Geoinformation for European-wide Integration, Benes (ed.)
© 2003 Millpress, Rotterdam, ISBN 90-77017-71-2

Forest monitoring at local and global scale with passive microwave sensors

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Keywords: forest ecosystems, microwave radiometry, woody biomass

ABSTRACT: This paper aims to evaluate the capabilities of multi-frequency microwave radiometers in monitoring forest ecosystems. Radiometric measurements were carried out on forest areas by using airborne and satellite sensors. The forests monitored with airborne sensors were six permanent plots selected among the most frequent ecosystem types of broadleaved forests, including: beech, Turkey oak and Holm oak. The selected areas were located at various altitudes in Tuscany, Italy. The performed radiometric observations have indicated the sensitivity of multi-frequency microwave emission to forest type and biomass. The highest frequencies (Ka and X) have been successful in distinguishing different forest types, whereas L- band has been found to be the most significant frequency for estimating woody volume and basal area.
Satellite data were collected from SSM/I over two yearly cycles on the Evergreen Spruce forest in Russia, and the Needle-leaved deciduous forest of Larix (Jiagedaqi) in China. Results obtained on the evergreen forest indicated that different levels of brightness are mostly due to surface temperature variations, whilst the measurements on Jiagedaqi confirmed the sensitivity of microwave emission to vegetation cycle. Simulations performed at L-band with a discrete element radiative transfer model were found to be in reasonable agreement with experimental data.

1 INTRODUCTION

In recent years, the interest in remote sensing observation of forest ecosystems both on local and global scale has significantly increased. Indeed, forests act as an interface between soil and atmosphere for the flux exchanges of oxygen, carbon dioxide and water vapor and are involved in the carbon cycle which is a topical subject for the climate global changes. An efficient monitoring and an early detection of natural and anthropic changes can help gain an understanding of the hydrological and biochemical processes of gas and water exchanges between soil and atmosphere through vegetation.

The contribution of passive microwave remote sensing to the global study of soil and vegetation parameters in forests has been pointed out in several theoretical studies (e.g. Karam 1994, Ferrazzoli and Guerriero1996). The use of microwave radiometers from satellites is hampered by the coarse ground resolution (of the order of several tens of kilometers). However, a much better resolution is achievable by using airborne sensors. This approach makes it also possible a surveillance of forests subject to fires or other sudden damage. It should also be considered that the next generation satellite sensors (SMOS, AMSR) will be able to attain much more enhanced performances.

Experimental investigations on boreal conifer forests were carried out by the Helsinki University of Technology by using satellite and airborne sensors (Hallikainen et al. 1988, Kurvonen et al. 1998, Hallikainen, et al. 2000). More recently, L-band radiometer measurements of conifer forests have been performed by Lang et al. (2000), who flew ESTAR radiometer over loblolly pine stands in Eastern Virginia. The evolution of water status in the Amazon Forest from SMMR data was studied by Calvet et al. (1994). Only a few data are available on Central and Southern European forests, which are mainly characterized by deciduous trees (Vichev et al. 1995).

A few significant studies for discriminating land surfaces and estimating quantitative parameters with microwave passive sensors from space have been conducted using data from the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave Imager (SSM/I). The research led to establishing empirical or semi-empirical rules for land surface classification (Ferraro et al 1986; Neale et al., 1990).

The aim of this research was to investigate the potential use of microwave radiometry in the study of characteristics of Mediterranean forests. Two significant aspects refer to forest classification and estimation of woody biomass. Major characteristics of land surfaces were derived from their emissivity spectra and polarization state, while a further classification of surfaces was carried out through clustering of multi-frequency, dual-polarized data.

After a short description of the sensors and test areas, performed in section 2, the paper presents the experimental results in section 3, and discuss them by using a radiative transfer model in section 4.

2 MICROWAVE SENSORS AND TEST AREAS

2.1 *Airborne data*

Two surveys using IROE multifrequancy radiometer were carried out in June 1999 on six forest stands in Tuscany (Italy). At that time the weather was warm and dry and no significant rainfall occurred between the two surveys.

