# An evaluation of C-Band radar to detect openings in moist tropical forests

by

F. J. Ahern
Canada Centre for Remote Sensing

H. J. H. Kux
Instituto Nacional de Pesquisas Espaciais (Brazil)

R. Salcedo
Ministerio del Ambiente y de los Recursos Naturales Renovables (Venezuela)

R. W. Pietsch
Dendron Resource Surveys, Ltd. (Canada)

**ABSTRACT**

Airborne and satellite SAR data sources which are currently or imminently available offer the possibility to monitor the status of moist tropical forests. In an effort to develop this area of applications, we have investigated the use of a number of C-band SAR data sources to detect openings in moist tropical forests. The smallest openings, typically 0.25 to 3 ha in size and are often associated with shifting cultivation, were reliably detected with 7-look airborne SAR with 6 m resolution in range and azimuth. Openings in the range 1 - 10 ha in area, associated with settlements in extractive reserves in Brazil were also reliably detected with the high resolution airborne data. These small openings were not visible on simulated or actual satellite SAR images with four looks and 25 to 30 m resolution.

Agricultural settlement projects typically create many contiguous openings which total 100 to 1000 ha or more in area. These were reliably detected with both airborne and satellite images. However, mapping of boundaries was found to be much more accurate with the higher resolution airborne data than with the actual and simulated satellite data.

Land clearing for cattle ranching creates large rectangular openings of 1000s of ha in size. These clearings were, in general, reliably detected and mapped with all of the data sources evaluated. However, detection and mapping with satellite SAR data is more difficult while the land is still in the process of conversion to pasture, and again when it is overgrown at an early stage of primary succession. Under these conditions, the average backscatter from the cleared land is often similar to that of the surrounding forest. This finding indicates that the most reliable mapping of clearings may be possible if radar data is acquired annually, to detect each pasture in its "clean pasture" stage when it has the highest contrast with its surroundings. There is a tendency to underestimate the area of clearings using SAR data alone. However, optical satellite data can be used to produce a regression model to remove much of this systematic error.

## 1. Introduction

In an environment characterized by the growth of moist tropical forests, the ability to map and monitor openings in the forest cover can be a valuable aid for resource management and environmental protection. Openings in tropical forests can be classified as either natural or anthropogenic, although it should be appreciated that some openings which are considered to be natural may be cases of unrecorded and unrecognized human activity.

Table 1 provides a partial list of the many types of information which can be inferred from a study of the size, shape, and changes in tropical forest openings, when their geographical context is included in the interpretation.

Human clearing of tropical rainforests has become a worldwide environmental concern, under the name of "tropical deforestation." Although there is agreement that very large areas of moist tropical forests are being cleared every year, there is a great deal of uncertainty about the area which remains permanently deforested, how much is converted to plantation forests, how much regenerates naturally, and of the latter, how much has the potential to return to its pre-clearing state.

Table 2 gives an example of how observations of the sizes, shapes, and temporal behavior of individual forest clearings can be used to infer their causes.

Once the cause of the clearing is identified, its land cover can often be inferred. The geographical context (e.g. local slope, soil type, proximity to streams and reservoirs, proximity to other clearings and uncleared areas) leads to information on vegetation type, productivity, biodiversity, erosion potential, slope stability, and other types of useful data.

The prospect of reliable, repetitive observation of tropical rainforests with synthetic aperture radars (SAR) on aircraft and satellites prompted us to investigate the use of C-Band SAR for monitoring the spatial and temporal changes to forest openings and clearings. This effort is a step toward enabling resource managers to use airborne and satellite radar data (available now or soon to be available) as a tool for monitoring the status of moist tropical forests. It was carried out as part of the South America Radar Experiment (SAREX), sponsored by the European Space Agency, and the Tropical Forest Initiative, sponsored by the Canada Centre for Remote Sensing and the Canadian International Development Agency.

## 2. Objective

The objective of this work was to investigate the use of a number of C-band synthetic aperture radar data sources for mapping cleared areas within otherwise continuous tropical rainforest. Two criteria were used to characterize mapping accuracy: errors in placement of boundaries, and errors in the areal measurement of clearings.

## 3. Background

Numerous studies, including some at C-band, have been made of the ability of SAR to provide information on the location, sizes, and shapes of forest clearings in temperate and northern latitude forests (see review by Werle, 1989a). Much less work has been done in moist tropical forests, and nearly none at C-band (see review by Ahern *et al.*, 1990). The SIR-A mission in 1981 provided a large amount of optically processed L-HH data over moist tropical forests. Werle (1989b) evaluated SIR-A images of tropical forests in Africa, South America, and Southeast Asia. He was able to identify and label clearings of many sizes and shapes on the image using tone, texture, shape, and context information. However, without an independent verification data source, it was impossible to estimate errors of omission and commission. The SIR-B mission in 1984 provided digitally processed L-HH data with a range of incidence angles. Ford and Casey (1988) were able to identify cleared areas in lowland rainforests. They were not able to discriminate any vegetation information in the mountainous interior, but there was no independent information on the presence or absence of clearings, so it remains unknown whether clearings were present and not detected, or simply not present.

At the onset of SAREX, the only experience with C-band in the tropics came from the ERS-1 sensor. Sökeland *et al.* (1992) evaluated two ERS-1 images of West Africa. In level terrain they were able to distinguish gallery forest from savannah grasslands, but unable to differentiate unbroken primary forest from a mosaic of small patches of grassland, agricultural clearings, primary forest, and secondary forest. In mountainous and undulating terrain, topographic effects dominated the radar backscatter and vegetation cover could not be assessed. Although their two images were only separated by 9 days, the authors noted a pronounced difference in the contrast between the gallery forest and savannah between the two images. This is a cause for concern, since there are no confirmed explanations for such a difference. Environmental factors, particularly rainfall, are suspected to be the cause of many such ephemeral effects in SAR data.

