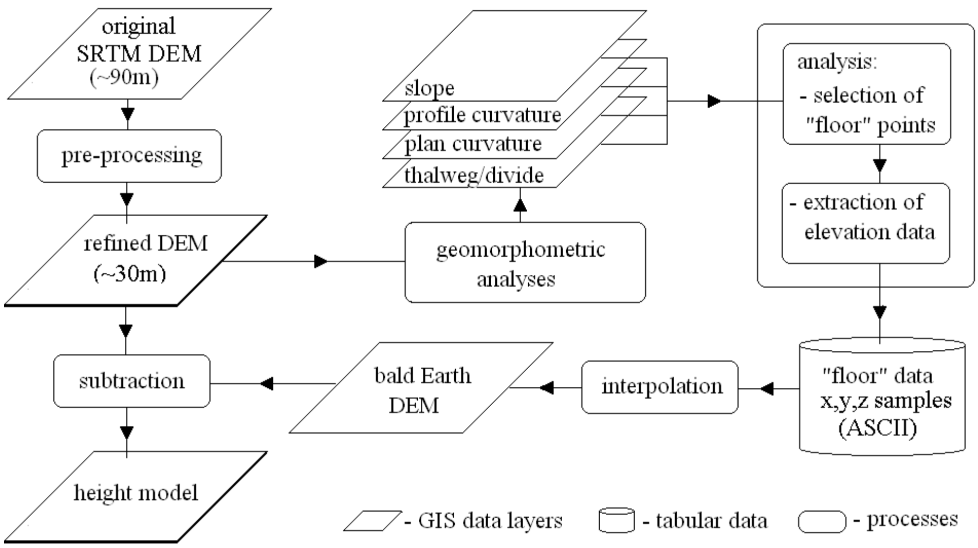

Figure 2 - The GIS processing of a height model from SRTM elevation data (DEM).

Image interpretation of elevation itself was made possible by the use of the software Global Mapper. Given the very low topography, the study area had to be visualized accordingly using customized shade schemes and palettes to efficiently highlight the morphologic features of interest to this paper. When examining different locations, color schemes had to be rearranged in order to present strong hue transitions along the height span of the observed features, requiring often adjustments from a local to another. This was applied only for the recognition of features, since local adjustments would affect internal consistence when observing the whole image.

Results and discussion

The SRTM data pre-processing contributed to significantly enhance the topographic features in the Marajó Island (Figure 3). This procedure, combined with the application of appropriate color schemes and palettes, highlights minor features, allowing observations at detailed scales.

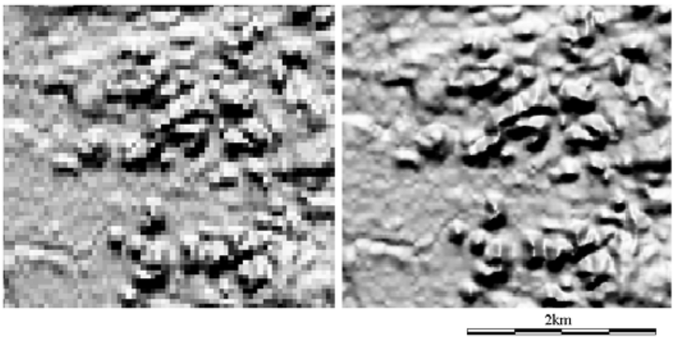

Figure 3 - Shaded relief of original (left) and refined (right) SRTM data.

A hypsometric presentation of the Marajó Island shows a clear bi-modal distribution of heights, reflecting two main topographic regions (Figure 4). Hence, although the overall mean height for the entire island is 12.55 m, the western side is of higher relief, recording heights averaging 20 m, with a maximum height of 36 m. In contrast, the relief in the eastern half of the island, which is flooded through several months every year, commonly ranges from 2 m to 6 m, occasionally reaching a maximum of 30 m. Beside elevation differences, the western side of the island showed higher topographic features than those observed in its eastern side, as can be seen in section A-A' of Figure 4