The profiling passive microwave sensors, developed by IROE, operated at 1.4, 6.8, 10, and 37 GHz. The high frequency channels were installed in a "side-looking" configuration on the French aircraft ARAT (Fokker 27) to observe land at vertical and horizontal polarization simultaneously, at 30^o incidence angle. The L- band, vertical polarized, radiometer was flown "forward-looking" on an ultralight aircraft. Both sensor packages were equipped with a TV camera used for ground reference, and a thermal infrared sensor (8-14 µm) used for estimating surface temperature and normalizing the microwave brightness temperature. Both aircrafts surveyed each forest plot with two crossed flight paths.

The microwave instruments were self-calibrating digital radiometers with an internal calibrator based on two loads at different temperatures (250 ± 0.2 K and 370 ±0.2 K). The high frequency channels used corrugated horn antennas, while the L-band system made use of a microstrip antenna. For all sensors the footprint diameter was close to 100m. Calibration checks in the 30 K - 300 K range were carried out before and after the flights by means of an external blackbody and a noise source added to the sky emission measured by means of a reflecting plate. The radiometer accuracy (repeatability) was estimated better than ± 1K.

The investigated stands were six permanent monitoring plots selected among the most frequent ecosystem types of broadleaved forests in Tuscany, including: beech, Turkey oak and holm oak. The selected areas were located at various altitudes between the coast and the Tosco-Emilian Apennines. The average size of plots, of the order of some hectares, was large enough to contain several antenna footprints. Several ground parameters (tree height and density, trunk diameter, Leaf Area Index, foliar analysis, ground vegetation, soil characteristics, etc.), were made available by the Tuscan Regional Administration (Macelloni et al. 2001). Since the measurements were performed in warm weather, two weeks after the last significant rainfall, soil under trees was rather uniform and dry. During the flights microwave data were collected on some other forest stands of pines and firs and have also been analyzed in this paper, although no ground data were available on them.

2.2 *Satellite data*

The Special Sensor Microwave Imager (SSM/I) is a conical scanning multifrequency microwave radiometer on board DMSP (Defense Meteorological Satellite Project) series satellites. The frequencies are: 19.35, 22.23, 37 and 85.5 GHz, with an incidence angle of 51^o and a swath width of 1394 km. All the channels, except the one at 22 GHz, measure both linear vertical (V) and horizontal (H) polarisation components. The 3 dB footprint size ranges from 15 km to 69 km along-track and 13 km to 43 km cross-track, in accordance with the observation frequency.

Radiometric data relative to the test sites under study were selected from global data collected for the entire year of 1997. The area dimensions were determined as a compromise between the number of measurements necessary for a statistical analysis and the homogeneity of the area itself. Usually, the areas included more than 100 brightness temperature measurements at the lower SSM/I frequency. The standard deviation was less than 5 K at the highest frequency. Radiometric data were not corrected for atmospheric attenuation, which may represent a significant uncertainty for the 85 GHz band. However, a check for the presence of precipitations was performed by using the same data and the standard algorithms suggested in the SSM/I User's Guide and in the scientific literature (Hollinger et al., 1987; Neal et al., 1990). In order to separate the effects of surface temperature and emissivity variation, data collected in the morning (ascendent orbits) were divided from those collected in the afternoon (descendent orbits). All groups of data were averaged over a four-day period. The analysis was based on the following parameters:

- Brightness temperature (Tb) in horizontal (Tbh) and vertical (Tbv) polarization;
- Polarization Index:

$$PI=2*(Tbv-Tbh)/(Tbv+Tbh);$$

- Frequency Index

$$FI = [(Tbv(19\ GHz) - Tbv\ (37\ GHz)+(Tbh(19\ GHz)- Tbh\ (37\ GHz)]/2)$$

Two types of forests were investigated: The Needle-leaved deciduous forest of Larix (Jiagedaqi) in China, characterized by cold winter with snowfalls, and the Evergreen Spruce forest in Russia, with cold winters and snowfalls;

Information on ground features and on precipitation events was derived from an atlas and from meteo stations located close to the sites (http://www.wunderground.com).

