STEREO RADARSAT DATA FOR CANOPY HEIGHT IN BRAZILIAN FORESTS

Thierry Toutin
Canada Centre for Remote Sensing
588, Booth Street, Ottawa, Ontario
K1A 0Y7 Canada

Silvana Amaral
Instituto Nacional de Pesquisas Espaciais - INPE
CP. 515, CEP 12227-010
São José dos Campos, SP, Brazil

ABSTRACT

This paper demonstrates the applicability of RADARSAT stereo-images for the interpretation and measurement of some characteristics of the Brazilian tropical rain forest. Clearing boundaries, vegetation cover and canopy heights were qualitatively interpreted and quantitatively measured on a fine mode RADARSAT stereo-pair using a PC-based softcopy stereo workstation. Since no ground truth was specifically acquired for this project, the validation of the results is realized in two steps using previous research studies of the same site. The clearing boundaries were first overlaid on a previously ortho-rectified Landsat-TM image to verify their planimetric accuracy and the interpretation of the vegetation cover. The planimetric positioning error of 30 metres for the clearing boundaries was mainly due to the accuracy of the input cartographic data. Larger errors were a result of the deforestation and regeneration between image acquisition dates, the dominant scattering regime from the forest and the mis-interpretation of SAR backscatter. The computed canopy heights were then compared to an existing vegetation map, which described the tree species and their characteristics of each class. The results in canopy heights were generally consistent and a good representation of terrain reality. With few exceptions, a mean height variation of about 5 metres with the "expected" canopy heights based on previous studies was obtained. In the context of monitoring the Amazon forest in Brazil, these results based on radar stereo geometry show promise as a complementary tool to traditional methods based only on radar radiometry.

RÉSUMÉ

Cet article démontre la possibilité d'utiliser les images stéréoscopiques de RADARSAT pour interpréter et mesurer certaines caractéristiques de la forêt pluviale tropicale du Brésil. A partir d'un couple stéréoscopique d'images en mode fin de RADARSAT, on interprète qualitativement et on mesure quantitativement les limites de coupes, la couverture forestière et la hauteur de la voûte sur une station de travail stéréo PC ("softcopy").

Comme aucune donnée de vérification n'a été spécialement acquise pour ce projet, la validation se réalise en deux étapes à partir des résultats de précédents travaux de recherche sur ce site. En premier lieu, les frontières des coupes sont superposées sur une image TM de Landsat déjà ortho-rectifiée pour vérifier leur précision planimétrique et l'interprétation de la couverture végétale. Leur erreur de positionnement planimétrique de 30 mètres est principalement due à la précision des données cartographiques d'entrée. De plus grandes erreurs résultent de la déforestation et la régénération entre les dates d'acquisition des images, du type principal de la rétrodiffusion radar avec la forêt et de l'erreur d'interprétation de cette rétrodiffusion. Ensuite, les hauteurs calculées de la voûte sont comparées à une carte existante de la végétation, qui décrit les essences forestières et les caractéristiques de chaque classe. Les résultats pour les hauteurs de voûte sont cohérents et représentent bien la réalité du terrain. A part quelques exceptions, une variation moyenne de hauteur de 5 mètres est obtenue en comparant les hauteurs extraites par stéréoscopie avec les hauteurs de voûte dérivées des précédentes études. Ainsi, dans le contexte de suivi de la forêt amazonienne au Brésil, ces résultats démontrent le potentiel de cette méthode, fondée sur la géométrie de la stéréoscopie radar, comme outil complémentaire aux méthodes traditionnelles fondées seulement sur la radiométrie.

1 INTRODUCTION

The forest biome is studied intensively because of its importance in the carbon cycle, for its uptake and release of CO_2, and as an input parameter for climate and global modeling. Furthermore, there are strong anthropogenic influences among the different environmental parameters such as pollution, logging, fires, etc. (Wegmüller and Werner, 1995). The tropical forests represent 80 to 90% of the terrestrial biomass, and 35% of this forest is in Brazil. Logging, recent permanent or semi-permanent settlement and other human activities have differently affected large forested areas. Since the Amazon forest has 60-70% of the renewable and non-renewable resources of Brazil, the forest condition has to be assessed not only for ecological reasons, but also for economic reasons. In fact, large areas of dense tropical forest have trees of high commercial value. For both these reasons, there is a strong need to monitor the deforested and regenerated areas of the Amazon forest on a regular basis.

Remote sensing provides the means to collect information repeatedly on a regional or global scale, particularly in remote areas where monitoring vegetation changes and forest preservation are a challenge. Radar sensors are very suitable for regions where near-perpetual cloud cover limits monitoring on a regular basis with optical sensors.

Interpretation of SAR images is not as straightforward as for optical images because of the complex interaction between the electromagnetic wave and the target. Due to the image noise caused by coherent effect (speckle), overlapping of signatures for different land classes and the strong effect of local topography, forest mapping has been found to be quite difficult (van der Sanden, 1997). Tropical forest canopy can be discriminated from new deforested areas using radar backscatter, mainly when the vegetation is strongly related to geomorphology (Shimabukuro *et al.*, 1998). They found more difficulty in discriminating forest and regenerated areas. Contextual and textural information has been useful in eliminating mis-classification since canopy roughness is identified as an indicator of tree species (Oldeman, 1983). Van der Sanden (1997) confirmed that texture, such as the grey level co-occurrence (GLCO) textural descriptor, is a better source of information for identifying tropical land cover types than radar backscatter, but only with high-resolution radar images. However, the classification potential associated with different GLCO attributes varies widely since texture confusion can also occur between smooth canopy forest types (secondary and regenerated forest) and non-forested types (van der Sanden and Hoekman, 1999).

These research studies used only the radiometric aspects of SAR images. The third dimension (3D) based on geometric aspects enhances the ability to interpret two-dimensional (2D) imagery. The naturalness of 3D representation has major advantages in perceiving and extracting physical information when compared to flat 2D representation because it incorporates geometric aspects in addition to radiometric aspects (Bemis *et al.*, 1988). It also supplies important information about the relationship between land shape and structure, slopes and waterways, surface and vegetative growth. Furthermore, it enables the extraction of quantitative values for canopy heights, which is usually the most powerful variable for diameter or volume estimation (Dempster and Scott, 1979). It is therefore critical in an inventory project.

Under a national deforestation project known as PRODES, the National Institute for Space Research (INPE) of Brazil and IBAMA (Environment and Natural Renewable Resources Brazilian Institute) developed a research project in the Tapajós National Forest region for evaluating a forest inventory method based on a multiple stage sampling system (Hernandez Filho *et al.*, 1993). INPE and the Canada Centre for Remote Sensing (CCRS) initiated the ProRADAR project to assess the potential of RADARSAT data to provide reliable information about the Amazon forest environment (Amaral *et al.*, 1996; Shimabukuro *et al.*, 1998). Since RADARSAT's synthetic aperture radar (SAR) offers a variety of stereoscopic configurations of a given location that are very different in terms of radiometry and geometry, it enables us to take advantage of the 3D representation with various SAR stereo-pairs. Consequently, another objective related to the stereo capabilities of RADARSAT has been added to ProRADAR to evaluate the complementary aspects of the radar stereo geometry.