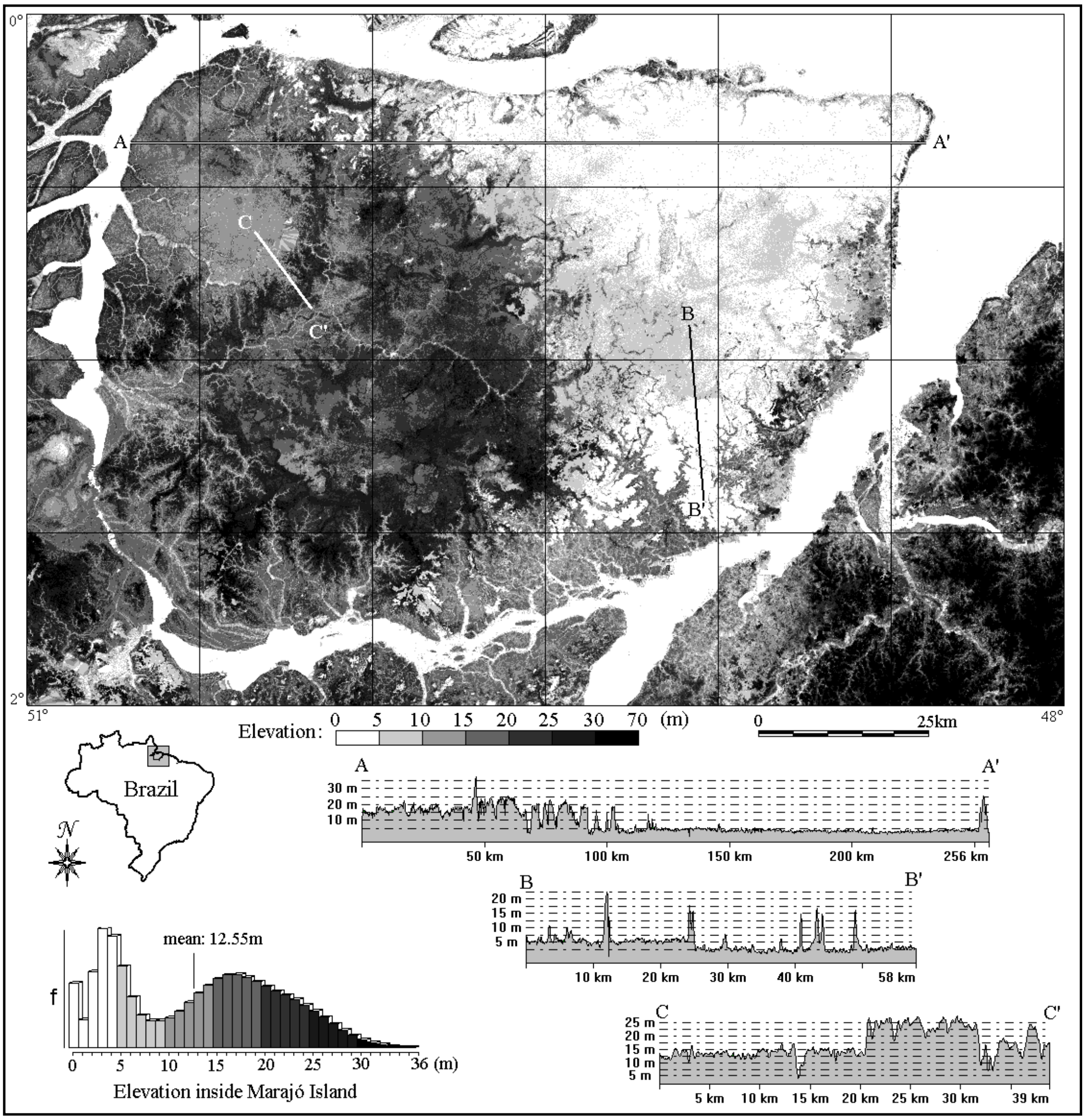

Figure 4 - SRTM data of Marajó Island.. Three topographic profiles are illustrated, where: A-A' shows the topographic gradient existing between the western and eastern side of the island, which higher values to the west; B-B' cuts through an area with circular nature having an overall slightly lower topography to the south; and C-C' illustrates a higher belt in the northwest side of the island, probably related to a paleochannel.

Furthermore, the morphometric maps derived from the refined DEM showed very dense patterns of terrain features. Since their calculation depend on slope vertical and horizontal angles rather than height variations, the low topography of the island behaves as a rugged terrain when observed through morphometric analyses (Fig. 5). A remarkable observation was a circular feature of flat and low elevation in the southeast portion of the island (transect B-B', Figure 4), between Afuá and Arari rivers.

