Assessing JERS-1 Synthetic Aperture Radar Data for Vegetation Mapping in the Brazilian Savanna

Edson E. SANO¹, Giane G.C. PINHEIRO² and Paulo R. MENNES²

Abstract

The use of synthetic aperture radar (SAR) data for savanna vegetation mapping in central Brazil is investigated. A wet season (February, 1996), L-band, JERS-1 SAR scene over diverse savanna vegetation types in central Brazil was acquired. A statistical analysis of 1133 backscatter samples extracted from the most representative land cover classes of the study area as well as analysis of the relationship between field leaf area index measurements and corresponding radar returns were the basis of this study. The SAR data separated the grassland, mixed grass/shrub/woodland and woodland units in the study area. We also found an exponential relationship ($r^2=0.63$) between $\sigma^0$ and LAI. These results indicate the potential of the L-band SAR data for savanna-like vegetation mapping and monitoring.

Keyword : tropical savanna ; JERS-1 ; synthetic aperture radar

1. Introduction

The Brazilian savanna, locally known as "Cerrado", covers about 2,000,000 km² and represents the second largest biome in the South America. Cerrado is an upland, species-rich vegetation with more than 450 vascular species per hectare, and occurs mostly in Oxisols¹. Regarding its vertical structure, there are three major land covers : grassland, shrubland, and woodland. Variations in their proportion is the basis for classifying different types of Cerrado.

Current vegetation cover monitoring in the Brazilian Cerrado region using remote sensing techniques are restricted to optical data²-³. In spite of promising results, the widespread cloud cover in the wet season and the presence of smokes from burning activities in the dry season impose a strong constraint in the use of optical data. Synthetic aperture radar (SAR) systems can overcome such restriction because they operate in long wavelengths (magnitude of centimeters). In this spectral region, SAR signals can penetrate into clouds and smokes and are not significantly sensitive to variations in the smoke-filled atmospheric conditions.

Considerable relationships between radar backscatter and vegetation parameters such as leaf area index (LAI), total biomass and plant water content, obtained from experimental and theoretical investigations, have been reported in the literature⁴-⁶. However, the dielectric characteristics and the structure of plant constituents affect backscattering process in different manners, depending upon sensors frequency, polarization and incidence angle. The purpose of this work was to investigate the potential of the L-band Japanese Earth Resources Satellite (JERS-1) SAR data for Cerrado vegetation mapping and monitoring.

2. Background

There are two distinct seasons in the Brazilian Cerrado region: a wet summer, from October to April, with approximately 90% of total annual rainfall occurring in this time period, and an average temperature of 22-28°C; and a dry winter, from May to September, with an average temperature of 16-24°C. Such weather seasonality causes the drying and the shedding of the Cerrado’s leaves in the winter season⁷. Another important climate-related phenomenon in the Cerrado is the occurrence of dry spells⁷. As most of the grain production in the Cerrado is rainfall-dependent, the mapping of frequency or probability of dry spell occurrence in this region is of great value.

Flat or gentle topography associated with seasonal fluctuation of rainfall regime in the Cerrado have contributed to the
development of highly weathered, deep, and structured soil profiles. These soils often present shortage of calcium and toxicity of aluminium, because of the intense desilification and base leaching processes. Iron concentration and formation of ferruginous crusts are also commonly found in the Cerrado soil surfaces.

Regular human-induced fire is another important aspect of the Cerrado ecosystem. In fact, most tropical savannas in the world are currently shaped by man-made regular biomass burning and their occurrence are important to the functioning of these ecosystems8,9). Fire acts as a decomposer, provoking oxidation of organic matter, which accelerates mineralization and nutrient cycling. Thus, fire temporarily increases soil fertility and minimizes Al toxicity10, and can be considered as part of this biome.

Physiognomically, the Cerrado is formed by a continuous layer of grasses with a discontinuous layer of contorted shrubs and trees. Differences in the proportion of these structures result in different Cerrado classes, ranging from pure grasslands to woodlands. The distribution of each Cerrado type in Brazil is quite heterogeneous and follows the variations in soil morphology, drainage, local topography, depth of water content and fire frequency.

In the past decades, the natural vegetation of the Cerrado has been rapidly removed for grain (soybean, corn, rice, bean and wheat, among others) and meat productions. The flat topography, low land prices, and the construction of Brasilia have contributed for such tendency. The large-scale human induced changes have transformed Cerrado into a fragile ecosystem. Thus, the monitoring of its vegetation conditions is of great value.