Such phenomena have been observed in SAR data of agricultural areas (Brisco *et al.*, 1993).

Since the mid 1980s, Intera Information Technologies has operated an X-HH airborne SAR with 6 x 6 m and 6 x 12 m resolution in narrow and wide modes, respectively. This instrument has been used in moist tropical forests in Australia (Lowry *et al.*, 1986), Costa Rica (Dams *et al.*, 1987), and Malaysia (Thompson and Dams, 1990). The authors have reported consistently good results in identifying and mapping clearings of a wide range of sizes, shapes and types, including areas of shifting cultivation down to 0.25 ha in size. They find that texture, the shadow at the near edge of a clearing and the bright return from the far edge provide good discrimination between forest and non-forest, even when tonal contrast is lacking. This is a particular benefit of the high spatial resolution of the airborne radar, compared to the civilian satellite radars from which data have been available to date. Early results indicate that multi-frequency polarimetric SAR has the potential to provide much more vegetation discrimination in moist tropical forests than possible with single frequency, single polarization radars (Pope *et al.*, 1992).

The effects of incidence angle need to be taken into consideration. Airborne radars typically acquire data at larger incidence angles than satellite radars. Striking effects have been observed between images of the same area obtained at two different incidence angles with satellite radars (Ahern and Raney, 1993).

## 4. Test areas

The eastern portion of the State of Acre, Brazil was used as the test area for most of this investigation because of the variety of types of land use encountered there. In particular, there are areas of small clearings by rubber tappers, larger clearings in agricultural settlement projects, and very large areas cleared for cattle ranching. A second test area is located along the Rio Padamo, a tributary of the Rio Orinoco in southern Venezuela. This area has many very small clearings for shifting cultivation by the indigenous Yanomami population.

### 4.1 Acre, Brazil

The State of Acre, is located in the Southwest of Amazonia, and has approximately 95% of its surface still covered by the original tropical rainforest. Its soils are mostly poorly-consolidated Cenozoic sediments. As a result, the area presents a rolling relief with low hills, which are remnants of a former plateau, approximately 100m above the average terrain level. The plateau is strongly dissected at its edges. The drainage erodes deeply in the sedimentary layers, forming well-defined floodplains with meanders as well as rivers carrying sediments. The soils are normally deeply weathered, and due to their chemical composition, are easily erodible.

The economy of Acre is based primarily on extraction of latex from *Hevea Brasiliensis*, for rubber production, and the collection of Brazil nuts and timber from tropical hardwoods. Beginning in the 1970's, due to a land occupation policy then in place for Amazonia, deforestation rates increased quickly. Large areas were cleared for cattle ranches ("fazendas") and for agricultural settlements, both planned and spontaneous.

Rubber tapping is an economic activity that is well adapted to the local tropical environment. The rubber tappers deforest very small sections of land, the so-called "colocações", to plant annual crops for their own use. The colocações are usually a few hectares in size. They are more numerous to the south of Rio Branco, which is an old rubber extraction area.

A number of government-assisted agriculture colonization projects have been started in the state, primarily near the cities of Rio Branco, Sena Madureira, Cruzeiro do Sul, and Brasiléira. We have chosen the PAD Humaitá project to assess medium sized clearings. Unlike most of the colonization projects which are based on a rectilinear road network, Humaitá has eight roads, each approximately 10 km long, radiating at 45° intervals from a central circle. Most of these eight radial roads bend or branch at their end into one or more straight roads, resulting in a more irregular network at the periphery of the settlement project. Lots 400 m wide and typically 1500 m deep (60 ha) have been laid out along these roads. When settled, these typically contain one family dwelling and one or more outbuildings. Land is cleared from the road back, resulting in a very irregular back boundary of the deforested area, which shifts rapidly from year to year. Secondary regeneration is very rapid, with *cecropia* the most common pioneer genus. As many farmers initially clear more land than they find they can manage, it is quite common to see fairly advanced regeneration at the backs of the lots. A wide variety of crops is grown, depending on the farmer's individual choices. As is common in the tropics, monocultured fields are small or non-existent, except for pasture, which is very popular.

The largest clearings, typically tens of $km^2$ in size, have been made along the major highways for large cattle ranches, or fazendas. The two roads with most of these fazendas are BR-364, from Rio Branco to Sena Madureira, and BR-317, from Rio Branco to Assis Brasil.

The clearing of the rainforest, particularly for ranching, has resulted in land-use conflict between the recent settlers and the established rubber-tappers. The Government of Brazil has designated sizable areas within Acre as "Extractive Reserves" to allow the rubber tappers to pursue their traditional way of life.

There is a strong commitment of the government of Acre State to protect its forest resource, especially the extractive reserves. As a consequence, our cooperating agency in Acre State, Fundação de Tecnologia do Estado do Acre (FUNTAC), generates an annual map of the increment of deforested areas, using primarily data from the Thematic Mapper supplied by INPE. FUNTAC is actively engaged in evaluating SAR data for the same applications.