The objectives of this study are first to give a background on methods to extract 3D information from different data sources, mainly for specific targets. It further investigates the feasibility and the potential of the stereoscopic capabilities of RADARSAT using radargrammetric techniques for target elevation extraction. A geometric-based method was then developed to interpret and extract geophysical information of the Amazon tropical forest, taking into consideration the objectives and needs of deforestation mapping in a Brazilian context. Discrimination of forested and non-forested areas was first done qualitatively, and quantitative canopy height measurements were calculated from stereo RADARSAT fine mode images. Finally the study results were evaluated using a previously ortho-rectified Landsat-TM image (Amaral *et al.*, 1996) and an existing vegetation map (Projeto RADAMBRASIL, 1976).

2 BACKGROUND

Since the 60's investigators have been developing successful methods and systems for acquiring and analyzing large to medium scale photographs for forest inventory purposes. In the 70's color infrared photographs were used for interpreting stand characteristics with 6m height classes (Dempster and Scott, 1979). General coverage panchromatic photos at a scale of 1:50 000 to 1:20 000 have also been used to estimate stand height to within 5 m using a traditional stereo-plotter, provided that crown openings permit a view of the ground.

Individual trees in a stand can be measured on the ground or on a large-scale photo (1:1 000 to 1:4 000) within 2 m with 95% confidence (Aldred and Lowe, 1978). But Jano (1979) indicated that there is a general tendency to overestimate heights by as much as 4 m. This overestimation is also dependent on the species and its height. He also noticed that distortion due to a small base-to-height ratio has a serious effect on the accuracy of model height measurements. In an analysis of an aerial photography system designed for large-scale forest inventory, Spencer (1987) also confirmed there is still scepticism about the accuracy potential of photogrammetric methods.

Gagnon and Agnard (1989) clarified important uncertainties relative to these effects of the small base-to-height ratio and of the deviations of the orientation parameters. They investigated the system developed by Rivest (1980): twin-camera 70 x 70 mm photography taken with 100-mm focal length Hasselblad camera from a helicopter with a 10-m fixed-based boom-mounted transverse to the line of flight. Their theoretical analysis indicated that with a second order stereo-plotter (Wild B8 type), the cumulative effect of all the factors gives an accuracy superior to 0.3 m for a 10-m tree. In fact, later tests using helicopter 1: 1 100 colour photographs from the Rivest's system processed on a PC-based softcopy stereo-workstation, the Digital Video Plotter (DVP), have shown a tree height accuracy of less than 0.5 m depending on the photo digitizing resolution (Gagnon *et al.*, 1993).

The detection of objects and the determination of their height by shadow structure have also been successfully performed with image processing: Huertas and Nevatia (1988) used edge detection techniques to identify buildings on aerial photos. The difficulties related to shadow identification were due in part to the poor contrast and texture, but mainly to the small size of buildings and their high density. Hartl and Cheng (1995) used a statistical analysis of grey values on a SPOT image, with the image characteristics and the digitized map of the buildings to determine building heights and the building heights' distribution. They also reported that the main factors leading to error are the high building density and the overlap of the grey value distribution between shadow and other objects such as trees/bushes. These factors should further reduce the feasibility of measuring canopy heights in a forest with optical data.

To our knowledge, no attempt has been made to use radarclinometry for object height measurement. However the potential of SAR interferometric signatures for land use classification has been demonstrated with ERS-1 SAR repeat-pass data (Wegmüller and Werner, 1995). The interferometric correlation over forested areas was found to be significantly lower than over open canopies, small vegetation, bare soils and urban areas. The results strongly support deforestation studies, forest mapping and monitoring since it was possible not only to distinguish coniferous, deciduous and mixed forest stands, but also regrowth and clear-cut areas. Furthermore, the interferometric height discontinuity at the forest to open field boundary shows good agreement with *in-situ* canopy height measurements for a dense boreal forest during the wintertime (Hagberg *et al.*, 1995). The good coherence obtained is a result of the stiffness of the branches on the top of the Scandinavian boreal forest. Other types of forest will probably have different responses to wind. They also noticed increased sensitivity of the degree of coherence to other environmental parameters (temperature, precipitation, snowfall and soil moisture change).

One solution to overcome the difficulties related to these environmental parameters is to use single pass interferometry. Some experiments have been performed with the CCRS airborne dual antenna C-band SAR system over the Petawawa Forest, Canada. Preliminary results achieved so far show good consistency with actual heights, on the order of 1m (Leckie *et al.*, 1999).

Since the stereo photogrammetric techniques are the most frequent and successful techniques used by the forest community in an operational environment, our research interests were to evaluate how these techniques can be applied to stereo RADARSAT images and what planimetric and altimetric accuracy can be expected. Since scattering by the crown layer dominates the general back-scattering coefficient at C-band (Dobson et al., 1992), and the canopy mimics the terrain quite well, dense and homogenous forests, such as the Amazon forests are good candidates for investigation of RADARSAT stereo capabilities for forest mapping.

3 STUDY SITE AND DATA SET

The study site is located in the Amazon forest in Brazil and comprises the Tapajós National Forest and its surroundings (Figure 1), that several investigators have already studied (Projeto RADAMBRASIL, 1976; Caillez, 1977). The Tapajós National Forest is located south of the Santarém City in Pará State, Brazil. Restricted to the overlapping area between RADARSAT Fine Mode images, it ranges from 55° 05’ W to 54° 48’ W in longitude, and from 02° 55’ S to 03° 10’ S in latitude.

The rainy season occurs from February to May, mainly during March (358 mm) and April (361.9 mm), and the dry season goes from August to November, when monthly precipitation is less than 4% of the year amount. Temperature ranges from 20°C to 35°C, with the lowest temperatures during the rain season (Hernandez Filho *et al.*, 1993).

Two morphostructural units characterize the geomorphology of the region: the Amazon Debased Plateau, with altimetric values of about 100 m, and the Tapajós-Xingu Plateau with altimetry varying from 120 m to 170 m. Based on geomorphological, physiognomic and botanical characteristics, the Tapajós National Forest can be divided into sub-areas:

1. the Amazon low plateau, which can be sub-divided into:

- Low Plateau Ecosystems, occurring in low terrain, low slope, and clay texture predominant soils. A few economic wood species can be found;
- Low Dissected Plateau Ecosystems, having an accentuate relief with dissected and narrow valleys, and medium texture soils. Lianas and palm species are frequent.

2. the Xingu and Tapajós rivers high plateau, which is characterized by a tropical dense forest with economic high value species.