3. Experimental Design

3.1 Study Area

The test site corresponded to the Brasilia National Park, a 30,000 hectares, preserved area located in the northern Federal District, Brazil, between 15°35'S and 15°45'S latitude and 47°53'W and 48°05'W longitude (Figure 1). Sorted by both biomass content above the ground and vegetation height, the major vegetation units in the Park are (Figure 2): Savanna Grassland; Shrub Savanna; Savanna Grassland or Shrub Savanna with ‘termite’; Wooded Savanna; Savanna Woodland; and Gallery Forest. The descriptions of each class are shown in Table 1, while Figures 3a, 3b, 3c, 3d and 3e represent their sketches. Other important land cover classes in the Park are the Santa Maria Lake in the central portion (elevation = ~1100 meters), and the anthropic and reforested areas, both located in the eastern part of the test site.

The average annual precipitation in the Park (1979–1997 period) registered by the Santa Maria raingage (15°40’S latitude and 47°57’W longitude) was 1259.3 mm. The average monthly precipitation in the same time period is shown in Figure 4.

3.2 Methods

Remote Sensing Data

A JERS-1 SAR image from February 1st, 1996 was the basis of this study. Although we intended to obtain a representative wet season SAR scene, it is important to point out that unfortunately 1996 was unusually dry (Figure 5). JERS-1 was successfully launched by the National Space Development Agency of Japan (NASDA) on February 11, 1992. Its
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Fig. 2 Vegetation map of the Brasilia National Park. Savanna Grassland = open grassland; Shrub Savanna = open grassland with sparse shrubs; Savanna Grassland or Shrub Savanna with “Termiters” = open grassland found in the middle of small elevations (~20-40 cm height) randomly distributed and built by termites and earthworms; Wooded Savanna = shrubland with sparse trees; Savanna Woodland = mixed grassland, shrubland and trees up to seven meters high. (Adapted from Macedo).

Table 1 Characteristics of the major savanna types in the Brasilia National Park.

<table>
<thead>
<tr>
<th>Savanna Class</th>
<th>Above-Ground Characteristics</th>
<th>Arborescent Cover (%)</th>
<th>Average Height of Trees (m)</th>
<th>Brazilian Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savanna Grassland</td>
<td>Open grassland</td>
<td>&lt; 1</td>
<td>2</td>
<td>Campo Limpo</td>
</tr>
<tr>
<td>Shrub Savanna</td>
<td>Open grassland with sparse shrubs</td>
<td>&lt; 5</td>
<td>2</td>
<td>Campo Sujo</td>
</tr>
<tr>
<td>Savanna Grassland or Shrub</td>
<td>Open grassland with or</td>
<td>&lt; 5</td>
<td>2</td>
<td>Campo com Murundus</td>
</tr>
<tr>
<td>Savanna with “Termiters”</td>
<td>without sparse shrubs found</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>in the middle of small elevations (~20-40 cm</td>
<td></td>
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<tr>
<td></td>
<td>height) randomly distributed and built by</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>termites and earthworms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wooded Savanna</td>
<td>Shrubland with sparse trees</td>
<td>5 - 20</td>
<td>2 - 3</td>
<td>Cerrado Ralo</td>
</tr>
<tr>
<td>Savanna Woodland</td>
<td>Mixed grassland, shrubland</td>
<td>20 - 50</td>
<td>3 - 6</td>
<td>Cerrado Tipico</td>
</tr>
<tr>
<td></td>
<td>and trees up to seven</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gallery Forest</td>
<td>Evergreen woodland mainly</td>
<td>40 - 70 % in the dry</td>
<td>20 - 30</td>
<td>Mata de Galeria</td>
</tr>
<tr>
<td></td>
<td>along streams</td>
<td>season; 50 - 90 % in</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>the wet season</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Classification system proposed by Ribeiro & Walter.  

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Fig. 3a Profile and arboreous cover sketches of Savanna Grassland, showing topographic locations of dry condition, wet condition and occurrence of “termiters” within an area of 40×10 meters in the Brasilia National Park (adapted from Ribeiro and Walter).

Fig. 3b Profile and arboreous cover sketches of Shrub Savanna, showing topographic locations of dry condition, wet condition and occurrence of “termiters” within an area of 40×10 meters in the Brasilia National Park (adapted from Ribeiro and Walter).

