

Application of SAR Remote Sensing in Land Surface Processes Over Tropical Region

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Abstract. Spaceborne SAR (Synthetic Aperture Radar) systems and related programs currently envisioned by the international science community provide an important framework for addressing key science issues and applications inland surface processes. The models that simulate these processes require surface parameters such as vegetation structure and biomass, land cover, soil and canopy moisture that SAR measurements being sensitive to surface geomerty and dielectric properties can provide. This paper outlines the potential applications of polarimetric SAR systems over tropical regions such as mapping land use and deforestation, forest regeneration, wetland and inundation studies, and mapping land cover types for biodiversity and habitat conservation studies.

Keywords: SAR, Polarimetry, Land Use, Biomass, Moisture

1. Introduction

At present, several interdisciplinary studies around the world are concentrated on understanding the processes that govern the interaction of the land surface with the atmosphere and the changes that are occurring in both, primarily as a result of human activities. These processes are modeled at different scales require parameterization of the land surface to be included eventually in the climate models. Although climate models require global specification of land properties on a spatial scale of 25 -50 km, sub-grid models dealing with the surface hetrogeneity may require parametric inputs of finer spatial resolution (Dickinson, 1995). These parameters are fundamentally used as controlling variables in land-atmosphere carbon, energy, and water exchange models that characterize the thermodynamic, chemical, and biological processes involved in the interaction between the land surface and the lower atmosphere (Hall, et al., 1995). The general categories of parameter inputs consists of vegetation and soil parameters, among them, land vegetation cover, community composition, vegetation structure such as leaf area index, biomass density, phenology, vegetation condition, primary productivity, canopy roughness, and soil moisture. Remote sensing techniques are beginning to play an important role in providing these parameters on global and regional scales and

to contribute in improving and validating these models.

Tropical forests, because of the large area of land surface they cover (about 1600 million hectares at the climatic climax), their humid climate (rainfalls of above 2000 mm per year), and being the most luxuriant and species-rich forests are responsible for the major proportion of the earth's biological productivity. This represents a vast yearly intake of the CO₂ which is stored in the tree's tissues. A large number of ecological studies conclude that the conversion of this ecosystem is realizing a as much CO₂ in the atmosphere as were the industrial processes (Detwiller and Hall, 1988). Reducing the uncertainty in estimating the release of CO₂ requires an accurate estimate of the deforested and new regrowth areas. Monitoring and mapping the land use change in tropical region, therefore, is still a challenging scientific problem. Deforestation of the tropical rainforest and its conversion to other land cover types such as pasture introduces several other scientific problems to be tackled. For example, the dynamics of the conversion of forest to pasture, agricultural crops and forest regeneration that in turn affects the potential of the land for sustainable production of food and protein. Deforestation in the entire tropical belt, encompassing Africa, Asia, Central and South America is estimated to be 42% of the total moist

tropical forest (Buschbacher, 1986). Checking the accuracy of this estimate is hindered by insufficient database and remote sensing techniques are the main source of providing the required database.

The hydrological problem associated with the river basins in tropics such as in the Amazon rainforest, also requires information about the dynamic of land use change and its impact on the routing of water and its chemical load from precipitation input through the drainage system back to atmosphere and to the ocean. Remote sensing techniques can provide information such as land use change, surface soil moisture and forest inundation dynamics that can be used directly in the tropical river catchment studies (Richey, et al., 1989). Furthermore, in studies related to biogenic trace gas exchange, the knowledge of type and distribution of wetlands and the temporal distribution of inundation in tropical region can reduce the uncertainties due to spatial and seasonal extend of the methane source and sink areas. Several other issues such as the increasing rise of insect related disease outbreaks in tropical wetlands are correlated with rainfall events and flooding episodes and the type of vegetation cover (herbaceous and woody vegetation) that can be monitored with remote sensing techniques (Hess, et al., 1995, Pope, et al., 1994).

In this paper, we attempt to demonstrate the potential application of radar remote sensing in the above mentioned processes. The data presented in this study are taken from a series of experiments involving airborne and spaceborne systems over the tropical ecosystems in South America. The characteristics of polarimetric SAR systems and the factors that affect SAR backscatter measurements are described in section 2. In sections 3 to 6, several examples pertaining to land surface process studies are discussed and references are provided for further discussion and approaches.