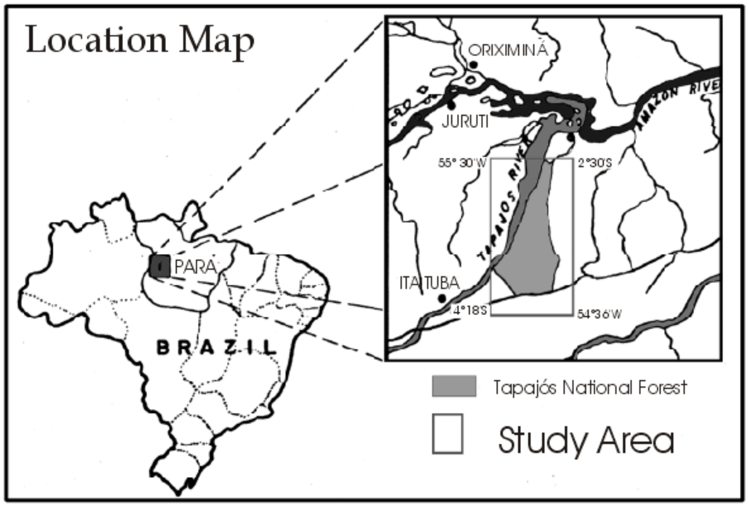

Figure 1. Study area localization of Tapajós National Forest in Brazil.

The vegetation types of the Tapajós National Forest have been divided into 17 classes and the predominant tree species of each class have been classified (Projeto RADAMBRASIL, 1976; Shimabukuro *et al.*, 1998). Although no specific canopy height measurements have been done *in situ*, the canopy height for a primary mature forest is known with a fairly good estimation from the predominant tree species in the class (Jacobs *et al.*, 1988). Furthermore, according to Hoekman and van der Sanden (1987), the canopy heights vary from 10 to 25 m, with trees reaching up to 30-40 m in a plot over the Tapajós river high plateau, while trees in another plot over the low plateau range from 10 to 20 m.

Human activity is increasing in the region. Several areas affected by this human activity border the Tapajós National Forest with undisturbed forest. For example, an intensive deforestation activity took place along the Cuiabá-Santarém Road (BR-163), and some agricultural and pasture land areas can be observed within the Tapajós Forest boundaries. Since the deforested areas are used for a variety of crops for a period of a few years (5 and more), most are in a stage of regeneration to provide nutrients for the next cropping cycle (Shimabukuro *et al.*, 1998). These points are important when analyzing multi-date images.

The remote sensing data consist of two RADARSAT-SAR data and one Landsat-TM image. The RADARSAT-SAR images (C-band, HH-polarization) were acquired from descending paths in fine mode with beams 5 (45^o-48^o incidence angle) and 2 (39^o-42^o incidence angle), on May 3 and May 20, 1996 respectively. The SAR has a resolution of

8.0 m in range by 8.4 m in azimuth. The F2 and F5 images were generated in 16-bit ground range format with a 6.25-m and 3.125-m pixel spacing, respectively. No radiometric processing was applied. Figure 2 is a sub-area of the F5 RADARSAT image over the study site for the stereo extraction of the clearings and of the canopy heights. These images formed a stereo-pair with an intersection angle of less than 6^o over the full stereo-model. Figure 3 is an example of the stereo-pair at full resolution: F2 on the left and F5 on the right.

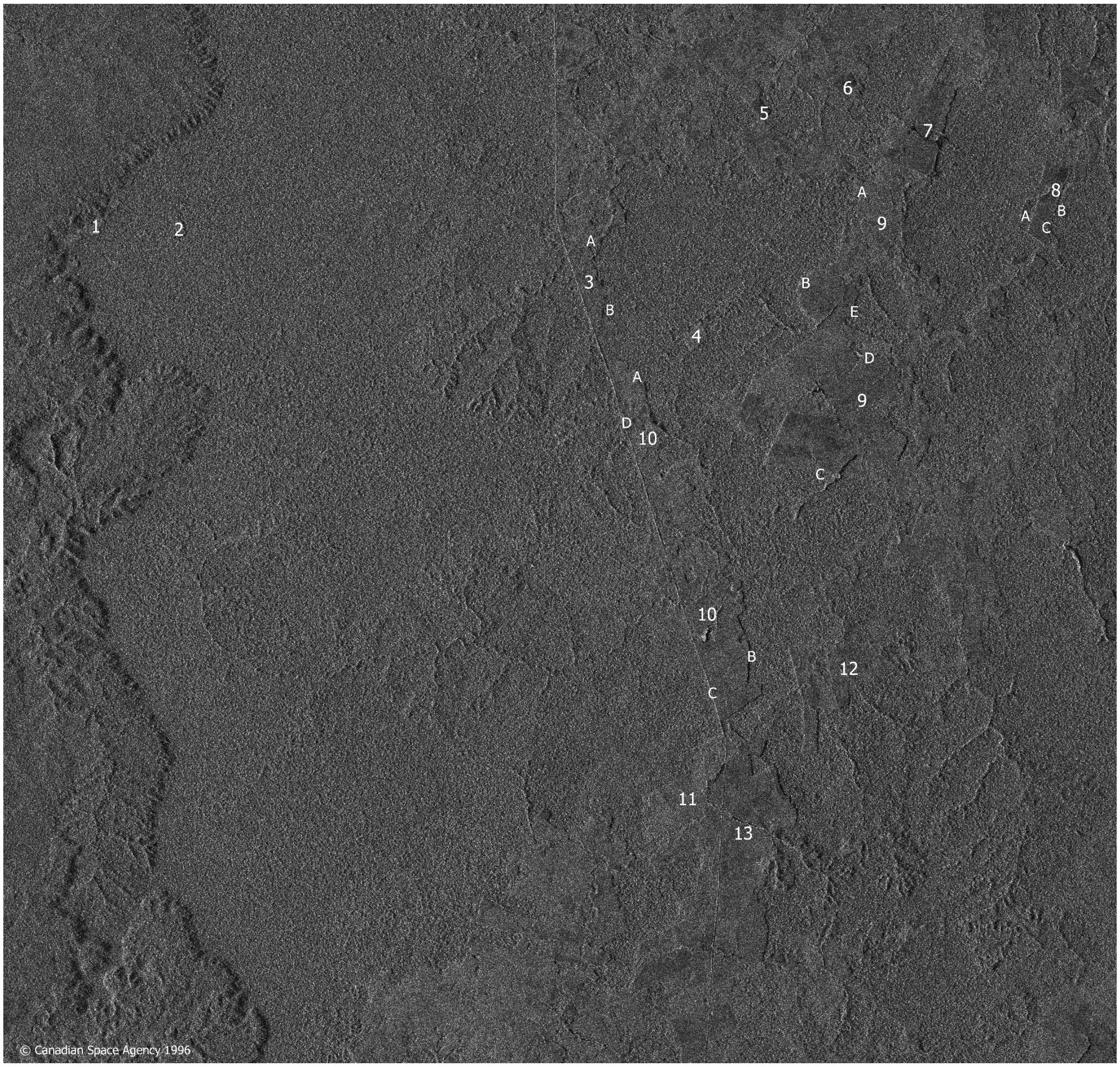

Figure 2: F5 RADARSAT sub-image (4200 pixels by 4000 lines; 3.125-m pixel spacing) over the study site with the identification of the 13 clearings (1 to 13) and sub-areas (A to E). RADARSAT image © Canadian Space Agency, 1996.