Fig. 3c Profile and arboreous cover sketches of Wooded Savanna within an area of 40×10 meters in the Brasilia National Park (adapted from Ribeiro and Walter).

Fig. 3d Profile and arboreous cover sketches of Savanna Woodland within an area of 40×10 meters in the Brasilia National Park (adapted from Ribeiro and Walter).

Fig. 3e Profile and arboreous cover sketches of Gallery Forest within an area of 8×80 meters in the Brasilia National Park (adapted from Ribeiro and Walter).
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SAR system operates at a frequency of 1275 MHz (L-band, 23.5 cm wavelength), HH polarization, and a range of incidence angle from 36° (near range) to 41° (far range). The swath width is about 75 km, and the nominal spatial resolution, considering three looks in the azimuth direction, is 18 meters.

A single sensor configuration and single date SAR image of this study was acquired as part of the JERS-1 Verification Program supported by the National Space Development Agency (NASDA) of Japan. The original image was georeferenced to the Universal Transverse Mercator (UTM) projection; the earth ellipsoid was WGS84; the processing level and resampling method were 2.1 and nearest neighbor, respectively; and the pixel spacing was 12.5 m.

In this study, the SAR image was georeferenced to the Universal Transverse Mercator (UTM) projection and 1969 South American Datum, so that image statistics would be easily related to field measurements. Seventeen control points were obtained from 1:25,000 scale, topographic map sheet of the study area. The pixel size after the geometric correction was kept as 18 meters. We used the nearest neighborhood as the resampling method. The root mean square (RMS) error of the image-map registration was about 10 meters, that is, an error smaller than one pixel.

SAR Statistical Analysis

From the georeferenced SAR image, overlaid by a land cover vector file, several samples of backscatter coefficients ($\sigma^0$) were extracted from uniform and representative areas of the six dominant vegetation communities encountered in the Park: Savanna Grassland, Shrub Savanna, Savanna Grassland or Shrub Savana with “Termiters”; Wooded Savanna, Savanna Woodland and Gallery Forest. Backscatter coefficients from the Santa Maria Lake were also included in the statistical analysis as a reference target.

Regular polygons (circle of 100 meter diameter), containing approximately 97 digital numbers were used to calculate the backscatter coefficients. The constraint of the sampling size was given by the Gallery Forest class. As its occurrence depend upon high soil moisture contents, which is found along streams, its maximum width was not greater than 100 meter in the terrain.

The mean ($\bar{\sigma}$) digital number and accompanying standard deviation ($\sigma$) were calculated for each sampling polygon. Concerning the backscatter coefficients, these were estimated by the following equation:

$$\sigma^0 = 10 \log \left( \frac{\sum (DN^2)}{n} \right) + CF$$

where $DN =$ digital number; $n =$ number of pixels in the sample (polygon); and $CF =$ sensor calibration factor ($-68.5$ dB).

The SAS statistical package was used to rank the backscatter coefficients. The lowest $\sigma^0$ corresponded to the first position in the ranking, while the highest $\sigma^0$ corresponded to the last position in the ranking. The Analysis of Variance (ANOVA) of N independent, ranked samples of backscatter coefficients was also obtained by using the non-parametric Kruskal-Wallis test. Finally, a multiple comparison test was used to verify which Cerrado's vegetation classes were significantly different.

Field Measurements

Leaf area index (LAI, leaf area per unit area on the ground) measurements were obtained from the following vegetation classes: Savanna Grassland, Shrub Savanna, Wooded Savanna, and Savanna Woodland in a field campaign in February, 1998 by using a LAI-2000 Plant Canopy Analyzer. This instrument uses a fisheye light sensor that measures diffuse radiation simultaneously in five silicon detec-
tors, arranged in concentric rings. The original design was to obtain three different sampling sites for each vegetation unit in the Park. Unfortunately, during the field work, we concluded that the sites classified initially as Shrub Savanna were in fact located over the Wooded Savanna unit. Therefore, the authors decided to regroup the Shrub Savanna sites into Wooded Savanna in the final analysis. For each site, thirty randomly distributed replicates were averaged to one reading.

As a result, a total of 12 LAI measurements were obtained in this study. Figure 6 shows the georeferenced JERS-1 image along with the locations of the field LAI sampling sites. The UTM coordinates of these sites were acquired in the field by using a Global Positioning System. Radar backscatter coefficients from these 12 sampling sites were also obtained and compared with the LAI measurements.