### 4.2 Venezuela

The Rio Padamo is a tributary which flows southward with an average slope of 0.5 to 0.8 % into the Rio Orinoco approximately 45 km southeast of the settlement of La Esmeralda. The region surrounding the Orinoco is a peneplain, interrupted by isolated mesas and eroded granitic blocks (Ministerio del Ambiente y de los Recursos Naturales Renovables, 1983). Rainfall in the region is 2900 to 3400 mm per year. In the peneplain area, vegetation is dense evergreen forest consisting of medium height (20 m) trees without emergents. Along watercourses, a gallery forest of taller trees with a rougher canopy is sometimes present. The trees decrease in size with altitude, becoming shrublike at highest elevations. Except for two missionary settlements in the area, the only inhabitants are Yanomami Indians who live in small settlements along the river and practice shifting cultivation. The soils in the area are very poor, but the shifting cultivation is a sustainable agricultural practice as long as rotation intervals do not become too short.

## 5. Data Sources and Methods

A number of C-band SAR data sources were evaluated in this study (Table 3). High resolution data were provided by the CCRS C-SAR sensor mounted in a Convair 580 aircraft (Livingstone *et al.*, 1987). The data were acquired in both HH and VV polarizations. This is relevant because ERS-1 has VV polarization, while Radarsat has HH polarization. However, most of the airborne data were acquired at incidence angles greater than 45°, which is outside the range of ERS-1 and near the maximum incidence angle for Radarsat, making it difficult to make unqualified statements about the performance of the satellite SARs on the basis of the airborne data.

The airborne data were corrected for slant range distortion and range-dependent radiometric effects, contrast stretched, and recorded as photographic negatives and transparencies.

The C-SAR wide mode data have been used to simulate Radarsat using the parameters given in Table 3 and produced as a print at approximately 1:100 000 scale.

A digital ERS-1 image acquired on 1992.05.15 was used to produce a photographic print at 1:100 000 scale. A two-date positive transparency of ERS-1 data was supplied to us by H. Lauer of ESA and projected to 1:100 000 scale for interpretation. This image was produced using a 1992.05.11 image printed in green, and a 1992.06.15 image printed in red, allowing interpretation of changes in backscatter between the two dates.

Landsat Thematic Mapper data has been used as a source of independent verification of the information derived from the SAR images. The TM data was used in the form of 1:100 000 scale enhanced colour prints. The enhancements were made by linearly contrast stretching the data to fill the 256 gray level dynamic range and assigning band 3 to blue, band 4 to green, and band 5 to red. Numerous studies have demonstrated the ability of data from the Thematic Mapper to map high contrast edges with a positional accuracy of 15 to 30 m (see, for example, Beyer *et al.*, 1984; Moore, 1989; Hall *et al.*, 1989).

Finally, colour transparencies were obtained from a small aircraft on 1991.11.26 and 1992.04.16 with a hand held 35 mm camera equipped with a 28 - 80 mm focal length zoom lens. These were used to document the ground cover for areas of detailed study, which provided information which could be extrapolated to other areas.

Each data source was interpreted at a scale of 1:100 000, using either a print at that scale, or projection to that scale with a Procom-2 optical projector. The boundaries of all of the clearings were drawn and compared with the same boundaries delineated from the 1:100 000 Thematic Mapper image described above. In order to provide a number of observations, the BR-364 and Humaitá test areas were divided into twelve sections of approximately equal size. For each section, five measurements were made of the displacement between the map made with the SAR data and the map made from the Thematic Mapper image, and averaged to provide an estimate of the boundary mapping error for that section. Each of the twelve estimates were in turn averaged to provide the average boundary errors presented in Tables 4 and 5.

The cleared area for each of the twelve sections was measured with a digital planimeter. Tables 4 and 5 give the average difference between the area measured from the SAR data sources and the area measured from the TM data, expressed as a percent.

Finally, we have carried out a linear regression analysis relating the estimate of the area of forest cleared to the measurement obtained from the Thematic Mapper image for the twelve sections of the BR-364 and Humaitá test areas. The regression coefficients and $r^2$ values obtained from this analysis are included in Tables 4 and 5. Scatter diagrams relating the areas estimates from SAR data sources to the TM area estimate are provided in Figures 1 and 2.

## 6. Results and Discussion

We will discuss the results starting with the largest cleared areas, the fazendas along BR-364, then the medium sized areas along the roads in the Humaitá settlement, then the colocações in the Remanso Extractive Reserve, and finally the clearings made by the indigenous inhabitants along the Rio Padamo in Venezuela.

### 6.1 Fazendas along BR-364

The most visible form of deforestation was that caused by the fazendas, which was visible on all of the data sources. Their rectilinear edges, generally aligned with the road, aided in detection and interpretation of boundaries. Fazendas have very high radiometric contrast with the surrounding forest on all six reflective Thematic Mapper bands, and consequently on the colour composites used for this evaluation. "Clean" pastures of fazendas have high contrast with the surrounding forest on the 23° incidence angle ERS-1 scenes. Recently cleared pastures and overgrown pastures have lower contrast, but are generally visible. At the shallow incidence angles characteristic of airborne SAR data the fazendas have lower contrast in both HH and VV polarization, and at very shallow incidence angles (>75°) there is a contrast reversal in VV polarization, with the fazendas becoming brighter than the surrounding forest. We attribute this to the interaction of the vertical electric field with the nearly vertical blades of grass. Because of the low radiometric contrast, other characteristics of the airborne radar images are important in distinguishing between primary forest and areas cleared for fazendas. The "broccoli-top" appearance of the rainforest canopy creates a characteristic texture on airborne radar images. This appears to be caused by a brighter return from the crowns of the trees facing the radar, and a darker return, or shadow, from the portion of each crown facing away from the radar. This texture is quite visible even with the 10 m (range) by 20 m (azimuth) resolution with the wide swath mode. There is often a distinct texture difference between the primary forest, and the pastures, which have a much smoother texture.