3 EXPERIMENTAL RESULTS

3.1 *Airborne data*

The spectra of five forest stands, represented in Fig. 1, show a steep increase of the normalized temperature (Tn = the ratio between the microwave and infrared brightness temperatures) between 1.4 and 10 GHz, followed by a plateau. From this diagram we can see that, at the lowest frequency, forests of the same species (holm oak) but with different biomass, such as those of Cala Violina and Colognole, have a significantly different value of Tn. On the other hand, soil, which could also affect L-band emission, had similar characteristics in all the investigated forests. At the higher frequencies Tn shows an appreciable sensitivity to forest type. It should be noted that the error bars represent the fluctuation of the signal due to combined effects of radiometer error and inhomogeneity of the target. In general, the estimated total error in normalized temperature is ± 0.008 unit. However, in one case of data collected on beech, the L- band emission was affected by some man-made interference and the error in the recovered signal increased to ± 0.010.

The two-dimensional diagram of Fig. 2 confirms that, using data at Ka (37 GHz) and X (10 GHz) bands, four types of forest can be identified: beech, corresponding to the lowest values of Tn at both frequencies; Turkey and Holm oaks, which show intermediate and comparable values of Tn and are indeed rather similar trees; and fir which is characterized by the highest values of Tn at Ka band. The same diagram shows that, while for the

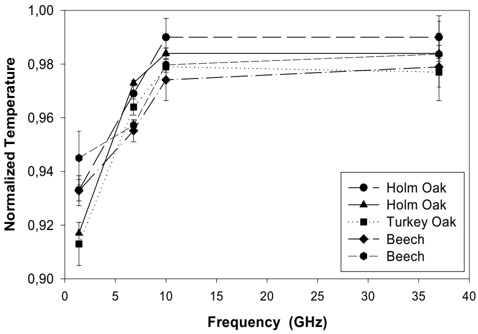

Figure 1. Spectra of normalized brightness temperature (Tn) of five forest types, at vertical (V) polarization and incidence angle $\vartheta = 30^{o}$

broad-leaved forest Tn at X band is higher or equal than Tn at Ka band, for fir Ka band emission is clearly higher than X band.

The sensitivity of microwave emission to forest biomass was evaluated by taking into consideration the basal area, BA, in m^2/ha (namely, the normalized total trunk base area) and the woody volume (WV, in m^3/ha, the volume of the whole tree cylinder computed by multiplying the previous parameter by the average tree height). The relationship between the normalized temperature Tn at Ka, X, C and L-bands (in V polarization) and WV is represented in Figure 3. As expected, the highest sensitivity to forest biomass was obtained at L-band where there is an increase of Tn as the biomass increases in accordance with the following logarithmic regression equations:

$$Tn = 0.015\ Ln\ (WV) + 0.84 \quad (1)$$

The correlations coefficient R^2 and the standard error SE are respectively $R^2 = 0.86$ and SE = 0.008. This behavior means that the forest stands behave as absorbing layers above the soil surface. It should be noted that a similar trend was obtained by Lang et al. (2000). On the other hand, at C-band and higher frequencies, as the forest parameters increase, there is a slight increase of Tn for the low values of biomass followed by a decrease for further increments of biomass. This trend can be interpreted as an initial phase, where absorption is still dominant, and a subsequent stage, where scattering plays a major role. These trends recall the ones already observed in agricultural crops (Paloscia and Pampaloni 1988, Paloscia and Pampaloni 1992).