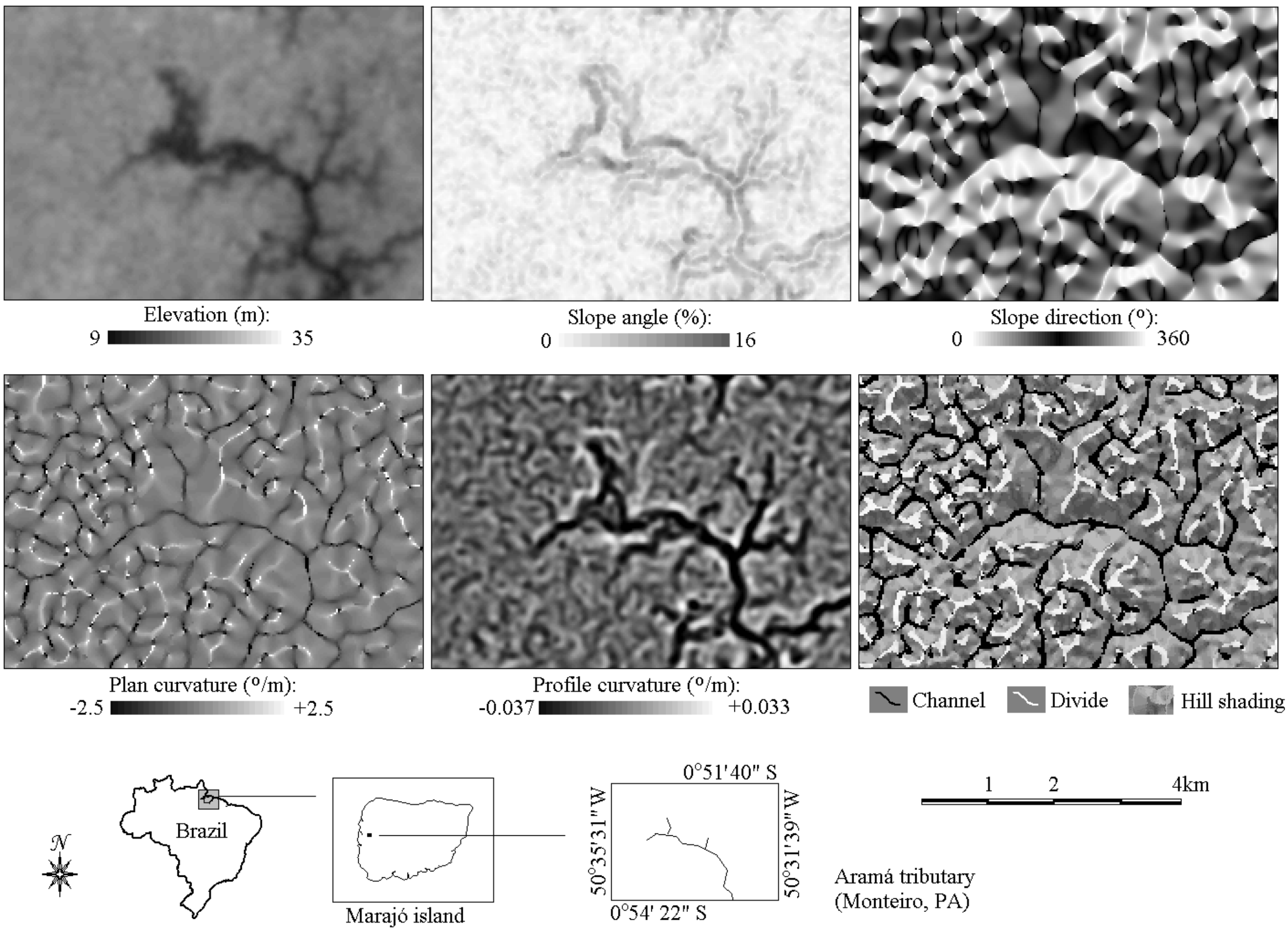

Figure 5 - Excerpt of morphometric maps derived from refined SRTM data, showing the predominance of canopy effects on the distribution of morphometric variables.

The above-mentioned bimodal relief distribution in the Marajó Island corresponds to sedimentary deposits of different ages, with the terrains to the west being related to older Plio-Pleistocene deposits, while the lower topographic terrains to the east encompasses mostly Holocenic deposits. The distribution of the morphometric variables, though, were not clearly conditioned by the altitudinal strata. While elevation histograms were distinct, among morphometric variables only slope angle slightly showed the west region to present a higher frequency of steeper slopes (Figure 6).

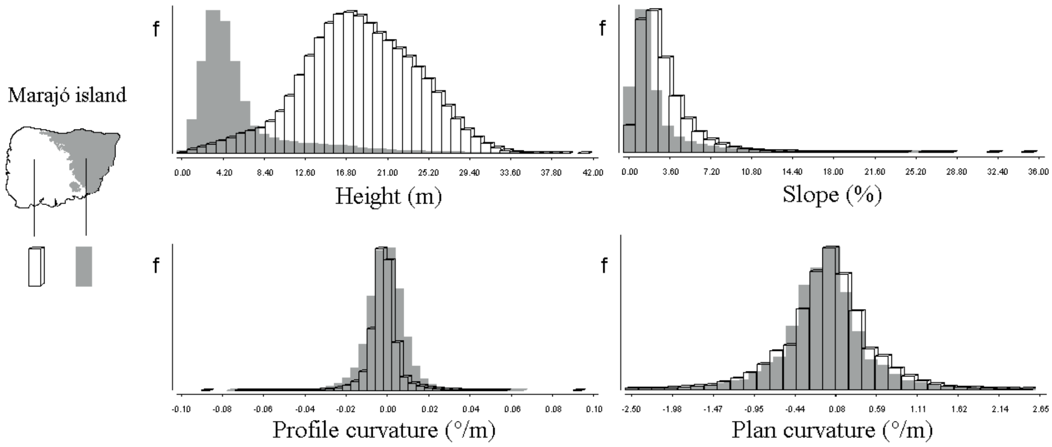

Figure 6 - Distribution of morphometric data in the two sectors of Marajó Island.

The morphometric analyses shown herein only helped to better define the details for characterizing the topography in large scales, feeding punctual parametric description needs. However, observations of refined elevation model, coupled with occasional verifications on morphometric maps, allowed a better (cleaner) characterization of a complex drainage network through identification of paleochannel systems, mostly in the western side of the Marajó Island. In the eastern side of the island, a smaller number of these features were detected in the topography. Additionally, field observations confirmed an exaggeration effect due to canopy affecting SRTM data, as forests cover the paleochannels while the surrounding terrain is covered by grasses and low vegetation. Indeed, paleochannel SRTM heights record tens of meters, but the terrain itself was observed to present only 2-3m elevation relative to its surroundings, being covered with high (tens of meters) dense forest canopy (Figure 7).

