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RECENT ADVANCES IN RADAR REMOTE SENSING OF FOREST

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I - INTRODUCTION

On a global scale, forest represents most of the terrestrial standing biomass (80 to 90%). Thus, natural and anthropogenic change in forest covers can have major impacts not only on local ecosystems but also on global hydrologic, climatic and biogeochemical cycles that involve exchange of energy, water, carbon and other elements between the earth and atmosphere. Quantitative information on the state and dynamics of forest ecosystems and their interactions with the global cycles appear necessary to understand how the earth works as a natural system.

The information required include the lateral and vertical distribution of forest cover, the estimates of standing biomass (woody and foliar volume), the phenological and environmental variations and disturbances (clearcutting, fires, flood) and the longer term variations following to deforestation (regeneration, successional stages). To this end, seasonal, annual and decadal information is necessary in order to separate the long term effects in the global ecosystem from short term seasonal and interannual variations.

Optical remote sensing has been used until now to study the forest cover at local, regional to global scale. Radar remote sensing, which provides recently SAR data from space on a regular basis, represents an unique means of consistent monitoring with different time scales, at all latitudes and in any atmospheric conditions. Also, SAR data have shown potential to detect several forest parameters that cannot be inferred from optical data. The differences -and complementarity- lie in the penetration capabilities of SAR data and their sensitivity to dielectric and geometric properties of the canopy volume ; while optical data are sensitive to the chemical composition of the external foliar layer of the vegetation canopy.

Basically, the radar backscatter is sensitive to the quantity and state of water distributed in the complex vertical and horizontal structure of the canopy. Thus, it is expected that the radar measurement contains information on the forest type, tree architecture, tree biomass by parts (trunk, branches, leaves), canopy structure and also in certain conditions, the ground topography, soil moisture, soil surface roughness and understory vegetation. The physical relationships between radar backscatter and forest parameters depend on the radar frequency, polarization, incidence.

Past results using SEASAT, SIR-A, SIR-B and airborne data demonstrated the use of SAR data for mapping of forest extent, mapping of wetland extent in forested areas, detection of disturbances due to deforestation, fires or flood. Some research attempts have been made to relate the radar backscatter to forest height, age class and biomass but the approach used was almost empirical. Given the complexity of the interaction mechanisms, to develop and validate algorithms which will provide the biophysical product from SAR data require a quantitative approach evolving both experiments and theory.

II - RECENT ADVANCES

During the past three years, significant progress has been observed in radar remote sensing of forest. There has been an emerging international concensus on the need for worldwide studies on processes associated with climate change, in which forest covers play an important role. Also, research in radar remote sensing has been driven by the numerous spaceborne SAR missions scheduled in the 90's, starting with ERS-1 launched in 1991 and J-ERS-1 in 1992.

Technical advances in the development of SAR systems have provided in the past years multiparameter airborne SARs. Such systems, when calibrated, are optimum tools for algorithm development. Among those the current NASA/JPL system is an operational, three frequency polarimetric SAR which has taken part in many data acquisition campaigns in the world since 1988. Observation of forest covers is currently one of the most important research topics of such airborne missions. Experiments have been performed on a diversity of forest ecosystems in the US, Canada, Europe and in the tropics. Experimental procedures have been refined and more relevant ground data have been collected. Meanwhile, significant improvement in theoretical modeling of forest backscatter has been observed. This resulted from the availability and the relevance of experimental data and a better integration of the experimental and modeling approaches in the research projects.

Since 1991, ERS-1 has open a new era of SAR data that can be used on a regular basis. The radiometric and geometric quality of the data currently provided by ERS-1 makes possible the use of multitemporal observations either for terrain identification or for changes detection.

Recent results in remote sensing of forests concern several aspects including forest type classification, determination of phenological and environmental states of the forests (*Way et al. 1992*) or the extent of flooded forests. However, the emphasis has been put on two main subjects : deforestation monitoring and biomass determination.