When there is an abrupt transition between primary forest and a clearing, there is a very bright return from the far edge of the clearing, presumably caused by a corner reflection between the tree trunks and the ground, and a dark shadow at the near edge of each clearing. With incidence angles as great as 85° with the wide-mode data, these shadows can be quite long and therefore very distinct.

The area chosen for this study was along highway BR-364 between the cities of Rio Branco and Sena Madureira. Errors in boundary placement and area estimation are reported in Table 4. Figure 1 shows the scatter plot of ERS-1 estimates as a function of the TM measurements, together with the equation of best fit and the coefficient of variation ($r^2$).

All SAR data sources had areas where the boundary between primary forest and degraded or cleared areas was indistinct. Typical displacements between the boundaries mapped from SAR and the TM boundaries ranged from about 100 m along long, distinct, straight boundaries to several hundred m along curved, less distinct boundaries. Areas of degraded forest are readily recognized on the TM images, but very hard to distinguish on the SAR images because of their low contrast and lack of distinct edge effects (bright edges and shadows). Errors of boundary positioning as large as several km were sometimes made in such areas. Table 4 shows that the average boundary error was larger for the satellite SAR data sources than for the wide mode airborne SAR data. Improvements may be expected through spatial filtering and greater geometric control of the data but further research is needed to determine the best approach.

In general the SAR data sources tended to underestimate cleared areas, as shown through the average area error and the slope of linear fit. This is because of the low radiometric contrast between primary forest, degraded forest, and advanced regeneration. Recently cleared areas, in particular, are often not recognized on the SAR images. The exception was the Radarsat simulation, where in several instances primary forest was interpreted as degraded forest, resulting in an overestimate of the cleared area.

The high correlation ($r^2 > 0.9$) between the cleared area from SAR and the cleared area from TM indicates that this is a systematic error which can be corrected. This shows that satellite SAR is a promising candidate for monitoring the area of tropical deforestation on regional, national, and global scales.

6.2 Humaitá agricultural colonization project

The Humaitá project was divided into 12 sections to provide a number of samples for analysis. The sections included the eight radial roads, plus four additional roads branching off their ends. Because of the small size of the individual lots, the total area cleared in each section was only about 1/10 the size of the cleared areas along BR-364 (see Figure 2). The boundary of the cleared area was very irregular because of the differing amount of forest cleared from lot to lot.

Only the TM image, the wide mode C-SAR image and the two-date ERS-1 image were interpreted, with the TM interpretation taken as the "correct" boundary of forest clearings. There was no single date ERS-1 scene available. The Radarsat simulation did not show the boundaries of the cleared area well enough for interpretation, primarily because of the irregular boundary of the cleared area and the low contrast resulting from the shallow incidence angle of the airborne radar used as input data for the simulations.

The interpretations of the clearings were evaluated in the same way as the experiment along BR-364. Figure 2 shows the relationship between the area estimated from the C-SAR data and that estimated from the TM image. Because the clearings are smaller and the boundaries are irregular, there is more scatter in these observations than in the corresponding sample for BR-364. The parameters determined from this analysis are collected in Table 5. The average boundary errors are similar in size to those obtained from the BR-364 study. Since there is more scatter in the area estimates, the R-square values are lower. However, they are still high enough to allow the systematic errors to be corrected, and provide reliable estimates of the total area cleared for a project such as Humaitá.

6.3 Colocações

Most of the colocações were only visible on the high resolution radar images (nadir and narrow modes), and on the Thematic Mapper image. Many of the larger ones were visible on the wide mode C-SAR image, but none were visible on the ERS-1 images. All of the colococoes in a portion of the Remanso Extractive Reserve were mapped using narrow mode C-HH data and with the Thematic Mapper image. Because of the high radiometric contrast, more colocações were visible on the Thematic Mapper image, but its spatial resolution was not adequate to map their boundaries. The boundaries could be reliably delineated on the radar image, allowing their sizes to be estimated. Figure 3 shows the distribution of sizes for the sample of colocações which were detected on the radar image. We see that, in general, these clearings are only a few hectares in size; in fact the actual distribution may include many smaller clearings which could not be detected on the radar image.

The clearings could be grouped into two distinct spectral classes on the TM image: magenta/pink and green/cyan. Our low altitude overflights and 35 mm photography allowed us to determine that the magenta or pink colour indicates areas of bare ground or pasture, while the green or cyan colour indicates areas which are being cleared (degraded forest) or abandoned and regenerating. With the radar image, we could also distinguish two texture classes of clearing: smooth and rough.

A clearing-by-clearing comparison of the maps produced from the two data sources resulted in a contingency table (Table 6). This table shows that more small clearings were detected with TM (185) than with the SAR (126). There does not seem to be a correlation between the class indicated by the relative spectral reflectance indicated by the TM data, and the texture on a high resolution radar image. More detailed information on the ground cover in each clearing would be necessary to explain this finding.

6.4 Shifting cultivation - Rio Padamo, Venezuela

Flight lines Ven 2.1 and Ven 2.3, flown on April 4, 1992, imaged the Rio Padamo and its valley in wide and narrow modes respectively. Many shifting cultivation fields were clearly visible on the narrow mode image. Most of these could be located in the wide mode image once their position was known, but they were at the limit of visibility. Clusters of several clearings which were resolved on the narrow mode images were unresolved on the wide mode image. A total of 75 clearings were counted on the narrow mode images. These were classified as to size and shape. The resulting distribution is shown in Figure 4. Note that we are detecting many small clearings, including some as small as 0.25 ha in area.