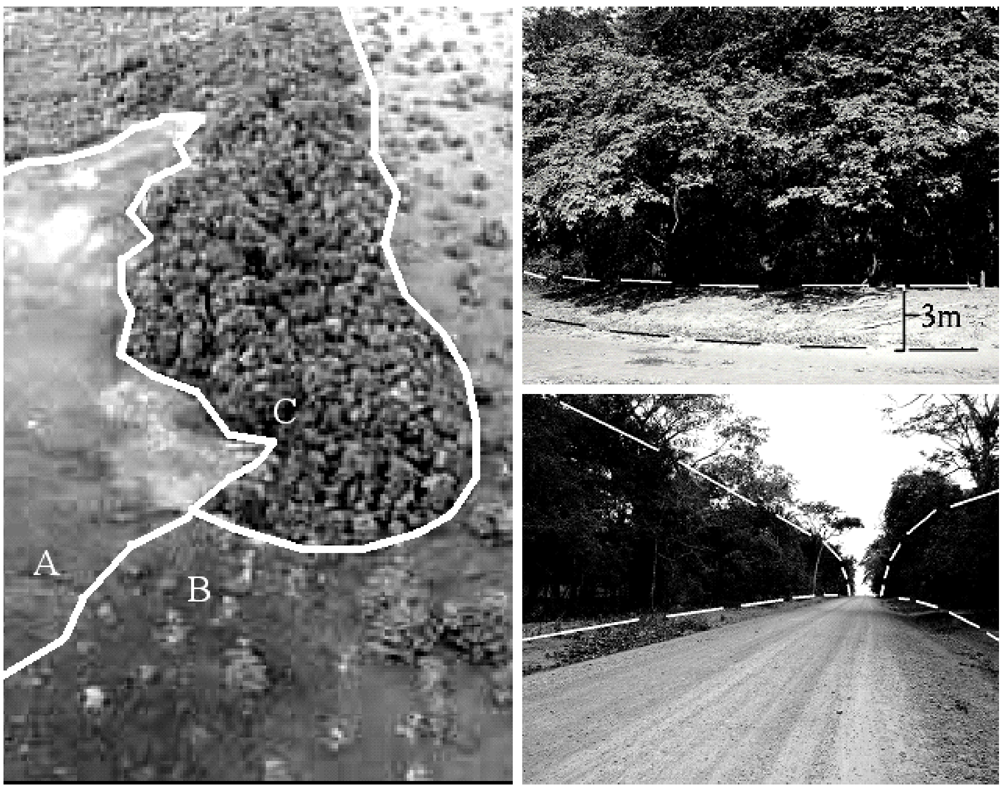

Figure 7 - Gallery forest along Cambu River observed through SRTM shaded relief.

Once promoted by canopy effect, it is reasonable to expect gallery forests to produce the same effect along modern channels. Fortunately, modern channels were easily identified in published survey maps, when available, or through a logical interpretation of the many linear features in the SRTM model otherwise. The typical effect of gallery forest on SRTM perception of drainage is the inverted topography (convex cross section) following the watercourses, as exemplified in Figure 8.