II-1 DEFORESTATION

The conversion of forests to agriculture and pasture and the harvest of forest for timber and fuelwood cause a net release of C02 and also other trace gases such as methane and nitrous oxide. Uncertainties in the estimates of the amount of carbon released globally from vegetation and soils result from different assumptions concerning 1/ the rate of land use change, in particular the rate of deforestation and 2/ the biotic response to disturbances.

Even today although much progress has been made in recent years, estimates of the current rate of conversion of tropical forests to agricultural land vary from 70.000 to 100.000 km2 per year.

The SAR is expected to contribute significantly to determine accurately the perturbation characteristics including the rate and location of 1/ecosystem conversion to agriculture and pasture, 2/forests degraded for timber harvest of fuelwood and 3/afforestation and natural regrowth.

To measure the extent of deforestation has been well demonstrated with SEASAT, SIR-A, SIR-B and with airborne SARs operating at low frequencies (e.g. L and P bands). The contrast ratio between radar backscatter intensity of forests and other land uses including clearcut, agriculture, pasture is of the order of several dB in most cases.

At higher frequencies (e.g. C and X bands), the radar backscatter of deforested areas varies as a function of the terrain characteristics including soil surface roughness, soil moisture, crop, grass or regrowth vegetation parameters. Thus, deforested areas can have a large range of backscatter values. With ERS-1 (5.3 GHz, 23° of incidence, VV) the conversion of forest to wide spreading pasture can logically be detected as shown on ERS-1 images in the Amazone basin (ESA, 1993). On the other hand, small patches deforested for shifting cultivation, e.g. in Africa, might be difficult to identify on the basis of their radar backscatter intensity at a single date.

The availability of reliable multitemporal data by ERS-1 offers possibilities to develop classification methods based on their temporal changes. In general, forest covers exhibit minor temporal change compared to clear cut, agriculture and other land uses. Through several examples of overlaid multitemporal images of ERS-1, the use of temporal changes for forest and land use classification and monitoring appear obvious.

In the past few years, a new approach of classification methods based on scattering behaviour of different surface types instead of their backscattering intensity have been developed (*Kong et al 1988, Van Zyl 1989, Evans et al 1990, Freeman et al 1992*). The development and validation of such methods have been possible since reliable airborne, polarimetric SAR data have been collected). In general, the polarization state of the received wave is compared to that of the transmitted wave in order to deduce the properties of the scatterer. The classification can be unsupervised, based solely on comparing general properties of the Stokes parameters of the scattered wave to that of simple scattering models. As an example, results at L band (*Van Zyl 1989*) indicated that scattering from clear cut areas and agricultural fields is mostly similar to that predicted by the odd number of reflection class while the scattering from forest covers generally is classified as being a mixture of characteristics odd and even reflections and diffuse scattering.
For future spaceborne SARs, the use of polarimetric data may improve significantly the robustness of algorithms of forest/non forest delimitation.

II-2 FOREST BIOMASS

Besides the rate of deforestation, one of the greatest uncertainties concerning the global carbon budget arise from a lack of information on forest biomass. First the assessment of the biomass of existing forests is necessary to determine the amount of CO_2 released to the atmosphere by forest burning. Also, to determine whether forests are a source or a sink of carbon, accurate estimate of biomass and carbon storage is needed, especially that of regenerating forests which accumulate carbon quickly during the first 20-30 years after disturbance.

Optical remote sensing of forests is based on spectral reflectance data governed mainly by tree foliage properties including leaf internal structure, leaf chemical composition and leaf angle orientation. With longer wavelengths, radar waves can penetrate into the forest canopy and the radar backscatter can give information on the trunk, branches, which represents 90% of the total above ground biomass.

In the past years, it was observed that the intensity in a SAR image at low frequency (L-band) is proportional to several forest parameters including tree height, stand age and above ground biomass of the forest stands.

However, to develop a robust algorithm for inversion of SAR data into forest biomass requires a thorough understanding of the interaction mechanisms between microwave and forest canopy. This is necessary to define the validity domains of inversion algorithm regarding the SAR parameters, the forest characteristics and the environmental conditions.