## 7. Conclusions

The sizes, shapes, and temporal behavior of clearings in tropical forests provide important information for resource management in tropical environments. We have evaluated several SAR data sources for their utility for mapping clearings in tropical forests, and for estimating cleared areas. Satellite SARs with four-look spatial resolution in the range 25 - 30 m were found capable of providing reliable area estimates of large (1000s to 10 000s of ha) and medium (100 to 1000 ha) clearings. Boundary placement errors were large (250 to 350 m), but improvements can be expected through spatial filtering and greater geometric control of the data. Smaller areas, cleared as extractivist settlements (1 - 10 ha) and for shifting cultivation (0.25 to 3 ha) could be detected and mapped with airborne SAR with seven-look spatial resolution of 6 m. At the steeper incidence angles characteristic of satellite data, the contrast between pastures and the surrounding forest is greatest during the "clean pasture" stage, indicating that monitoring a new image every year or two will provide the most reliable estimates of the boundaries and areas of pastures. These results confirm that spaceborne and airborne SAR imagery can provide valuable information for improved resource management in tropical environments.

## Acknowledgements

Data acquisition costs were borne by the European Space Agency and the Canadian International Development Agency. The authors are indebted to the director and staff of Fundação de Technologia do Estado do Acre (FUNTAC) for their enthusiastic help in the lab and in the field, and for the generous provision of flight time in their Cessna 172 aircraft. We also thank Mr. Henri Lauer of ESA for the two-date ERS-1 colour composite image analyzed in this investigation.

## Bibliography

Ahern, F. J. and R. K. Raney, 1993. An Almaz - ERS-1 comparison demonstrates incidence angle effects in orbital SAR imagery, Canadian Journal of Remote Sensing, 19, pp 259 - 262.

Ahern, F. J., R. K. Raney, R. V. Dams, and D. Werle, 1990, A review of remote sensing for tropical forest management to define possible RADARSAT contributions, Proceedings of International Symposium on Primary Data Acquisition, International Society for Photogrammetry and Remote Sensing, Manaus, Brazil, June 24 - 29, pp 141 - 157.

Beyer, E. P., J. Brooks, and V. V. Salomonson, 1984. Geometric Correction of Landsat 4 and 5 Thematic Mapper Data, Proceedings of Eighteenth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, pp 89 - 100.

Brisco, B., D. Bedard, J. Naunheimer, and R. J. Brown, 1993. Environmental effects on radar data of agricultural areas, Proceedings of the 16th Canadian Symposium on Remote Sensing, Canadian Aeronautics and Space Institute, Sherbrooke, Québec, Canada, June 7 - 10, pp 283 - 288.

Dams, R. V., D. Flett, M. D. Thompson, and M. Lieberman, 1987. SAR (STAR-1) image analysis for Costa Rican tropical forestry applications, Proceedings of 1987 SELPER Conference, Bogotá, Colombia.

Ford, J. P. and D. B. Casey, 1988. Shuttle radar mapping with diverse incidence angles in the rainforest of Borneo, International Journal of Remote Sensing, 9, pp 927 - 943.

Hall, R.J., A.R. Kruger, J. Scheffer, S.J. Titus, and W.C. Moore. 1989. A statistical evaluation of LANDSAT TM and MSS data for mapping forest cutovers. Forestry Chron. 65, pp 441-449.

John, L. 1989. Amazônia, Olhos de Satélite, Editoração Publicações e Comunicações Ltda, São Paulo, Brazil.

Livingstone, C. L., A. L. Gray, R.K. Hawking, and R. B. Olsen, 1987. CCRS C-Band airborne radar: System description and test results, Proceedings of the 11th Canadian Symposium on Remote Sensing, Canadian Aeronautics and Space Institute, Waterloo, Ontario, Canada, June 22 - 25, pp 503 - 518.

Lowry, R. T., P. Van Eck, and R. V. Dams, 1986. SAR imagery for forest management, Proceedings of IGARSS '86 Zürich, Switzerland, 8 - 10 September, pp 901 - 906.

Ministerio del Ambiente y de los Recursos Naturales Renovables (Venezuela), 1983. Atlas del inventario de tierras del territorio federal Amazonas.

Moore, H. D., 1989. SPOT vs Landsat TM for the maintenance of topographical databases, ISPRS Journal of Photogrammetry and Remote Sensing, 44, pp 72 - 84.

Pope, K. O., J. M. Rey-Benayas, and J. F. Paris, 1992. Characterization of wetland, forest, and agricultural ecosystems in Belize with airborne radar (AIRSAR), Proceedings of the 1992 Airborne Remote Sensing Workshop, NASA/JPL, pp 18 - 20.

Sökeland, A. D., H. DeGroof, J.Conway, and A. J. Sieber, 1992. TREES Project: A case study on the use of multi-temporal ERS-1 SAR data and SPOT data for monitoring tropical ecosystems, Proceedings of the first ERS-1 Symposium, Cannes, France, November 4 - 6, pp 671 - 675.

Thompson, M. D., and R. V. Dams 1990. Forest and land cover mapping from SAR: a summary of recent tropical studies, 23rd International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, Bankok, Thailand, April 18 - 25, pp 509 - 516.

Werle, D., 1989a. Radar remote sensing for application in forestry: a literature review for investigators and potential users of SAR data in Canada, Canada Centre for Remote Sensing, Energy, Mines, and Resources Canada.

Werle, D., 1989b. Potential application of imaging radar for monitoring depletion of tropical forests, Proceedings of 1989 International Geoscience and Remote Sensing Symposium, Vancouver, British Colombia, pp 1383 - 1390.