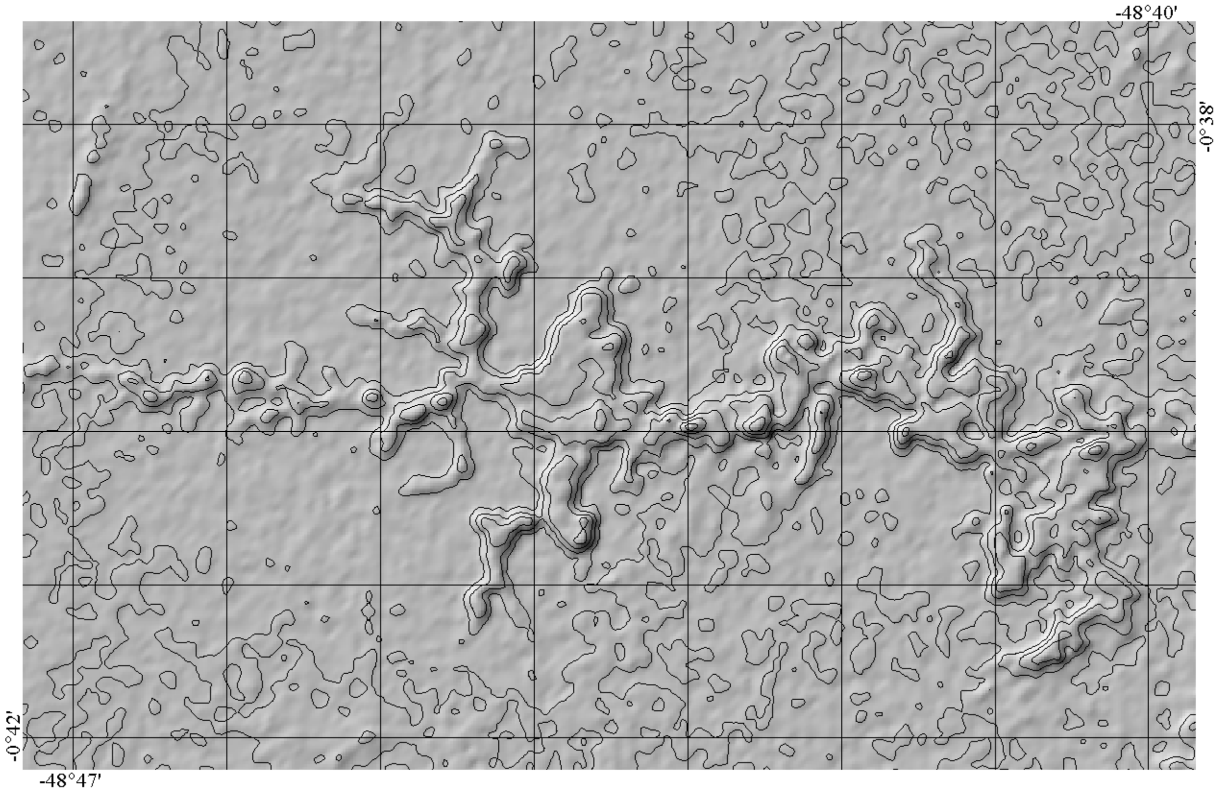

Figure 8 - Vegetation-terrain features related to paleochannels. In the upper left (from http://www.canalciencia.ibct.br/pesquisas/pesquisa.php?ref_pesquisa=189): A) grasslands. B) savanna woodlands. C) ombrophyla forest. Upper right: terrain height contrast in the grassland-forest contact. Bottom right: convex shaped cross section of the paleochannel terrain.

In the western part of the island, the paleochannels were easily detected in the SRTM data because they consist of elongated, highly sinuous, and usually branched features presenting positive relief (convex transversal sections) that differs from the relatively lower topography of the surrounding terrains (see section C-C´ in Figure 4). Additionally, hydrologically meaningful drainage networks of modern channels often intercept paleochannels, producing a number of disconnected segments. Despite that previous studies have already documented paleochannels in the Marajó Island (e.g., RADAM, ; Vital, 1988; Bemerguy, 1997; Lima, 2002), there have been no attempts to systematically characterize these features for the entire area, a procedure that is essential to fully reconstruct the succession of events that took place in the area in near past times. The SRTM observations of these paleochannels showed that more than one drainage system were successively replaced or covered by another, and suggested that their height relative to the surrounding terrain might help to distinguish the different paleodrainage networks.

We emphasize that height differences in SRTM modeled features must be explained not only by the terrain alone, but also by canopy effects, which may be linked to paleochannels through soil properties in these places. In the aerial photograph of Figure 7, a contact between grasslands (A), savanna woodlands (B) and a strip of dense ombrophyla forest (C) shows diverse canopy height and openness conditions, in agreement to the canopy effects on C-band backscattering explained by Le Toan et al. (1992). Ground observations (upper right) showed the forested areas to cover small elevations, of 2 to 4 meters relative to the surrounding terrain. The terrain cross section of paleochannels was also observed as convex shaped (bottom right).

In the low relief of Marajó Island, these non-topographic effects were enough to deprive the proposed height model calculation from producing meaningful results for numerical approach. In a vertically wide relief, low areas are expected to present concave curvature, low steepness, convergent flow lines or to match thalweg conditions.

However, the low relief amplitude caused much of the morphometric variations to result from roughness of surface data, due to terrain or canopy roughness or even data noise, rather than hydrological and geomorphological constraints. As noted, the distribution of local morphometry resulted in a crispy pattern, producing fragmented concavities and thalwegs everywhere, not only in lowlands (see Figure 5). Thus, the various morphometric criteria applied to automatically select floor pixels failed, with much of them being erroneously selected on positive relief features. Although the terrain particularities disabled numerical approach efforts for parametric description of the paleochannels, the procedure caused an interesting enhancement of these features, bringing new features where they could not be perceived before and enhancing the promptly visible ones (Figure 9).