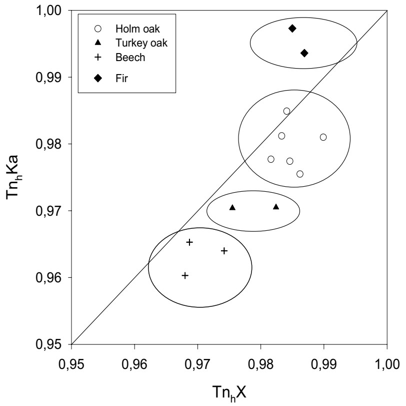

Figure 2. Forest discrimination. The normalized brightness temperature (Tn) measured at 36 GHz (Ka-band), horizontal polarization, as a function of the same quantity at 10 GHz (X-band), at $\theta = 30^o$. Four forest types can be separated.

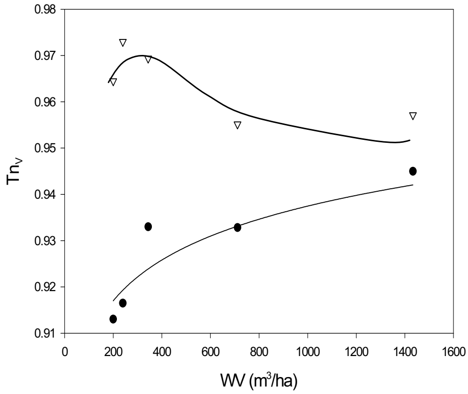

Figure 3. Sensitivity of microwave emission to tree biomass. The normalized brightness temperature (Tn), measured at two frequencies, as a function of woody volume (WV), (∇ = C-band, • = L-band). Continuous lines represent regression equations: logarithmic at L-band and polynomial at C-bands.

A small sensitivity to Leaf Area Index (LAI, m^2/m^2), which for trees represents only a small percentage of the woody biomass was noticeable at the higher frequencies only. The best correlation was obtained at Ka band with a correlation coefficient $R^2 = 0.55$ and standard error SE = 0.004. No significant correlation was noted at L-band (Macelloni et al. 2001).

One parameter related to the tree health status condition is the mean crown transparency, expressed in percentage, which is a direct symptom of leaf damage due to water stress, pollution, insect and/or fungi attack. We expected that the transparency of crowns would influence microwave emission in a different way depending on frequency. In fact, as the crown transparency (CT) increased up to 40%, emission at C-band showed a significant decrease, whereas at Ka-band it remained almost the same. On the basis of this observation, we assumed that the difference between the normalized temperatures at Ka- and C-bands ($\delta Tn = Tn_{Ka} - Tn_C$) could be an indicator of CT. In this case δTn at H polarization has been related to the mean crown transparency of each forest stand through the following equation:

$$\delta Tn = 0.0085 \, Ln(CT) - 0.003 \qquad (2)$$

with R^2=0.48 and SE = 0.006.

3.2 *Satellite data*

The emission features of the different areas were investigated on the basis of brightness temperature (Tb) spectra obtained from SSM/I data. Tb spectra at H polarization, measured in different months of the year on the Russian Evergreen Forest and the Chinese needle-leaved deciduous forest of Jiagedaqi, are represented in figures 4a and 4b, respectively. We can see that, in springtime and summer, the spectra are rather flat on both forests and that the different levels of brightness are only due to surface temperature variations. On the contrary, in winter the spectra show a decreasing trend typical of snow covered soil. It should be noted that the 85GHz data were affected by atmospheric conditions and the high values recorded in winter on Russian Forest are mostly due to a cloudy sky.

In order to better point out the characteristics of each region and the evolution in time of the vegetation covers, seasonal trends of microwave parameters were investigated. This was done by representing, for each area, the monthly values of polarization index PI at 19 GHz, and of frequency index FI (Figure 5). The diagrams indicate that FI is mainly sensitive to the presence of snow covering the soil of both forests from fall to springtime. The Polarization Index PI shows a different behavior on the two sites: on Russian conifer forest, where no appreciable change in vegetation cover is noticeable along all the year, it shows a yearly variation mostly related to the snow cover, similar to the one of FI. Instead, on the Larix forest, PI is more influenced by the vegetation cycle (larix leaves germinate in springtime and drop off in autumn) and shows a different trend respect to FI. The Polarization Index is