2. SAR Polarimetry

Radar remote sensing instruments operate in microwave region of the electromagnetic spectrum where the atmospheric interference is minimum and the water vapor column and cloud cover do not affect the propagation of the radar signal. Because radar furnishes its own illumination, images could be obtained either during the day or night, a considerable advantage over optical sensors that depend on the sun as the light source or obscured by the presence of clouds. In the past two decade, radar systems have evolved from a real aperture single frequency and polarization system, to synthetic aperture (SAR), polarimetric

systems operating at various wavelengths, providing measurements of wavelength-scale geometrical and polarization properties of the surface in the form of high resolution images. Polarimetric SAR systems allow measurements of the amplitude and relative phase of all polarization configurations of the transmit and receive antennas for all independent resolution elements in a scene (Ulaby and Elachi, 1990). A typical polarimeter is configured such that it uses the horizontally and vertically polarized antennas to achieve the polarization diversity by measuring the true scattering matrix of a resolution element. From the scattering matrix measurements, the Stokes matrix that relates the transmitting and receiving wave intensities are formed. The quantity that is often used to characterize the resolution element is referred as backscattering coefficient and is defined by the radar equation as the effective scattering area subtended by the scatterer divided by the resolution area. In what follows, we use H as horizontal polarization and V as vertical polarization of either transmit or received antennas. Therefore the backscattering coefficient are measured in HH, HV, VH, and VV polarizations that refer to the combinations of transmit and received polarizations (HV and VH are equal in backscattered direction).

Polarimetric measurements permit better identification of the scattering mechanisms that in turn help resolve the electrical and geometrical properties of the surface (Figure 1). Depending on the wavelength of the system, the penetration depth of the radar signal through vegetation and soil surface varies, allowing stratification of the geometrical properties of the land surfaces. Overall the information embedded in the polarimetric multifrequency SAR data can be related to three major categories of parameters of the land surfaces: geometry, penetration, and moisture. Looking at forests, the backscatter measurements related to several scattering mechanisms such as direct backscattering from crown (branch and leaves), crown-ground scattering, trunk-ground scattering and the direct scattering from the forest floor. The significance of these mechanisms vary in different polarization configurations.

Several spaceborne and airborne SAR systems are used in land surface applications. The airborne JPL AIRSAR system has three frequencies P-band (60 cm wavelength), L-band (24 cm wavelength), and C-band (6 cm wavelength) and operates in fully polarimetric mode. The SIR-C/X-SAR system has L-, and C-band polarimetric and X-band (3 cm wavelength) VV polarization and was used in two ten day missions in April and October of 1994 aboard the Space Shuttle Endeavor. In addition, currently

there are three orbital radar systems: the European ERS-1 system (at C-band VV polarization), the Japanese JERS-1 system (L-band HH polarization), and the Canadian RADARSAT system (C-band HH). Image data available from these instruments have been used in several studies to demonstrate their unique applications in land surface processes in tropics. Although, these studies are by no means perfect and many factors that contribute to the radar backscatter from soil and vegetation are yet to be fully explored, the results obtained so far indicate that the signal penetration through forest canopy and its sensitivity to vegetation moisture and morphology are relevant to any future studies of the tropical biosphere.

3. Land Use and Deforestation

The causes of deforestation and land use change in tropical region depend on several factors among them the colonization programs, legal systems of tenure, relation of natural resources such as timber and production systems to economic and social variables. Recent estimation of the rate of deforestation in Amazonia implies that the conversion of forest to pasture and agricultural crops has a rapid pace. By 1991, the total area of Brazilian Amazon reached 426,000 km² with annual rate of approximately 22,000 km² over 1978-1988 and 14,000 km² in 1989-1990 and 19,000 km² for 1990-1991 (Fearnside, 1993). These figures imply that the process of deforestation is dynamic and any monitoring techniques must be accurate and frequent. The main source of deforestation studies over Amazon basin has been the Landsat imagery (Skole and Tucker, 1993; INPE, 1992). Despite exalting results from Landsat data, difficulties of obtaining more frequent data over areas where continuous cloud cover obscures the ground and inconsistent means of delineating secondary forest from primary forest and/or from various practices of forest disturbances suggest that accurate land use and deforestation mapping is still a major scientific challenge. Other regions of the tropical rainforests such as Africa and Asia are yet to be mapped routinely.

Spaceborne radar systems are potential tools for resolving some of the ambiguities in optical remote sensing techniques. The first contiguous mapping of vegetation and land use in the Brazilian Amazon was performed by the RADAMBRAZIL using an airborne X-band radar system supported by extensive field surveys. A recent study using the SIR-C polarimetric data over Rondonia has shown that polarimetric radar systems at L-band (1.25 GHz) and C-band (5.3 GHz) with HH and HV polarizations are

successful in separating forest and nonforest and furthermore delineating land use practices and forest regeneration (Saatchi, et al., 1996a). Figure 2 shows the results from this study. Using the four channels of the SIR-C data, five class types of primary forest, secondary regrowth, disturbed forest, quebradao, and pasture/crops with 72% accuracy. When the classes were reduced to three and only L-band polarimetric data were used, the accuracy of classification increased to 94%. The classification was based on the statistics of the backscatter data using a maximum a posteriori Bayesian classifier. The sensitivity of the HH and HV polarized backscattering coefficients to biomass and vegetation structure and moisture were among the main reasons for identifying the land cover classes.