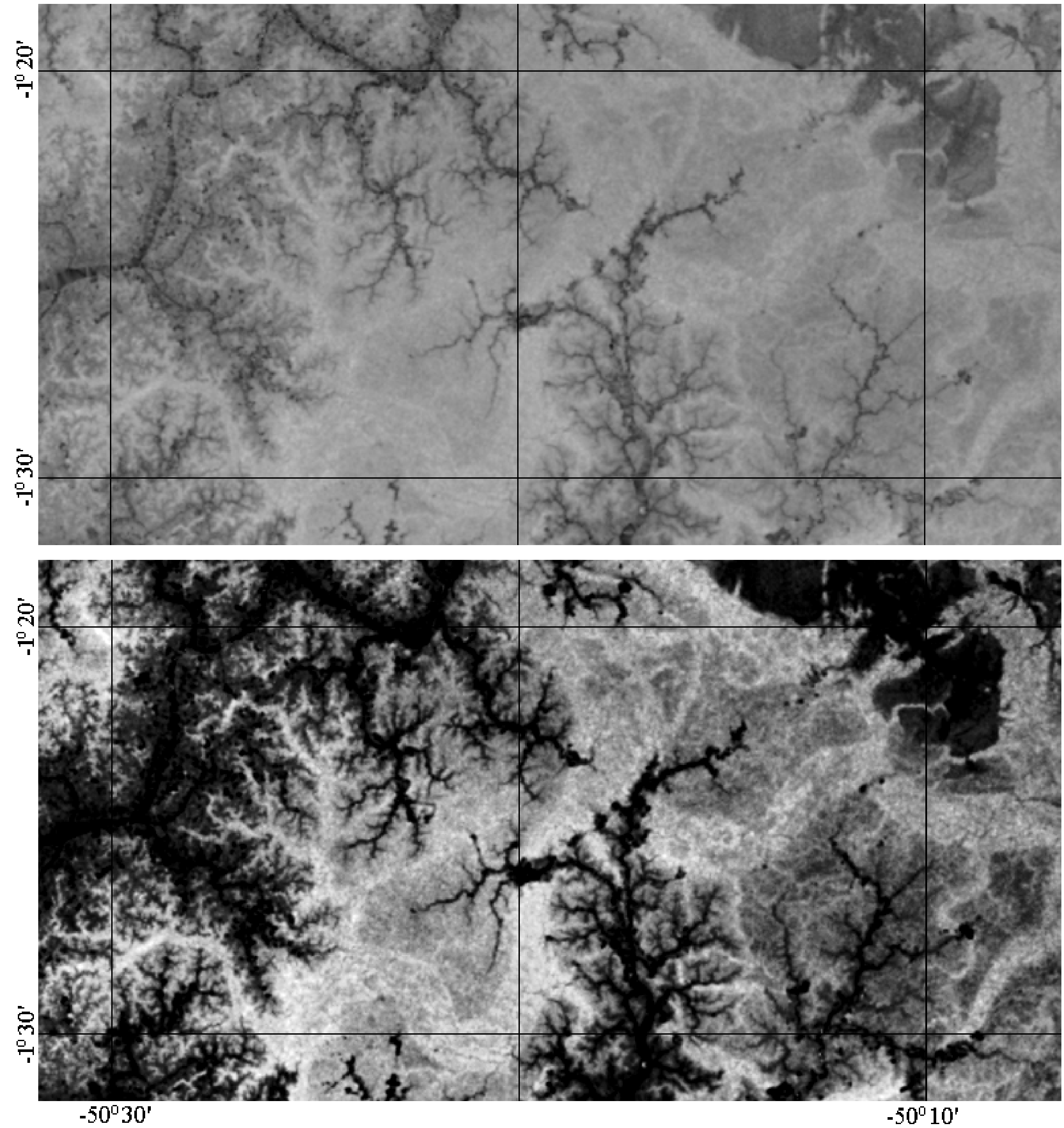

Figure 9 - Enhancement of paleochannels: SRTM full DEM (top) and height relative to the island "floor" (bottom).

In Figure 9, the top image presents the full refined SRTM elevation, where modern channels can be observed as the dark network and paleochannels as the brighter networks of varying widths. Removing the island floor (bottom), a higher contrast between paleochannels and the remaining terrain is achieved, enhancing the large drainage courses (upper right) and revealing lower order networks of paleochannels (lower left). In the detailed excerpt of Figure 10, two paleo-watersheds, extracted by interpreting the relative height image of Figure 9, mouth into the same large paleochannel.