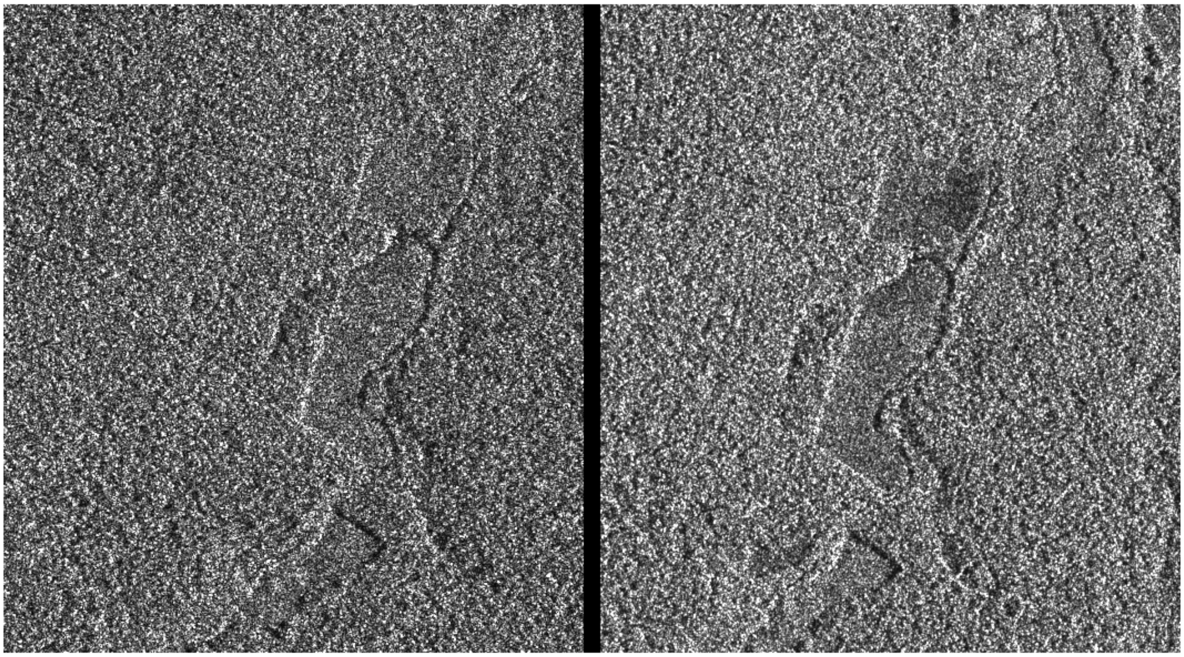

Figure 3: Sub-area of the RADARSAT stereo-images (500 pixels by 600 lines each; 6.25 m pixel spacing) from descending orbits: F2 on the left and F5 on the right. The largest clearing in the centre is the clearing no. 8 (Fig. 2), in which sub-areas were difficult to interpret without stereoscopic capability. RADARSAT images © Canadian Space Agency, 1996.

Previous studies on elevation extraction from stereo RADARSAT images show that an intersection angle of about 6^o-8^o is sufficient, and there is little improvement with larger intersection angles (Sylvander *et al.*, 1997; Toutin, 1998). In fact, the greater the variation between two viewing angles, the more the quality of the stereoscopic fusion deteriorated. This cancels out the advantage obtained from the better stereo viewing geometry.

The Landsat-TM image (WRS-227/62) was acquired on August 7th, 1995 and ortho-rectified in a previous project (Amaral *et al.*, 1996). The ground control points (GCPs) were obtained from a 1:100 000 topographic map, and the DEM for the Tapajós region was generated from every five 10-m isolines and interpolated through linear scaling of the triangular irregular grid to compose a 30-m regular grid. Bands 3, 4 and 5 of the Landsat-TM were thus ortho-rectified with the DEM using the integrated and unified geometrical modeling method and software developed at CCRS (Toutin, 1995a). The ortho-image accuracy was estimated to be about 20-25 m, due mainly to the GCP co-ordinate accuracy (Amaral *et al.*, 1996).

4. STEREO PROCESSING

The softcopy stereo workstation, the DVP, used in the data processing was based on a standard personal computer. It was originally developed at Laval University (Quebec, Canada) to process aerial photographs (Gagnon *et al.*, 1990), and subsequently adapted at CCRS to process VIR and SAR data (Toutin, 1995b). The stereo viewing is related to conventional photogrammetric viewing with a split screen method and a simple mirror stereoscope. Further details about the system and the stereo extraction method can be found in Toutin (1995b).

The digital data were first transferred to the DVP: it includes the SAR images linearly stretched on 8 bits, their geometric description (line, pixel number and spacing), the SAR parameters (look angles and direction, resolution), the satellite parameters (position, velocity) and the Earth parameters (semi-major axis, eccentricity). They were used to initialize the geometric modeling. The F5 image was also resampled at 6.25 m using a cubic convolution kernel with a 3 by 3 pixel window to allow stereo viewing with the F2 image (Figure 3).

Twenty GCPs distributed in the full stereo model were plotted in stereoscopy with an accuracy of about two pixels. The GCP cartographic coordinates were obtained from the 1:100 000 topographic maps with a planimetric accuracy of 50 m and an elevation accuracy of 10 m, due to the poor quality of the map. The elevation varied between 10 m and 520 m. Furthermore, 14 tie points, without known cartographic coordinates, were also stereo-plotted and were used to reinforce the stereo-geometry when GCPs were not available.

Using the GCPs and tie points, an iterative least square bundle adjustment was performed to refine the geometric modeling parameters initialized in the first step. The *a-priori* stereo mapping accuracy relative to the map was reported as with the residuals of the least square bundle adjustment: 16 m, 18 m and 27 m in the X, Y, and Z directions, respectively. These GCP residuals were mainly due to the accuracy of the planimetric co-ordinates. However, this geometric modeling has already proven to be robust and consistent over the full stereo-pair without local or systematic errors, and served as an indicator of restitution accuracy (Toutin, 1995a, 1995b).

As a result, the stereo-model was directly generated from the raw images without any resampling in a quasi-epipolar geometry. It does not degrade the radiometry of the image, the stereo interpretation and the extraction of the information. Image positioning control then follows the dynamic change to cancel the Y-parallax from the raw imagery, and retains real time performance in the stereo viewing and plotting. When the operator cancels the X-parallax to fuse the two floating marks of the measured point, a 3-D stereo-intersection is performed. Cartographic co-ordinates (planimetry and height) in the user-defined map projection system are determined in real time for the measured point using a least square intersection process based on the equations and parameters of the geometric modeling (Toutin, 1995b).

5. EXPERIMENT

5.1 Stereo-extraction

The extraction and measurement process was accomplished in two steps. The first step was qualitative and based on with visual and interactive interpretation. Figure 2 displays the 13 identified clearings. By combining the radiometric image content of both images and the depth perception in the stereo-model, the operator stereoscopically and interactively digitized 13 clearing borders. Inside four of them, sub-areas (3A, 3B, 8A to 8C, 9A to 9E, 10A to 10D) were also delimited (Figure 2). Some clearings and most of the sub-areas were impossible to interpret and extract in a single image without depth perception. Figure 3 shows the advantage of stereoscopy for the clearing #8 with its three sub-areas.