It has also been demonstrated that for routinely estimating the rate of deforestation, a single polarization low frequency radar system such as JERS-1 (L-band, HH polarization) may be sufficient (Saatchi, et al., 1996b). Figure 3 shows a mosaic of the JERS-1 images over Rondonia that has been classified into forest and non-forest using SAR backscatter and texture information. Currently, JERS-1 satellite is engaged in mapping rainforests over three continents of South America, Africa, and Asia that can improve the current estimates of the areas of forest and deforested land surfaces in the tropics.

4. Biomass Regeneration

Secondary forests cover more than 600 million hectares of tropical rainforest. The forest regeneration are created by both natural causes and human activity. After the forest is cleared for pasture, crop cultivation or timber, the process of succession begin shortly after the land is abandoned. The early stages of succession are characterized by a very dense undergrowth with weedy herbaceous plants and fast growing vines. The rapid growing of early colonizers are due to seed distribution in the soil immediately after disturbance. During this period, several forest structural attributes such as biomass and leaf area index increase rapidly that make the secondary regeneration a viable area to be detected by remote sensing techniques (Foody and Curran, 1994). One study shows that the leaf area index and woody biomass reach a maximum after about 20 and 40 years respectively (Brown and Lugo, 1990). The lack knowledge of the process of deforestation and forest regrowth in a large scale are the main sources of uncertainty in estimating the rate of the CO₂ exchange of terrestrial biota with the atmosphere. SAR systems operating at low frequency appear to be the only tool available for estimating the biomass distribution. Several

studies over boreal and temperate forests have demonstrated that the capability of SAR systems for measuring biomass is approximately 200 tons/ha at P-band, 100 tons/ha at L-band, and 50 tons/ha at C-band. Since most secondary forests up to 20 years of age do not necessarily have woody biomass values exceeding 100 tons/ha, the SAR systems can improve the estimation of the biomass regrowth in the tropical forests (Figure 4).

The analysis of airborne SAR data over primary forests in Manu National Park in Peru shows that at P-band wavelength, HV polarization is correlated with the branch biomass, whereas HH channel is correlated with stem biomass (Rignot, et al., 1995). In a similar study, the analysis of the SIR-C data over Tapajos National Forest in Para, Brazil shows that at L-band, HV polarization has the highest sensitivity to forest regrowth up to 9 years old (Yannse et al., 1996). Figure 5 illustrates the biomass variation over the Tapajos secondary forests by employing a biomass estimation algorithm that has been developed from forest backscatter modeling (Saatchi and Moghaddam, 1996). Further studies are required to understand the sensitivity and limitations of SAR measurements to biomass regrowth in tropics. Nevertheless, the limited studies performed so far implies that P-band polarimetric data correlate better with biomass regeneration than L-band. However, L-band polarimetric systems appear to be more operational than P-band in near future.

5. Forest Inundation

The large river basin and the periodic heavy rainy seasons responsible for the rise and fall of the river level, create large areas of inundated forest types in the tropics. These forests are distinct because of their limited diversity as compared to upland forests due to the stress caused by the waterlogging of their root systems. Inundated forest types are often divided into the permanent swamp forests (e.g. permanent white water and black water swamps, igapo), periodically flooded forests (e.g. mangrove, seasonal varzea and igapo, tidal swamp), and gallery forests. Information on distribution, morphometry, and the areal extend of these forests is important in the regulation of water balance and biogeochemical cycle, and trace gas exchanges such as methane. In addition, these areas are important for supporting fisheries and cultivation because of the relatively fertile soil left from the river sediments.

Polarimetric backscatter measurements at L-band and C-band can be used operationally to map floodplains and forest inundation because of the penetration of the signal into the vegetation

layer. Results from the SIR-C/X-SAR experiment shows that using radar can accurately delineate the herbaceous versus woody and flooded versus non-flooded cover types present in the Amazon river basin. Figure 6 shows the radar mapping of forest inundation in April (rainy season) and October (dry season). The results indicate that LHH accurately separated flooded versus nonflooded forests, CHH provided the best separation between flooded and nonflooded herbaceous vegetation, and LHV distinguished well between woody and nonwoody vegetation (Hess et al., 1995). Application of SAR systems in many ecological and biogeochemical studies of wetlands and floodplains has shown that polarimetric measurements provide a suitable tool for mapping various types of forest inundation (Pope, 1994, Melack, et al., 1994).