4. Results and Discussion

Table 2 shows the area (in hectares) and percent coverage of major vegetation classes in the Brasilia National Park. The Savanna Grassland and the Savanna Woodland, with 34.2 and 25.7%, are the two largest savanna units in the study area. The total number of areas, which were used to calculate the backscatter coefficients, for each major vegetation classes in the Brasilia National Park are also shown in the table. For instance, 410 values of \( \sigma \) were calculated and analyzed statistically over the Savanna Grassland unit. As each \( \sigma \) calculation involves 97 digital numbers in average, a total of 39,770 pixels were analyzed only for the savanna unit. The two human-induced land cover classes (Reforestation and Anthropic Area) were not included in the analysis because the primary objective of this study was to assess the L-band SAR data for natural vegetation mapping and monitoring.

A direct comparison between mean and corresponding standard deviation values obtained from 1133 samples of digital numbers (Figure 7) shows that grasslands (Savanna Grassland, Shrub Savanna and Savanna Grassland or Shrub Savanna with “Termites”) can be separated from mixed grass/shrub/woodlands (Wooded Savanna and Savanna Woodland) and from woodlands (Gallery Forest). The group of grasslands presented lowest mean \( \bar{x} \) and standard deviation \( \sigma \) values, while the group of mixed grass/shrub/
Table 3 Statistical results of JERS-1 SAR backscatter coefficients from the Brasilia National Park.

<table>
<thead>
<tr>
<th>Grouping</th>
<th>Mean Backscatter Coefficient (dB)</th>
<th>Vegetation Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-6.67</td>
<td>Gallery Forest</td>
</tr>
<tr>
<td>B</td>
<td>-9.09</td>
<td>Savanna Woodland</td>
</tr>
<tr>
<td>C</td>
<td>-10.60</td>
<td>Wooded Savanna</td>
</tr>
<tr>
<td>D</td>
<td>-12.93</td>
<td>Savanna Grassland or Shrub Savanna with “Termites”</td>
</tr>
<tr>
<td>D</td>
<td>-13.59</td>
<td>Savanna Grassland</td>
</tr>
<tr>
<td>D</td>
<td>-13.67</td>
<td>Shrub Savanna</td>
</tr>
<tr>
<td>E</td>
<td>-16.89</td>
<td>Santa Maria Lake</td>
</tr>
</tbody>
</table>

Note: Means with the same letter of grouping are not significantly different.

woodlands presented intermediate mean and standard deviation values. As expected, water body (Santa Maria lake), a smooth and homogeneous target, showed low digital numbers ($\bar{x} < 390$). Its standard deviation was also low ($\sigma < 129$). On the other hand, Gallery Forests presented both the highest DNs ($\bar{x} > 1084$) and standard deviations ($\sigma > 333$). The statistical results (Table 3) confirmed the above discussed results: only the average backscatter coefficients from the three groups of grasslands were not significantly different.

As we can see in the sketches presented in Figures 3a, 3b, 3c, 3d, and 3e, the three major physiognomic types of Cerrado (grassland, shrubland, and woodland) present distinct vegetation structures (different leaf area index, crown spacing, amount of standing, dry biomass, etc.). Thus, the high penetration capability of L-band, in comparison to, for instance, C-band (wavelengths of about 5 cm) or optical sensors (wavelengths of microns), will produce a strong sensitivity of radar returns to the 3-D structural differences among the vegetation. Both Figure 7 and Table 2 confirmed that L-band SAR signals responded well to these structural differences.

Differences in soil moisture content and plant water content among these three savanna types would also produced differences in backscatter coefficients. As reported by Lewis et al., microwave backscattering is particularly sensitive to water in matter. Although measurements of soil moisture or plant water content were not available for the day of satellite overpass, we can assume, based on precipitation data, that dielectric constant over grasslands and shrublands were relatively lower than that from woodlands. Precipitation records from Santa Maria raingage showed only 7.0 mm of rainfall between January 13-31, 1996 (19 days time period before the JERS-1 overpass). Cerrado soils over grasslands and shrublands are also well-known by their high permeability. Thus, Gallery Forests, usually found along the streams, were distinguished from grasslands and shrublands also by their relatively higher plant water and soil moisture contents.