The second step deals with quantitative aspects. Since the stereo-model was oriented in the user map projection system, orientation, distance, surface, volume, or elevation variation can be computed directly from the stereo-pair measurements (X, Y and Z). The determination of the canopy height was then possible by computing the elevation difference between clearings and forest. Stereo measurements (more than 460) of elevation at the forest canopy and clearing level were performed on both sides of the borders for each clearing and sub-clearing. Each elevation was measured three times to reduce the plotting elevation error. A first validation of the clearing elevation was directly done with the topographic map 10-m contour lines, and shows consistent values.

Assuming a dense and even-canopy height forest, the difference in elevation between the measurements at the canopy and clearing level was considered representative of the canopy height “of this clearing” when the clearing was small, and the canopy height at the border of the clearing was perceived the same. If not, the clearing was subdivided in sub-areas, such as clearings no. 3, 8, 9, 10 (Figure 2). To compute the canopy height, two solutions were considered:

1. If the clearing or sub-clearing was perceived horizontal, the canopy height of this clearing or sub-clearing was computed from the difference of the means between all elevation stereo-measurements outside (Z_{canopy}) and inside ($Z_{clearing}$) the clearing, respectively.

$$h_{canopy} = \frac{1}{n}\sum_{1}^{n} Z_{canopy} - \frac{1}{m}\sum_{1}^{m} Z_{clearing}$$

Equation 1

2. If the clearing was not perceived horizontal, the canopy height of this clearing was computed from the mean of the difference between a pair of two close-elevation stereo-measurements outside (Z_{canopy}) and inside ($Z_{clearing}$) the clearing.

$$h_{canopy} = \frac{1}{p}\sum_{1}^{p}\left(Z_{canopy} - Z_{clearing}\right)$$

Equation 2

For both equations, h_{canopy} was the canopy height; Z_{canopy} and $Z_{clearing}$ represented the measurements of the forest canopy and clearing elevation, respectively; n and m were the number of elevation stereo-measurements outside and inside the clearing, respectively; p was the number of the elevation stereo-measurement pair.

5.2 Validation of the stereo measurements

Unfortunately, there was no ground truth available in this remote area specific to the objectives related to the stereo capabilities of RADARSAT for extracting qualitative and quantitative 3D information. However, the vegetation in this area is well known (Projeto RADAMBRASIL, 1976; Caillez, 1977; Hernandez Filho *et al.*, 1993; Amaral *et al.*, 1996) The validation of the results was performed in two steps using these previous research studies and results with their ground evaluation:

1. for the clearing boundary positioning and their 3D interpretation; and
2. for the canopy height measurements.

The clearing boundaries were first transferred onto the ortho-rectified Landsat-TM as they have the same map reference system (Figure 4). In general, there was a relatively good superposition of the extracted boundaries with the Landsat-TM taking into account the input cartographic data accuracy (25 m); and a general planimetric error of one pixel (about 30 m) was measured. Some larger errors (about a hundred metres) can be noticed in the sub-clearings 9C, 9D, in the southern part of the clearing 11 and in the eastern part of the clearing 12. The cartographic data can be only accounted for a small part of these errors. The other potential sources of errors, which were also cumulative, included:

- the deforestation and some regeneration during the one-year difference in the image acquisition dates;
- the dominant scattering regime (direct, double-bounce, volume) between the transmitted C-band radar wave and the target (ground or forest); and
- the mis-interpretation of the SAR backscatter by the operator, who was a specialist in stereo viewing and plotting but not in SAR forest interpretation.

As mentioned in the Introduction, the effects of the two last points have been noticed by Shimabukuro *et al.* (1998) when the vegetation was not strongly related to geomorphology, such as in this "relatively flat" study site, and by van der Sanden (1997) for discriminating forest and regenerated forest form the SAR backscatter. However, in the context of PRODES, where clearings smaller than 6.25 ha are not mapped (INPE/IBAMA, 1998) these general and maximum errors can be considered acceptable.

For the 3D-interpretation evaluation, the land use types identified by Amaral *et al.* (1996) were based on visual interpretation of the Landsat-TM ortho-image. In relation to the classes defined in Projeto RADAMBRASIL (1976) a more simple class graduation of the vegetation content from bare soil to primary forest was defined for this experiment:

- Bare soil was without vegetation cover;
- Overgrown pasture and pasture referred to areas where some bushes and woody species occurred;
- Regeneration was the cover type between overgrown pasture and secondary forest, where there was a homogeneous woody cover, but it did not have the same forest structure;
- Secondary forest represented clearings that were abandoned a long time ago, and represented a cover type very similar to the original forest, but it could still be discriminated from primary forest;
- Disturbed forest is related to original forest with small clear-cut occurrences; and
- Primary forest was the original forest.