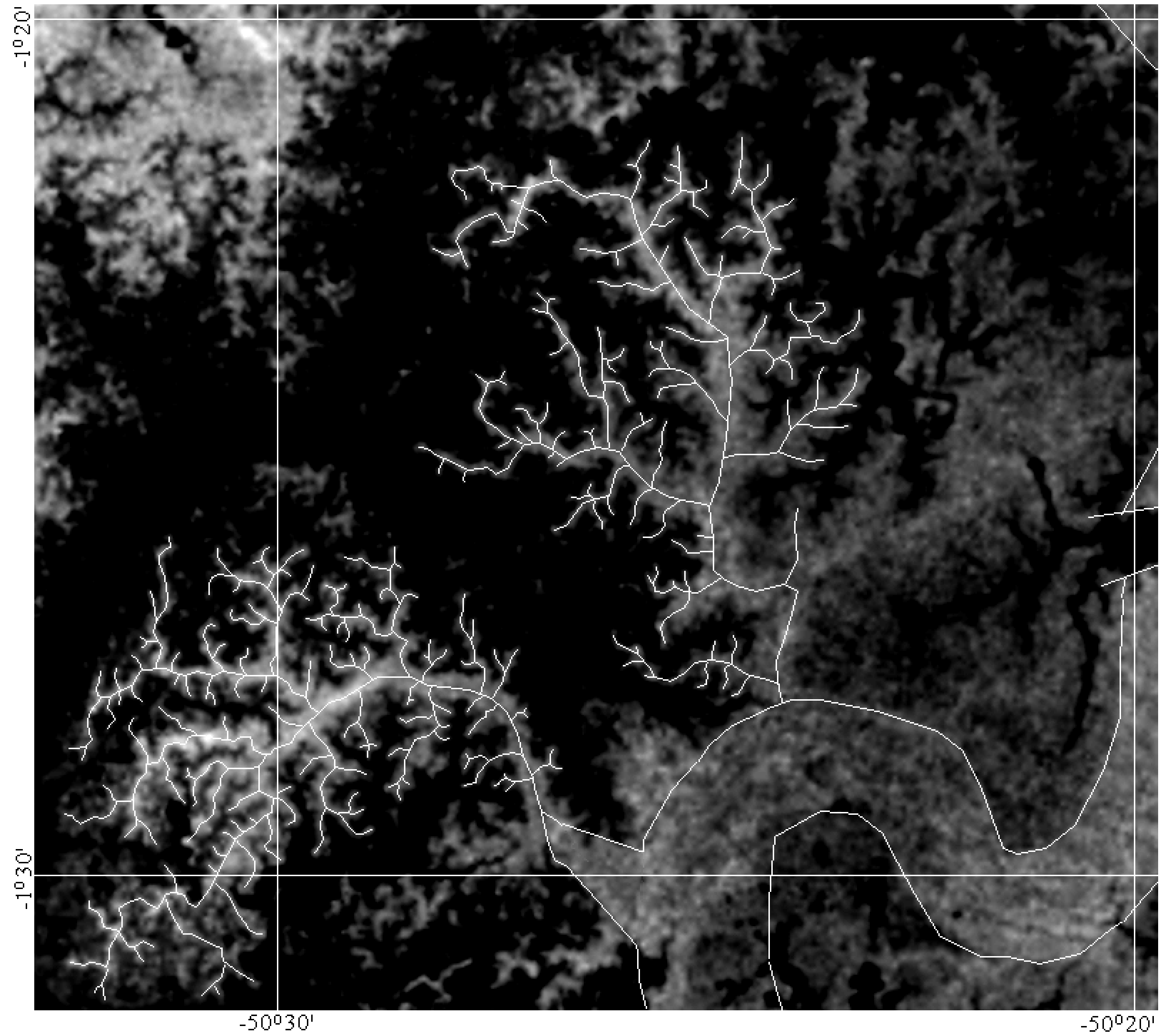

Figure 10 - Digitized interpretation of paleo-watersheds running into a larger paleochannel.

While the vertical aspects of the mapped paleo-watersheds are liable to reflect modern pedo-botanical effects rather than the ancient morphometry, the horizontal characteristics of their drainage networks can be partially recovered. The remaining question in this matter is the level of completeness of the recovered network relative to its original, but, at some extent, the general drainage geomorphology can be retrieved, such as density measures, shape, caption area, channel hierarchy and sinuosity, for example. During the interpretation of the example presented in Figure 10, it was clear that the upper limits of first order springs were undetectable, as well as the widths of minor channels and the extent of confluence enlargements. But remarkable features were retrievable, such as the denser drainage network and more frequent confluences at the southernmost watershed, and a notable heterogeneity of the confluence angles in both cases. The latter observation indicates a succession of strong geologic (structural) constraints to the arrangement of the channel segments. For the large paleochannels (like the meandering feature at southeast), the interpretation necessary for a reconstruction of the different ancient drainage systems shall be based on their width, sinuosity and inferred directions.

Concluding Remarks

Techniques for exploring SRTM data in the particular conditions of Marajó Island were presented. In the SRTM elevation model, the island relief presented very low elevation, with a maximum of 36m, and relative relief rarely exceeded 10m. In such a low topography, SRTM showed important advantages against the use of survey maps, because of its vertical resolution being much higher than the mapped contour intervals. These advantages were promptly available for the relief interpretation by visual approach. In the eastern side of the island, the observation of terrain features were related to structural changes in the overlying vegetation, since tall forest and *cerrado* canopies (tens of meters) were observed to systematically occur on the many 2-4m height features that characterize paleochannels, in contrast to the surrounding grasslands. In the western side, all covered with dense ombrophyla canopies, only subtle structural changes are expected to occur and, accordingly, the height contrasts around these features were smaller. The observations revealed Marajó Island to present numerous paleochannels displaced in distinct and overlapping drainage systems, which differ in width, curvature and direction. Further, an effort was made to digitally explore the data including kriging refinement and subsequent morphometric analyses. The applied processes improved spatial resolution and promoted clearness of the surface features, improving detailed characterization of local features. However, much of the classical procedures in digital elevation modeling were useless in this relief, where canopy effects prevailed over terrain expression, resulting in noisy maps of steepness, aspect and curvature. The contributions of morphometric analysis were restricted to occasional verifications to define feature boundaries where elevation was not enough by itself. An attempt to digitally estimate the height of paleochannels relative to their surroundings terrain failed in the precise determination of a featureless floor, to be subtracted from the full elevation. Nevertheless, the results showed an interesting enhancement of the paleochannels, allowing the perception of ancient drainage networks.

Bibliographical references

Azevedo, R. P. (1991). Tectonic evolution of Brazilian Equatorial Continental Margin Basins, Doctorate Thesis, London, UK, 455 pages.

Behling, H. & Costa, M. L. Holocene environmental changes from the Rio Curuá record in the Caxiuanã region, eastern Amazon Basin. Quaternary Research, v. 53, p. 369-377, 2000.

Behling, H., Cohen, M. C. L. & Lara, R. J. Studies on Holocene mangrove ecosystem dynamics of the Bragança Peninsula in north-eastern Pará, Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology v. 167, p. 225-242, 2001.

Bemerguy, R. (1997). Morfotectônica e Evolução Paleogeográfica da Região da Calha do Rio Amazonas, Doctorate Thesis, Belém, PA, 200 p.

Costa, M. L., Moraes, E. L., Behling, H., Melo, J. C. V., Siqueira, N. V. M. & Kern D. C. Os sedimentos de fundo da Baía de Caxiuanã.. In P.L.B. Lisboa (ed.). Caxiuanã. Belém: Museu Paraense Emílio Goeldi, 1997. p. 121-137.