6. Biodiversity and Conservation

In recent years, satellite remote sensing has also been used in regional conservation and biodiversity studies worldwide. Deforestation and forest disturbance as a result of the expansion of human populations and human activities are the main cause of decay in organic diversity. In particular, tropical rainforests as being the most biologically diverse ecosystems, the conversion of primary biome has caused the degradation of forest habitats the concentration of species. This process is by no means even and some areas of the tropics are being affected harder than others (Myers, 1988). For example, the Atlantic forest that once occupied an area of more than one million square kilometers along Brazil's coast, is reduced to less than 9% of its original size because of colonization, mining, and extensive agricultural and urban development. The remaining forest, much of which is concentrated in the state of Bahia is highly fragmented and the populations of threatened species are in many cases reduced to very low number of individuals (Saatchi, et al., 1994). Local and international government and non-government organizations are initiating conservation efforts, such as land protection and land purchase to enlarge the federal biological reserves such as Una in Bahia. These efforts are limited by lack of information about the locations of priority sites for conservation purposes. High resolution remote sensing data that can help identify vegetation types in these regions are the main source of information.

During SIR-C/X-SAR mission in October of 1994, polarimetric SAR data have acquired over the Atlantic coastal forest of Bahia in support of conservation activities around the Una biological reserve located in southern Bahia. SIR-C data complemented the optical remote sensing

data for mapping the primary patches of forest by providing information about the sub-canopy that helped discriminating forest from cocoa plantations and mangrove that was previously unavailable from optical data. The results of the analysis indicates that L-band HV polarization backscatter from large canopy elements such as branches and leaves and correlates with areas of high biomass. Areas of pasture and young secondary forest growth have higher backscatter at C-band HV polarization. In cocoa plantations (cabruca forests), the canopy is thinned and understory vegetation is removed and replaced by sub-canopy cocoa. This causes a slight reduction in tree bole biomass (reducing L-band backscatter) and an increase in branch and foliage density in the sub-canopy (increasing C-band backscatter). The areas of mangrove swamp along the Atlantic coast has higher backscatter in all the channels of SAR data due to scattering of the SAR signal from the underlying standing water. These areas do not appear clearly in the Landsat imagery (Saatchi, et al., 1994). These differences in radar signals due to land cover types produce a different texture and backscattering coefficients that can be used to identify patches of primary forest for conservation practices. Figure 7 shows the preliminary results of mapping primary forest patches using a texture and backscatter data in a supervised Bayesian classifier.

7. Conclusion

In this paper, the potential applications of polarimetric radar backscatter measurements in studying land surface processes in the tropical forest ecosystems were briefly reviewed. It was shown that polarimetric and multifrequency measurements of the tropical vegetation provide information about the structure of forest and its moisture status that help classify the radar images into land cover types, separate deforested and forested areas, monitor and map wetlands and inundated areas, and monitor and estimate forest biomass regeneration. The examples were taken mainly from the data collected by the SIR-C/X-SAR system in 1994. The results also demonstrate that the temporal frequency of calibrated SAR data over tropics suggest that it can monitor the dynamics of land use change better than optical sensors in this region. However, accurate land cover classification maps are often achieved if both sensors are used in synergism. Furthermore, the forest regenerated biomass can be estimated by lower frequency polarimetric data (P- and L-band) that are not currently available in space. It is expected that as polarimetric spaceborne systems become operational in future, SAR imagery may

become an invaluable source of information over tropics.

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Figure Caption

Fig. 1. Penetration capability of radar systems through vegetation.

Fig. 2. SIR-C derived land use map of a site in Rondonia, Brazil. The cover types are primary forest, secondary regrowth, disturbed forest, quebradao, and pasture/crops (Saatchi, et al., 1996).

Fig. 3. Deforestation map of Rondonia derived from JERS-1 mosaic in 1993-1994. The area covered by the top image is located north of Ouro Preto and by the bottom image is located east of Porto Velho.

Fig. 4. Biomass regrowth of leaves, roots and wood of different aged secondary forests in tropical forests (Brown and Lugo, 1990).

Fig. 5. Biomass variations of secondary regrowth in Tapajos National Park.

Fig. 6. SIR-C classified images of forest inundation of Amazon river basin in April and October (Hess, et al., 1995).

Fig. 7 SIR-C L-band and C-band color composite image of Una biological reserve in southern Bahia and the classified map of primary forest.