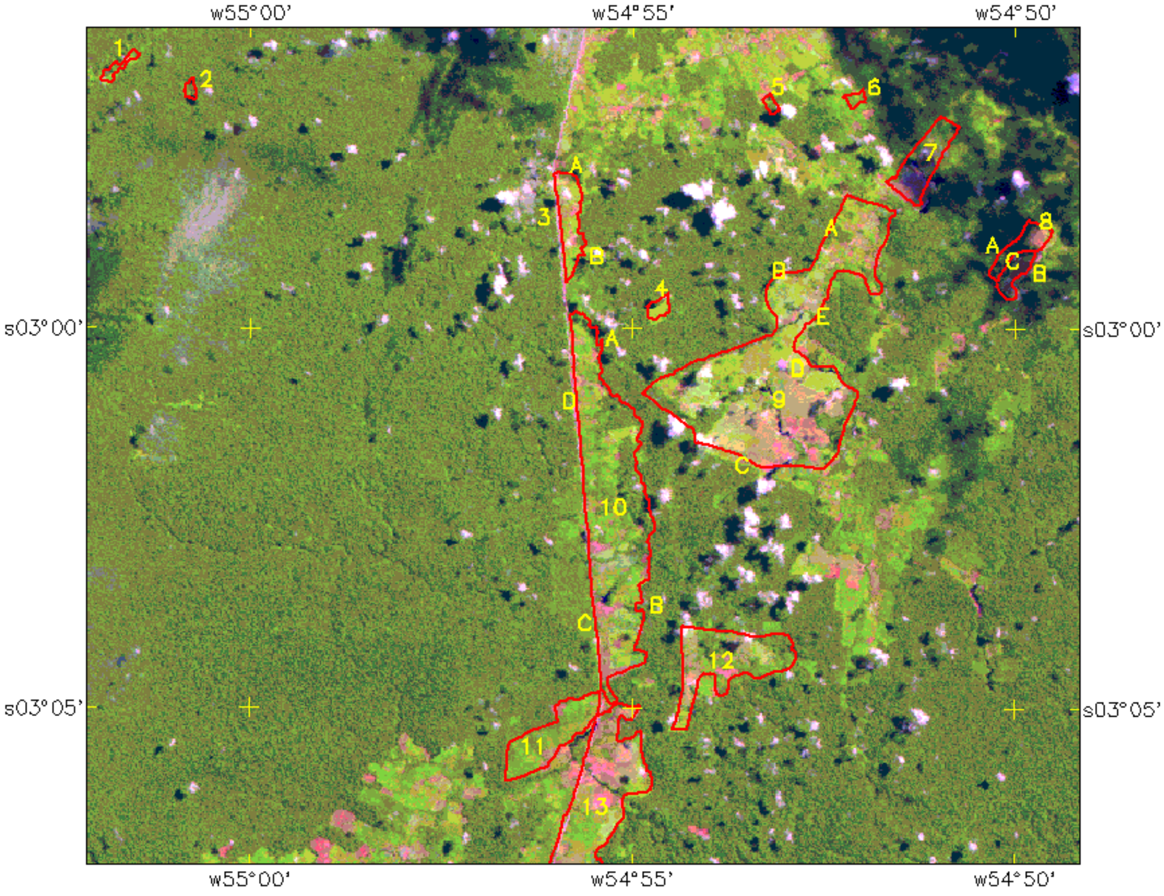

Figure 4: Clearings (1 to 13) boundaries and sub-areas (A, B, etc.) plotted from RADARSAT SAR stereo-images and overlaid over the Landsat-TM ortho-image.

Table 1 shows the combined results of the elevation stereo measurements inside and outside the clearing boundaries, the canopy height computation and the "expected" canopy height with the land cover classification inside and outside of each clearing. It enables a comparison between the canopy heights and the knowledge of the predominant tree species for each class. The "expected" canopy heights were approximated from the evaluation based on previous studies: about 30 m for the primary forest with emergent trees up to 40 m, and 15 to 20 m for the disturbed and secondary forests (Projeto RADAMBRASIL, 1976; van der Sanden and Hoekman, 1999). Since the overgrown pasture (bush and woody species) height was unknown, the "expected" canopy heights (values in brackets) with this cover type were less accurate. Figure 5 is a scatter plot of the canopy height computation for the different land use classes inside the clearing edges.

Table 1: Results summary of the elevation stereo-measurements, the height differences, the "expected" height differences based on previous studies (in metres) and the land cover type inside and outside the clearing edges. The values in brackets were less precise since the overgrown pasture height was unknown.

Clearing Number	**Clearing Elevation**	**Forest Elevation**	**Height Diff.**	**"Exp." Height**	**Cover type inside**	**Cover type outside**
1	152	164	12	10-15	regeneration	forest
2	136	155	19	(< 30)	overgrown pasture	forest
3 A	136	145	9	(< 15)	overgrown pasture	disturbed forest
B	133	152	19	(< 30)	overgrown pasture	forest
4	183	194	11	10-15	regeneration	forest
5	233	251	18	15-20	bare soil	disturbed forest
6	292	306	14	15-20	bare soil	disturbed forest
7	278	306	28	30	bare soil	forest
8 A	204	216	12	10-15	secondary forest	forest
B	189	217	28	30	bare soil	forest
C	188	201	13	15-20	bare soil	secondary forest
9 A	155	177	22	(< 30)	overgrown pasture	forest
B	154	177	23	(< 30)	overgrown pasture	forest
C	167	184	17	15-20	bare soil	disturbed forest
D	153	165	12	(<15)	pasture	disturbed forest
E	164	177	13	(< 30)	pasture	forest
10 A	110	138	28	(< 30)	overgrown pasture	forest
B	92	138	46	(< 30)	overgrown pasture	forest
C	94	137	43	15-20	bare soil	secondary forest
D	116	140	24	(< 30)	overgrown pasture	forest
11	87	133	46	(< 30)	overgrown pasture	forest
12	94	132	38	(< 30)	overgrown pasture	forest
13	89	141	47	(< 30)	pasture	forest

The computed canopy heights were generally close (around 5 m) to the expected canopy heights. They were then fairly good representative values of the existing canopy heights of the secondary and primary forest in this Amazon area. Some larger discrepancies in the result comparisons (e.g., 3B and 9E) were related to the pasture cover type, due to the uncertainty of the bushes and woody species height. However, the results with this cover type were consistent because all the computed values were less than the "expected" values, which were "over-evaluated".

Figure 5 is a scattergram showing the canopy height differences (ΔZ in metres) between the cover types outside and inside the clearing edges for the different clearings (1 to 13) and sub-areas (A to E). The X-axis represents the cover type inside the clearing edges (bare soil, overgrown pasture, regenerated and secondary forest). The triangles, squares and circles represent the cover types outside the clearing edges: the secondary, disturbed and primary forests, respectively. With some exceptions, the different symbols were generally well grouped around the expected height difference values:

1. the areas 5, 6, 8C and 9C have height differences around 15-17 m (secondary and disturbed forest versus bare soil);
2. the areas 2, 3B, 9A, 9B and 10D around 20-25 m (primary forest versus overgrown pasture);
3. the areas 1, 4 and 8A around 12 m (primary forest versus secondary forest), etc.