The soil roughness also plays an important role in the radar backscattering processes. As the roughness increases, backscatter coefficient also tends to increase. In this study, the influence of soil roughness in the L-band data can be seen comparing the average $\sigma^o$ values for the Savanna Grassland, Shrub Savanna, and Savanna Grassland or Shrub Savanna with “Termites”: $-13.59$ dB, $-13.67$ dB, and $-12.93$ dB, respectively (Table 3). The slightly higher $\sigma^o$ values for the last savanna unit were probably provoked by the presence of “termites”, which are small elevations randomly distributed in either Savanna Grasslands or Shrub Savannas. The presence of such irregularities in the terrain increased the amount of backscattered microwave energy over this type of Cerrado class.

Table 4 shows the LAI measurements and corresponding backscatter coefficients. Unfortunately, it was not possible to acquire both satellite and field data simultaneously. The technical problem in the recording device of the SAR system in the end of 1997 did not allow us to acquire SAR scene in 1998. Thus, although both types of data were obtained in the same time period of the year (February), some dispersion in the LAI/SAR relation can be expected because of this time gap. In fact, the comparison of 12 years average precipitation of February in the study area (Figure 5) indicates that 1996 (satellite overpass) was much drier than in 1998 (field measurements campaign).

In Figure 8, the L-band $\sigma^o$ is represented as a function of LAI of two Cerrado classes. The LAI and $\sigma^o$ values from Savanna Grassland was not included in the analysis because of the high level of standing, dry biomass in this savanna class, noticed during the field measurements. A clear increasing trend between both variables can be noticed when LAI is lower than approximately 3. However, the results confirmed previous findings that the estimation of LAI from L-band
SAR data is limited for LAI greater than 3 because of saturation problem. The best fit equation was found for the following exponential equation ($r^2=0.63$):

$$\sigma^2 \text{(dB)} = -28.67 - 234654 e^{(LAI/0.24)}$$

This relation was statistically significant at significance level ($a$) of 0.10.

5. Summary and Concluding Remarks

This study has explored the potential of the wet season JERS-1 SAR data to effectively separate the major types of Cerrado vegetation. Statistical analyses readily distinguished four savanna classes among a total of six. The three classes grouped together was the Savanna Grassland, Shrub Savanna, and Savanna Grassland or Shrub Savanna with "Termiters". These three classes are classified as open grasslands. Based on the SAR data analyzed at the Brasilia National Park, we can conclude that L-band, HH polarization presents a promising capability to map and monitor Cerrado vegetation types.

For Wooded Savanna, Savanna Woodland and Gallery Forest, which the arboreous covers are significant (5-20%, 20-50%, and 70-95%, respectively), the backscatter process seems to be controlled by the presence of shrubs and trees (individual scatterers) in each Cerrado class (Gallery Forest >Savanna Woodland >Wooded Savanna). Radar returns especially from Gallery Forests are also influenced by the high levels of water contents in both canopy and underlying soil surface. Therefore, L-band radar returns from Cerrado are dependent on canopy’s structure and dielectric constant. Indeed, such dependence is one of the major reasons to recommend the use of SAR data for tropical savanna mapping and monitoring, as strong as the famous SAR’s all-weather capability argument, reported in the introductory section of this paper.

Concerning Savanna Grassland and Shrub Savanna, that is, Cerrado classes with smaller individual scattering elements, lower levels of green biomass and higher L-band ground penetration, in comparison to the areas dominated by shrublands and woodlands, research needs to be conducted in order to determine the role of grasslands in the backscattering process. Whether the herbaceous vegetation over the Cerrado attenuates or contributes to the backscatter process is an important research question.

A major drawback in the LAI measurements from LAI-2000 instrument is related to the fact that nonphotosynthetic vegetation components such as branches, trunks and dry matters contribute significantly to the “green” LAI estimations. Therefore, the vegetation parameter measured by LAI-2000 is more related to Plant Area Index rather than Leaf Area Index. Some researchers have established empirical relationships between Plant and Leaf Area Index. The conclusions from these studies is that instruments based on radiation interception such as LAI-2000 and ceptometers can give consistent relative measurements within a study site. However, the obtaining of reliable quantitative measurements requires correction factors, which is site-specific. Such correction factor needs to be determined for Brazilian tropical savannas.

Concerning the influence of dielectric constant in SAR data is already well known. However, because there was no ground moisture measurements during the SAR overpass, we could not assess the influence of water contents in the Cerrado’s radar back-scattering process. We expect that the ongoing research comparing dry and wet season JERS-1 SAR scenes over the Park will be helpful to understand the role of moisture content in the L-band SAR data over the tropical savannas.

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References


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