Wessles, G. J., R. T. Lowry, and R. K. Raney, 1986. Validation and simulation of Radarsat imagery, Proceedings of the 10th Canadian Symposium on Remote Sensing, Canadian Aeronautics and Space Institute, Edmonton, Alberta, Canada, May 5 - 8, pp 841 - 854.

**Table 1. Information which can be inferred from the size, shape, spatial context, and changes in forest openings.**

| | Single date observation | Multitemporal observation |
|---|---|---|
| Natural openings | -groundcover type<br>-land use<br>-land productivity<br>-biodiversity measures<br>-erosion potential<br>-slope stability | -natural succession<br>-biodiversity measures<br>-change in erosion potential<br>-change in slope stability |
| Anthropogenic openings (clearings) | -land use<br>-productivity (inferred from land use)<br>-biodiversity measures<br>-erosion potential<br>-slope stability | -land use changes<br>-natural and artificial succession<br>-change in biodiversity<br>-change in erosion potential<br>-change in slope stability |

**Table 2. Relationship between size, shape, and temporal behavior of clearings, and their cause.**

| Size (ha) | Shape | Temporal Behavior | Cause |
|---|---|---|---|
| > 1000 | rectangular | permanent | cattle ranching |
| 100 (many) | herring-bone | permanent | agricultural settlements |
| 1 - 10 | oval | permanent | extractivist settlements |
| ~ 1 | rectangular | temporary | gold miners (airstrips) |
| ~ 0.5 - 3 | oval | temporary | shifting cultivation |
| ~ 2 | L-shaped | temporary | oil exploration |
| 10 - 100 or larger | irregular | permanent | mines |

This table is based on observations published by John (1989), supplemented with the authors' fieldwork in the Orinoco and Amazon basins of Brazil and Venezuela.

**Table 3. Data Sources used for this study.**

| Sensor | C-SAR narrow | C-SAR wide | Radarsat Sim | ERS-1 | TM |
|---|---|---|---|---|---|
| Band | C-band<br>5.66 cm | C-band<br>5.66 cm | C-band<br>5.66 cm | C-band<br>5.66 cm | 630-690nm<br>760-900nm<br>1.55-1.75μm |
| Polarization | HH | HH | HH | VV | unpolarized |
| Incidence angles | 45° to 76° | 45° to 85° | 45° to 85° | 20° to 26° | -15° to 15° |
| Resolution, ground range (m) | 6 | 20 | 27.1 | 25 | 30 |
| Resolution, azimuth (m) | 6 | 10 | 24.1 | 22 | 30 |
| Pixel spacing, range (m) | 4.0 | 15.0 | 12.5 | 12.5 | 30 |
| Pixel spacing, azimuth (m) | 3.87 | 6.9 | 12.5 | 12.5 | 30 |
| number of looks | 7 | 7 | 4 | 6 | not applicable |

**Dates of data acquisition:**
**Thematic Mapper:** 1991.07.03
**C-SAR narrow and wide, Radarsat simulation:** 1992.04.19
**ERS-1:** 1992.05.15 (single date image); 1992.05.11 and 1992.06.15 (two-date colour composite).

**Table 4. Parameters from analysis of fazendas along highway BR-364.**

| | Data Source | | | |
|---|---|---|---|---|
| **Evaluation Parameter** | **C-HH Wide** | **ERS-1 1-date** | **ERS-1 2-date** | **Radarsat Simulation** |
| average boundary error (m) | 146 | 325 | 283 | 258 |
| average area error (%) | -7.2 | -11.8 | -12.3 | 7.5 |
| slope of linear fit | 0.90 ± 0.03 | 0.84 ± 0.06 | 0.75 ± 0.10 | 1.04 ± 0.06 |
| intercept of linear fit ($km^2$) | 0.90 ± 2.34 | 1.32 ± 5.29 | 6.23 ± 6.01 | 0.94 ± 5.09 |
| $r^2$ of linear fit | 0.99 | 0.95 | 0.93 | 0.97 |

**Table 5. Parameters from analysis of clearings along Humaitá roads.**

| | Data Source | |
|---|---|---|
| **Evaluation Parameter** | **C-HH Wide** | **ERS-1 2-date** |
| average boundary error (m) | 137 | 313 |
| average area error (%) | 7.5 | -18.6 |
| slope of linear fit | 0.89±0.10 | 0.79±0.11 |
| intercept of linear fit ($km^2$) | 1.35 ± 1.03 | 0.17 ± 1.16 |
| $r^2$ of linear fit | 0.90 | 0.84 |

**Table 6. Contingency table comparing detectability of small clearings with TM and 6 m resolution C-HH SAR.**

| | SAR Class | | |
|---|---|---|---|
| TM Class | Smooth | Rough | Not Detected |
| bare or pasture | 50 | 2 | 39 |
| degraded or regenerating | 42 | 6 | 46 |
| Not Detected | 17 | 9 | unknown |