The last few years have seen several experiments conducted on forest covers using multifrequency, polarimetric SARs together with an appropriate ground data collection plan (*Kasischke et al, 1991, Dobson et al. 1992 Ranson et al. 1992, Le Toan et al. 1992*). To reduce uncertainties in measurements of forest parameters most experiments have been performed on coniferous forests, which present a relatively simple structure at the tree and stand level.

The observations confirmed past results on the strong correlation between radar backscatter at low frequencies (P and L bands) and forest parameters. With well calibrated radars, quantitative comparison between frequencies and polarizations is now possible. P-band backscatter intensity yields the best correlation and the best sensitivity to forest biomass. Also cross polarization gives better results compared to like polarizations (*Le Toan et al. 1992, Dobson et al. 1992)*. Polarimetric features, such as the polarization phase differences can be also related to forest age or biomass. However, their contribution compared to the backscatter intensity is not significant in terms of the retrieval of forest biomass. Nevertheless, polarimetric measurements have been very useful for the modeling of forest backscatter at different frequencies.

Theoretical modeling will constitute the foundation of inversion techniques. The requirement is that the models must include all the physical properties of the target involved in the interaction process so that they can cope with simultaneous observations of a large variety of active (and passive) systems using multiple frequencies and multiple polarizations.

In general, two main approaches have been used to solve the scattering problem : the field approach and the intensity approach. Also, approximations have been made to characterize the vegetation canopy either as a continuous medium or a discrete medium.

Most models developed to describe the backscatter of forest canopies use the radiative transfer theory with a discrete medium approach. The models consider vegetation as a collection of lossy scatterers representing vegetation components (leaves, stems, branches, trunks). The forest canopy is in general modeled as a multilayer medium, each with a specific distribution of dimension, orientation and dielectric constants of the scatterers of various shapes. Although the radiative transfer theory provides only the incoherent terms, with the vector formulation of the theory multiple scattering problems and polarimetric backscattering can be accounted for.

Recent improvements in modeling of forest canopies included :

a) the consideration of more complete structure of the trees instead of simplifications in the past assimilating the trees as leaves alone or branches and soil alone etc.

b) more accurate calculation of the scattering of vegetation elements assimilated to finite dielectric cylinders or dielectric discs,

c) the consideration of coherent interaction between elements of structured vegetation,

d) the addition of second order scattering and,

e) the consideration of the interaction between vegetation and rough soil surface.

However, the most important progress concerned the model validation which benefited from more concertation between experimenters and modelers. More appropriate vegetation data have been measured in view of their transformation into model input parameters. On the other hand, experimental observations on the polarization and frequency behaviour of the radar basckscatter have led to substantial improvements of the theoretical models.

Several results of model validation have been published recently (*Durden et al. 1989, Ulaby et al. 1990, Sun et al. 1991, Karam et al. 1992, Hsu et al. 1993*). Once validated, the models can be used to identify different scattering mechanisms at different frequencies and polarizations. It was found for example that at P-band, the most significant mechanism between radar wave and a pine forest is HH polarization from the interaction between trunk and ground and for HV and VV, the direct scattering from the branches (*Hsu et al. 1993*). Since there exists a strong correlation between different parts of the tree biomass, the correlation between radar backscattering coefficients and trunk biomass, branch biomass and total biomass as found experimentally are now understood (*Beaudoin et al. 1993*).

III - CURRENT AND FUTURE WORKS

More works are still needed to conduct experimental/theoretical studies on different forest ecosystems in order to generalize the results obtained on the retrieval of forest parameters. Also, the use of multifrequency, multipolarization data to retrieve different forest parameters including biomass by parts, canopy structure and ground information must be undertaken, at present with airborne SARs and in near future with SIR-C/X-SAR.

On the other hand, the use of data from current satellites (ERS-1, J-ERS-1) is presently assessed for forest observations.

One possible research direction concerns a reexamination of the types of forest parameters of interest retrievable from SAR data in relation with ecosystem modeling. The sensitivity of radar backscatter to tree water content, tree water status and tree structure can be taken into account to derive some condensed descriptors of forest ecosystems.

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