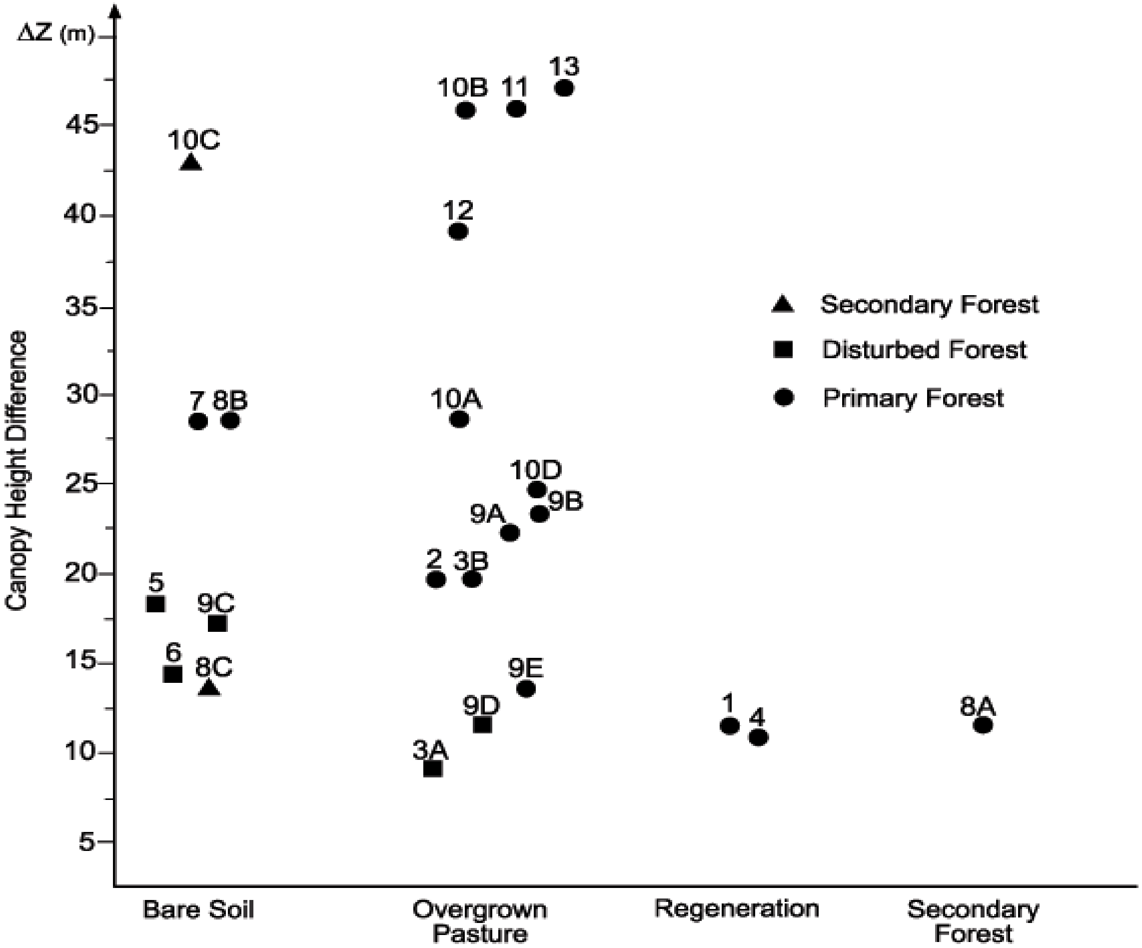

Figure 5: Scatter plot of the canopy height differences (ΔZ in metres) between the cover types outside and inside the clearing edges for the different clearings (1 to 13) and sub-areas (A to E). The X-axis represents the cover type inside the clearing edges. The triangles, squares and circles represent the cover types outside the clearing edges: the secondary, disturbed and primary forests, respectively.

Furthermore, boundaries between forest and bare soil represented higher height values than boundaries between forest and other land use with some vegetation cover, like overgrown pasture (5, 6, 9C, 9E versus 3A, 9D, 9E) or secondary forest (7, 8B versus 2, 3B, 9A or 1, 4, 8A). When the outside cover was different from forest, smaller heights were reported, suggesting consistency of the different measurements: 5, 6, 8C, 9C versus 7, 8B and 3A, 9D, 9E versus 2, 3B, 9A, 9B.

The exceptions (clearly noticeable in Figure 5) were for heights greater than 40 m (e.g., clearings 10B, 10C, 11 and 13). Although emergent trees of about 40 m have been reported, they were not grouped in a specific area, and there was no field description of emergent trees around 45 m (Projeto RADAMBRASIL, 1976). Deforestation inside the clearings, which could have one reason for height over-estimations, have not been noticed on these areas since the cover types inside the clearings were already bare soil or overgrown pasture in 1995. Furthermore, it was not a problem of planimetric positioning since these clearings were well overlaid onto the Landsat-TM ortho-image (Figure 4). Since these exceptions were grouped into the lower part of the stereo-model (Figure 2) there were two potential explanations for the systematic errors (about 5-10 m) in these clearings:

- The difficulty of finding a GCP to avoid extrapolation in this lower part of the stereo-model has forced the acquisition of a less accurate point for the stereo-model computation, resulting in a larger elevation error; or

- Because of a small base-to-height ratio of the same side stereo-pair, a differential Y-tilt error produced a serious effect on the accuracy of model height measurement by distortion of the image base, which could result in an over-estimation of the canopy height (Jano, 1979).

The first reason seems to be the most likely because: (i) only clearings (or sub-clearings) in this lower part (even clearing no. 12 with 38 m) have the less realistic height values; and (ii) the clearing measurements in the upper part of the stereo-model do not seem to be over-estimated by such height magnitudes (10 m).

Other forest types (boreal) with less dense canopy (immature, different age, non-homogenous, etc.) would change the dominant scattering regime due to more inter-action with trunks and ground, and the stereo measurements would not be representative of the canopy height.

6 CONCLUSIONS

Stereo SAR imagery can be a complementary approach to extract information by combining the radiometric content of both images and the depth perception of the stereo pair. This advantage is much enhanced when no elevation data are available to geocode the images. Planimetric and altimetric features can be extracted in the stereo-model, on a softcopy stereo workstation, since it provides a virtual 3D perception of the terrain.

This paper showed results of data extraction from RADARSAT-SAR fine mode stereo pair images (F2 and F5) with a 6°-intersection angle over a forest test site in the Tapajós National Forest, Brazil. Clearings and sub-clearings were first qualitatively identified and delimited using visual stereo interpretation on the PC-based softcopy stereo workstation, DVP. It allowed discrimination of different bare soils or overgrown pastures, and regenerated, secondary, disturbed or primary forests.

The clearing boundaries were overlaid onto a previously ortho-rectified Landsat-TM image (20-25 m accuracy) for validation. The positioning error of boundaries was evaluated to be about 30 m with maximum errors of a hundred metres in specific areas. These larger errors were mainly due to cartographic data errors, the deforestation and regeneration between image acquisition dates, the dominant scattering regime, and the mis-interpretation of SAR backscatter. However, these errors do not have an impact on the deforestation mapping in Brazil since clearings less than 6.5 ha are not mapped. For countries where the forest inventory standard is higher, it could be a limitation in the applicability of the method.

Elevation stereo-measurements were performed to compute the canopy height for each clearing and sub-clearing. For about 85% of the results, the canopy heights vary from 12 m to 38 m. Based on previous studies of different tree species and their characteristics in the Tapajós National Forest, it can be concluded that the canopy height computations are fairly good estimation values of the cover types. These results are sufficiently accurate for use in the context of the national Brazilian deforestation project. A less dense non-homogenous forest would not be a good candidate for this method because the stereo measurements would not be representative of the canopy height due to more interactions of the radar with trunks and ground.

Although specific *in-situ* canopy height measurements should confirm and emphasize these results, the defined method, based on the geometric aspects of SAR stereo images, indicates the potential of RADARSAT stereo plotting as a useful tool to detect and measure differences in vegetation cover height and, consequently, in vegetation cover type. In the future, it may be used in conjunction with traditional methods using SAR backscatter for forest inventory and monitoring.

ACKNOWLEDGMENTS

This research is part of the PRORADAR project from INPE of Brazil and CCRS of Canada. It was partially supported by the Canadian International Agency (CIDA). The Canadian Space Agency provided the RADARSAT data for this research under the ADRO program of the Canadian Space Agency. The authors thank Dr. Frank Ahern, Robert

Landry of CCRS for their useful comments. The authors would like also to thank Ms. Liyuan Wu of Consultants TGIS Inc. for the stereo-measurements.

REFERENCES

Aldred, A. H. and J. J. Lowe, 1978. "Application of Large Scale Photo to a Forest Inventory in Alberta", *Forest Management Institute, Information Report FMR-X-107, Environment Canada,* 57 pages.