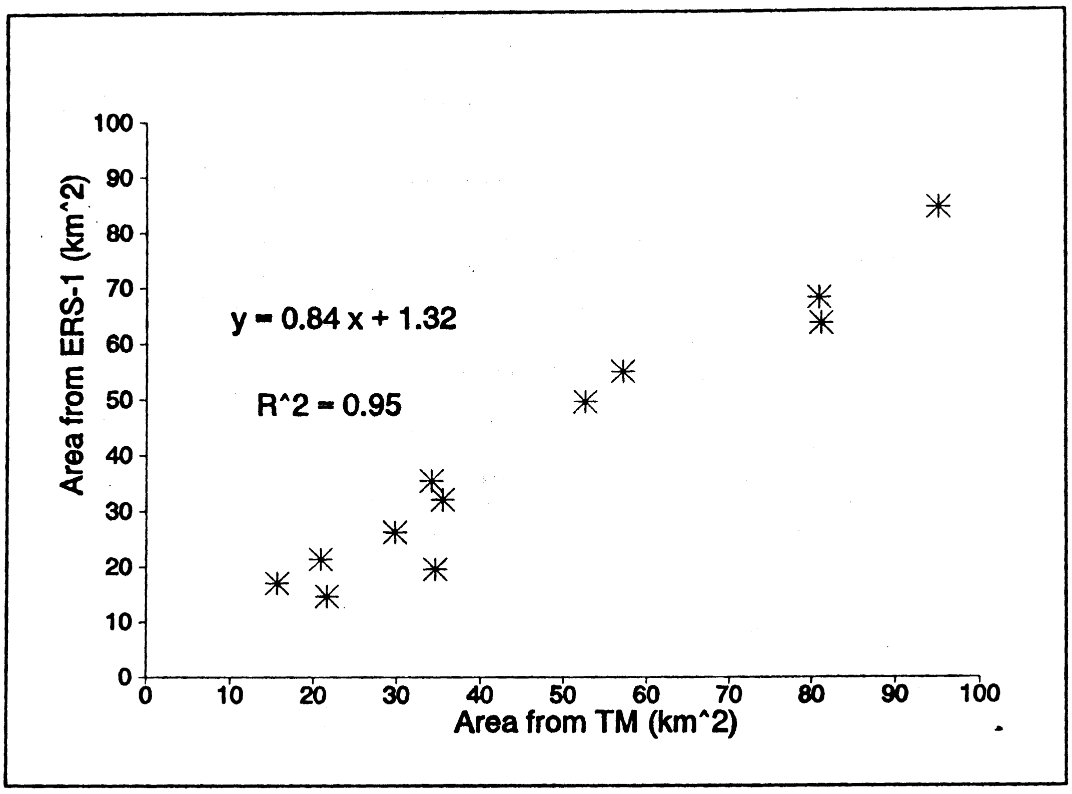


**Figure 1** Areas of clearings along BR-364 measured from ERS-1 data compared to areas of same clearings measured from TM image.

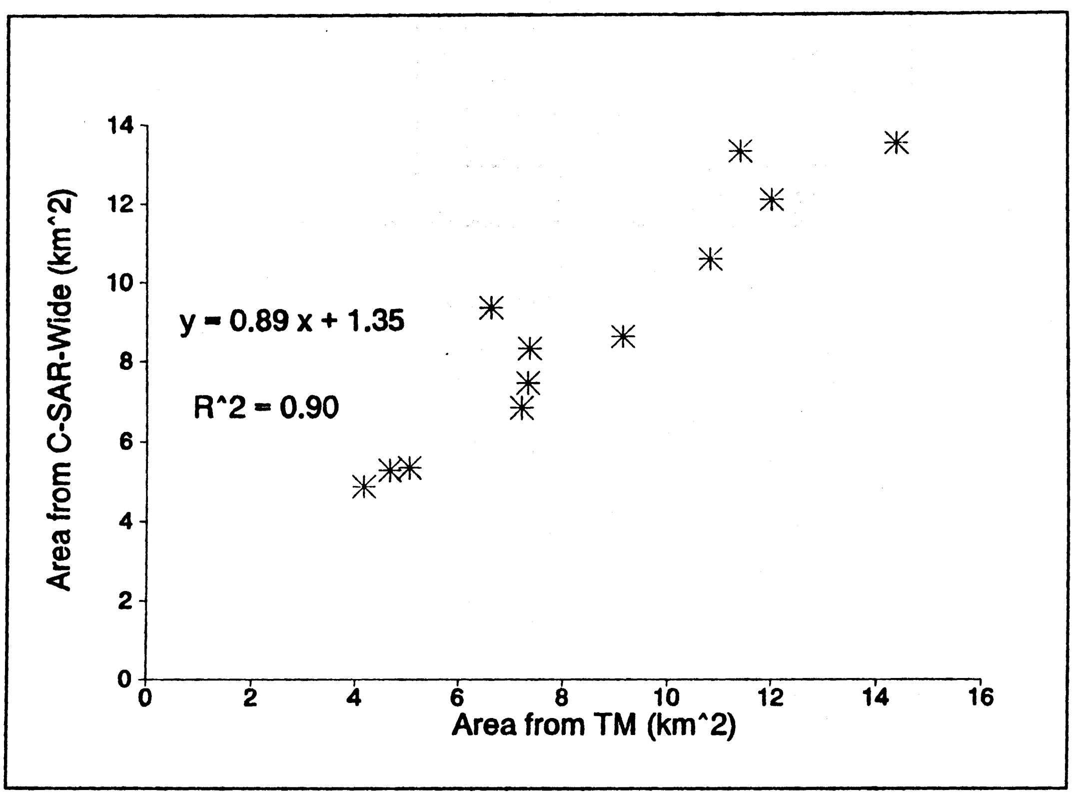


**Figure 2** Areas of clearings along Humaitá roads measured from C-SAR wide mode data compared to areas of same clearings measured from TM image.