Eastman, J. R. Idrisi for Windows - User's Guide. Worcester: Clark University, 1995. 440p.

Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M. & Tyler, D. The National Elevation Dataset. Photogrammetric Engineering and Remote Sensing, v. 68, p. 5-11, 2002.

Galvão, M. V. G. (1991). Evolução Termodinâmica da Bacia do Marajó, Estado do Pará, Brasil, M.Sc. Dissertation, Ouro Preto, MG, 193 p.

Golden Software. Surfer Version 6.01- Surface Mapping System. Golden: Golden Software, Inc., 1995. (not paginated)

Isaaks, E. H. & Srivastava, R. M. An Introduction to Applied Geostatistics. New York: Oxford University Press, 1989. 561 p.

Kellndorfer, J., Walker, W., Pierce, L., Dobson, C., Fites, J. A., Hunsaker, C., Vona, J. & Clutter, M. Vegetation height estimation from Shuttle Radar Topography Mission and Nation Elevation Datasets. Remote Sensing of Environment v. 93, p. 339-359, 2004.

Le Toan, T., Beaudoin, A., Riom, J. & Guyon, D. Relating forest biomass to SAR data. IEEE Transactions on Geoscience and Remote Sensing v. 30, p. 403-411, 1992.

Leckie, D. G. & Ranson K. J. Forestry applications using imaging radar. In: Henderson, F. M. and Lewis, A. J., (eds.). Principles and Applications of Imaging Radar. New York: John Wiley and Sons, 1998. p. 435-509.

Lima, M. I. C. Análise de drenagem e seu significado geológico-geomorfológico-paleomeandros região de Chaves-Ilha de Marajó. Belém: Universidade Federal do Pará, 2002. (CD rom)

Minitab Inc. Meet MINITAB, Release 13 for Windows. Pennsylvania: State College, 2000. (not paginated)

Özdamar, L., Demirhan, M. & Özpinar, A. A comparison of spatial interpolation methods and a fuzzy areal evaluation scheme in environmental site characterization. Computers, Environment and Urban Systems v. 23, p. 399-422, 1999.

Pannatier, Y. VarioWin: Software for Spatial Data Analysis in 2D. New York: Springer-Verlag, 1996. (not paginated)

Rabus, B., Eineder, M., Roth, A. & Bamler, R. The shuttle radar topography mission-anew class of digital elevation models acquired by spaceborne radar. Photogrammetry and Remote Sensing, v. 57, p. 241-262, 2003.

Research Systems Inc. Environment for Visualizing Images – ENVI Version 3.6. Boulder: ESRI, 2002. 126p.

Rossetti D.F. Paleosurfaces from northeastern Amazonia as a key for reconstructing paleolandscapes and understanding weathering products. Sedimentary Geology, v. 169, p. 151-174, 2004.

Rossetti, D. F. & Santos Jr., A. E. A. Facies architecture in a tectonically-influenced estuarine incised valley fill of Miocene age, northern Brazil. Journal of South America Earth Sciences, v. 17, p. 267-284, 2004.

Rossetti, D. F., Truckenbrodt, W. & Góes, A. M. (1989). Estudo paleoambiental e estratigráfico dos Sedimentos Barreiras e Pós-Barreiras na região Bragantina, nordeste do Pará. Boletim do Museu Paraense Emílio Goeldi, Série Ciências da Terra v. 1, p. 25-74.

Rossetti, D. F., Góes, A. M. & Truckenbrodt, W. A influência marinha nos Sedimentos Barreiras. Boletim do Museu Paraense Emílio Goeldi, Série Ciências da Terra, v. 2, p. 17-29, 1990.

Simões, M. F. Coletores-Pescadores ceramistas do litoral do salgado (Pará). Boletim do Museu Paraense Emílio Goeldi, Série Antropologia, v. 78, p. 1-33, 1981.

Valeriano, M. M. Modelos digitais de elevação de microbacias elaborados com krigagem. São José dos Campos: Instituto de Pesquisas Espaciais (INPE-9364-RPQ/736), 2002. 54p.

Valeriano, M. M. Programação do cálculo da declividade em SIG pelo método de vetores ortogonais. Espaço e Geografia, v. 5, n. 1, p. 69-85, 2002b.

Valeriano, M. M. Curvatura vertical de vertentes em microbacias pela análise de modelos digitais de elevação. Revista Brasileira de Engenharia Agrícola e Ambiental, v. 7, n. 3, p. 539-546, 2003.

Valeriano, M. M. & Carvalho Júnior, O. A. Geoprocessamento de modelos digitais de elevação para mapeamento da curvatura horizontal em microbacias. Revista Brasileira de Geomorfologia v. 4, n. 1, p. 17-29, 2003.

Valeriano, M. M., Kuplich, T. M., Storino, M., Amaral, B. D., Mendes Jr., J. N. & Lima, D. Modeling small watersheds in Brazilian Amazônia with SRTM-90m data. Computers & Geosciences v. 32, n. 8, 1169-1181, 2006.

Villegas, J. M. C. (1994). Geologia Estrutural da Bacia do Marajó. Dissertação de Mestrado, Belém, PA, 119 págiinas.

Vital, H. (1988). Estudo do geossistema do Lago Arari, Ilha do Marajó, Pará. Dissertação de Mestrado, Belém, PA, 105 páginas.