Amaral, S., Y.E. Shimabukuro, Th. Toutin and F. Ahern, 1996. "Sensoriamento Remoto por Radar (SAR): Pré-processamento de imagens RADARSAT ("Fine mode") na região da Floresta Nacional do Tapajós", *Proceedings of Primeras Jornadas Latinoamericanas de Percepción Remota por Radar: Técnicas de Procesamiento de Imágenes*, *(ESA/SP-407),* Buenos Aires, Argentina, December 2 a 4, pp. 37-42.

Bemis, S. W., J. L. Leeds and E. A. Winer, 1988. "Operator Performance as a Function of Type of Display: Conventional versus Perspective", *Human Factors*, Vol. 30, pp. 162-169.

Caillez, F. 1977, «Inventaire de préinvestment de la Forêt National de Tapags : Evaluation provisoire des résultats», *Brasìlia.* (PNUD/FAO/IBDF/BRA-76/027)

Dempster, W. R. and C. A. Scott, 1979. "A Multilevel Approach to Acquiring Resource Data for Timber Management Planning", *Proceedings of the Workshop "Practical Applications of Remote Sensing to Timber Inventory",* Edmonton, Alberta, Canada, Sept. 26-28 th, pp. 127-137.

Dobson, M. C., L. Pierce, K. Sarabandi, F. T. Ulaby and T. Sharik, 1992. "Preliminary Analysis of ERS-1 SAR Processing for Forest ecosystem Studies", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 30, No. 2, pp. 203-211.

Gagnon, P.-A., J.-P. Agnard and C. Nolette, 1993. "Evaluation of a soft-copy photogrammetric system for tree-plot measurements", *Canadian Journal of Forest Research*, Vol. 23, No. 9, pp. 1781-1785.

Gagnon, P.-A., J.-P. Agnard, C. Nolette and M. Boulianne, 1990. "A Microcomputer-based General Photogrammetric System", *Photogrammetric Engineering & Remote Sensing*, Vol. 56, No. 5, pp. 623-625.

Gagnon, P.-A. and J.-P. Agnard, 1989. "Twin-camera fixed-base photography of Tree Plots: Possibilities and accuracy of a System", *Canadian Journal of Forest Research*, Vol. 19, No. 4, pp. 860-864.

Hagberg, J., L. M. Ulander and J. Askne, 1995. "Repeat-Pass Interferometry over Forested Terrain", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 33, No. 2, pp. 331-340.

Hartl, Ph. and F. Cheng, 1995. "Delimiting the Building Heights in a City from the Shadow on a Panchromatic SPOT Image: Part 2, Test on a Complete City", International Journal for Remote Sensing, Vol. 16, No 15, pp. 2829-2842.

Hernandez Filho, P., Y.E. Shimabukuro, D.C.L. Lee, C.P. Santos Filho and R.R. Almeida*,* 1993*. Final Report of the Forest Inventory Project at the Tapajós National Forest.* Projeto de Cooperação Técnica desenvolvido pelo INPE/IBAMA-FUNATURA/IITO, *INPE, São José dos Campos (INPE-5423-PRP-171).*

Hoekman, D.H. and J.J. van der Sanden, 1987. Ground truth data report of ESA/INPE Amazonian Expedition, Wageningen Agricultural University, The Netherlands. 38 pages.

Huertas, A. and R. Nevatia, 1988. "Detecting Building in Aerial Images", *Computer Vision, Graphics and Image Processing*, Vol. 46, pp. 131-152.

INPE/IBAMA, 1998. "Amazonia: Deforestation 1995-1997" Internal Report, 23 pages.

Jacobs, M., R. Kruk and R.A.A. Oldeman, 1988. "The Tropical Rain Forest: A First Encounter", Springer-Verlag, Berlin, 295 pages.

Jano, A., 1979. "Large Scale Photography for Forest Inventory: Problems and Limitations". *Proceedings of the Workshop "Practical Applications of Remote Sensing to Timber Inventory",* Edmonton, Alberta, Canada, Sept. 26-28th, pp. 52-57.

Leckie, D., D. Hill, L. Gray, K. Mattar and F. Montgomery, 1999. "Some Influence of Stand Characterisrics on the Surface Elevation of Forested Terrain Derived from C-Band Interferometric SAR Data". *Proceedings of Fourth International Airborne Remote Sensing Conference/21st Canadian Symposium on Remote Sensing,* Ottawa, Ontario, Canada, June 21-24, pp. II214-II223.

Oldeman, R.A.A., 1983. "Tropical Rain Forest, Architecture, Silvigenesis and Diversity" in: Sutton, S.L., T.C. Whitmore and A.C. Chadwick (Eds.). "Tropical Rain Forest: Ecology and Management", Oxford, UK, (Blackwell Scientific Publications), pp. 139-150.

Projeto RADAMBRASIL, 1976. Folha S/A 21 – Santarém, Rio de Janeiro, Brazil, DNPM 1976. (Levantamento dos Recursos Naturais, v.10).

Rivest, J.F., 1980. Nouveau procédé photodendrométrique appliqué à un inventaire forestier. La Cie internationale du papier du Canada, Division La Tuque, Québec.

Shimabukuro, Y.E., S. Amaral, F.J. Ahern and R.W. Pietsch, 1998. "Land Cover Classification from RADARSAT Data of the Tapajós National Forest, Brazil" *Canadian Journal of Remote Sensing*, Vol. 24, No. 4, pp. 393-401.

Spencer, R. D., 1987. "Large-scale aerial photographic systems for forest sampling in Canada", *Canadian Surveyor*, Vol. 41, No. 1, pp. 9-21.

Sylvander, S., D. Cousson et P. Gigord, 1997. « Etude des performances géométriques des images de RADARSAT », *Bulletin de la Société Française de Photogrammétrie et Télédétection*, Vol. 148, pp. 57-65.

Toutin, Th., 1995a. "Multisource data fusion with an integrated and unified geometric modeling". *EARSeL Journal "Advances in Remote Sensing"*, Vol. 4, No. 2, pp. 118-129.

Toutin, Th., 1995b. "Generating DEM from stereo images with a photogrammetric approach: examples with VIR and SAR data", *EARSeL Journal "Advances in Remote Sensing"*, Vol. 4, No. 2, pp. 110-117.

Toutin, Th., 1998. « Evaluation de la précision géométrique des images de RADARSAT», *Journal canadien de télédétection*, Vol. 24, No. 1, pp. 80-88.

van der Sanden, J.J. and D.H. Hoekman, 1999. "Potential of Airborne Radar to Support the Assessment of Land Cover in a Tropical Rain Forest Environment", *Remote Sensing of Environment*, Vol. 68, pp. 26-40.

van der Sanden, J.J., 1997. "Radar Remote Sensing to Support Tropical Forest Management", Doctoral Thesis, Wageningen Agricultural University, Wageningen, The Netherlands, Tropenbos-Guyana series 5, 330 pages.

Wegmüller, U. and Ch. Werner, 1995. "SAR Interferometric Signature of Forest", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 33, No. 2, pp. 1153-1161.