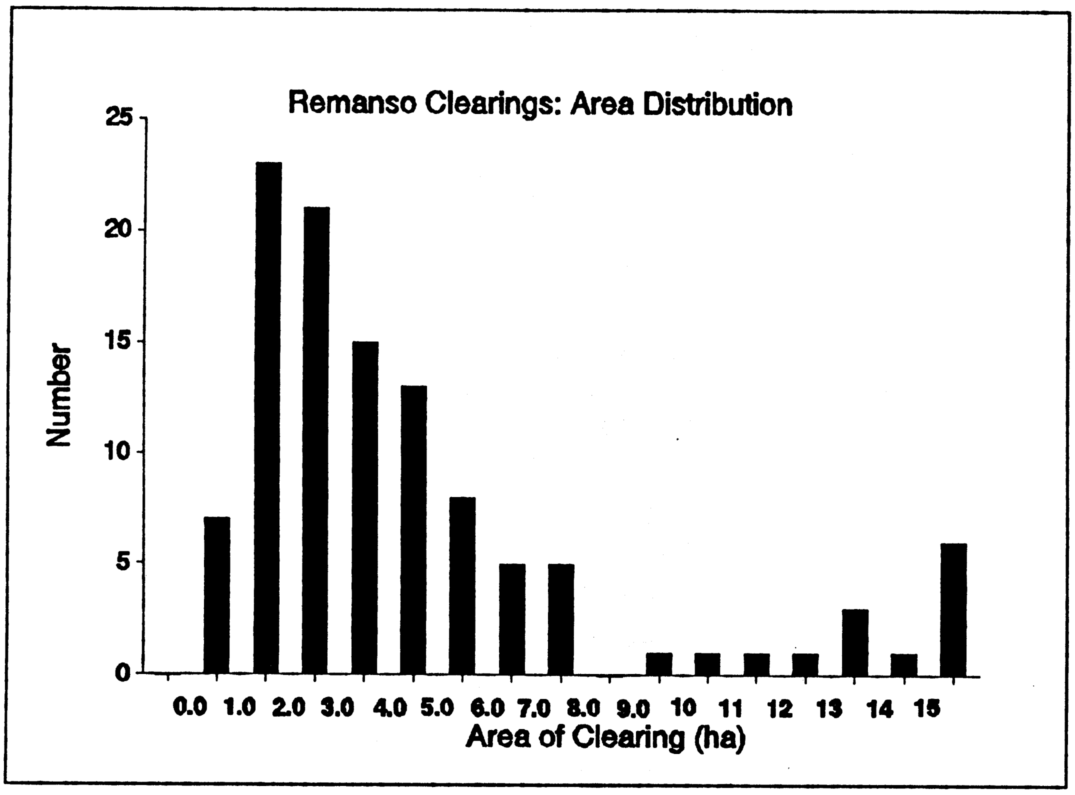


Figure 3 Frequency distribution of areas of clearings in Remanso Extractive Reserve.

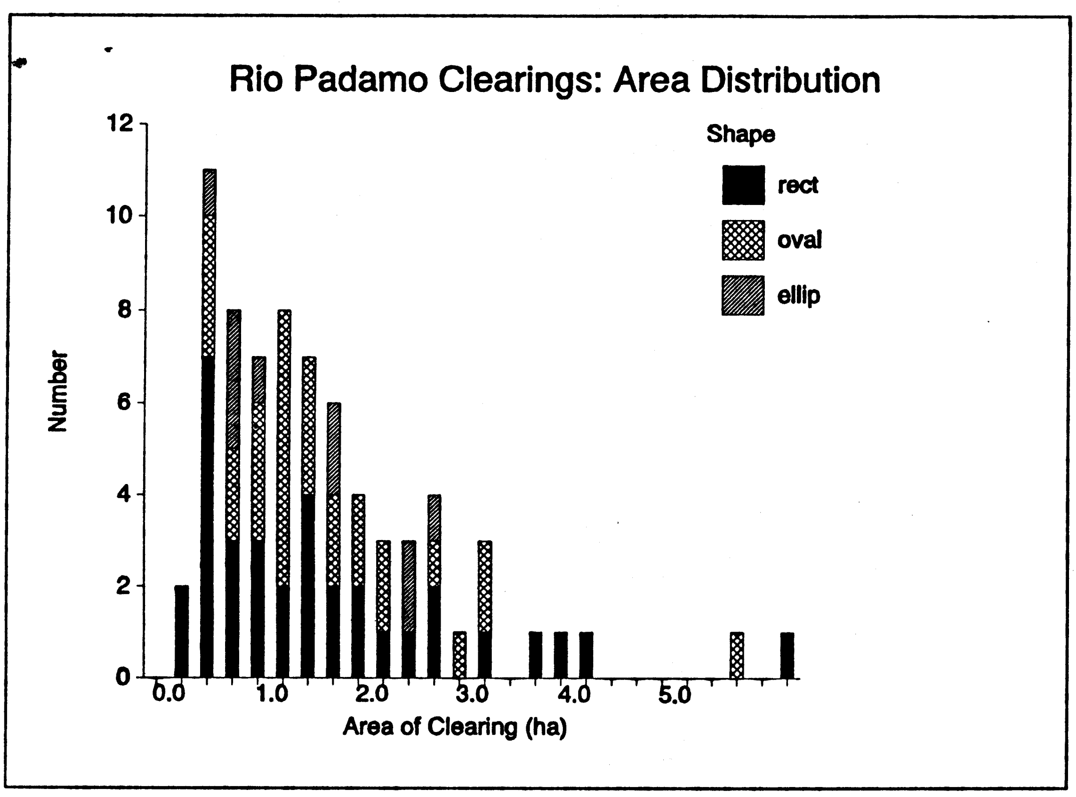


Figure 4 Frequency distribution of areas of clearings along Rio Padamo, Amazonas, Venezuela.