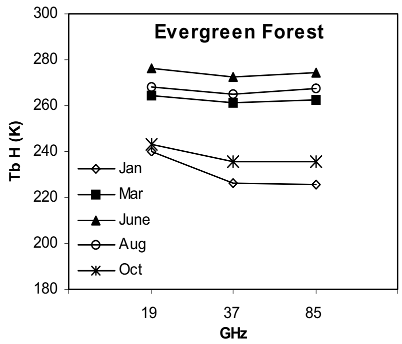

Figure 4 a. Evergreen Forest (Russia): Tb spectra at 19, 37 and 85 GHz, H polarisation for different months.

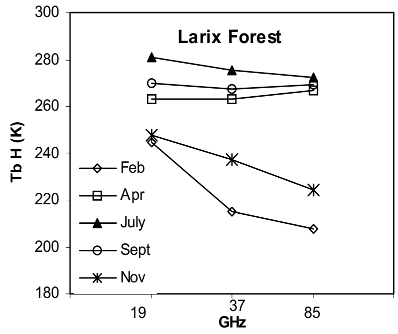

Figure 4 b. Larix Forest Jiagedaqi (China): Tb spectra at 19, 37 and 85 GHz, H polarisation for different months.

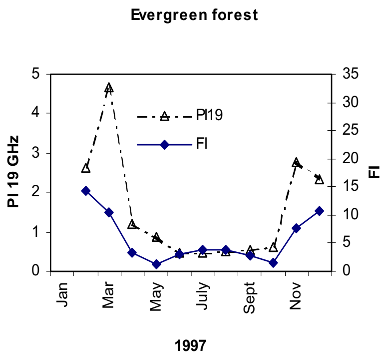

Figure 5 a. Evergreen Forest (Russia): Yearly variations of Polarisation Index at 19 GHz and Frequency Index

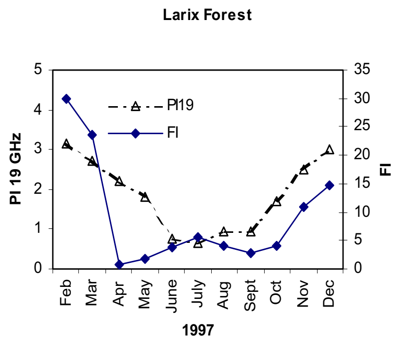

Figure 5 b. Deciduous Forest (Jiagedaqui - China): Yearly variations of Polarisation Index at 19 GHz and Frequency Index

in fact still high in springtime when FI is already low due to the fact that the snow disappeared but leafy vegetation is not yet developed. On the contrary, in autumn, PI begins to increase due to the fall of leaves when soil is still snow free (FI becomes >1 in November).

4 COMPARISON OF L-BAND EXPERIMENTAL RESULTS WITH MODEL SIMULATIONS

The sensitivity of L-band emission to woody volume of trees was a most significant result of this investigation. The relation between L-band brightness temperature and woody biomass was further analyzed by using a discrete element radiative transfer model (Tsang et al. 1985), which describes a forest as a two-layer medium (trunk and crown) over a rough soil. Trunks and branches were approximated by cylinders. Each crown consisted of four groups of branches with different dimensions. Due to very low sensitivity of L-band emission to LAI , the leaf contribution was disregarded whilst scattering from trunks and branches was computed by using the infinite cylinder approximation. Scattering from soil was computed through the Integral Equation Model (IEM) (Fung 1994).The emissivity was obtained from the bistatic scattering coefficients assuming reciprocity and conservation law. Model input parameters were obtained from ground data and allometric relations. A comparison of model simulations and experimental results obtained with airborne sensors on five forest types is represented in Figure 6 which shows a reasonable agreement of model simulations with experimental data.An analysis of various contributions to total emission from trees showed that the latter is mainly due to crowns and that contribution for double reflection from soil is negligible (Macelloni et al. 2001).

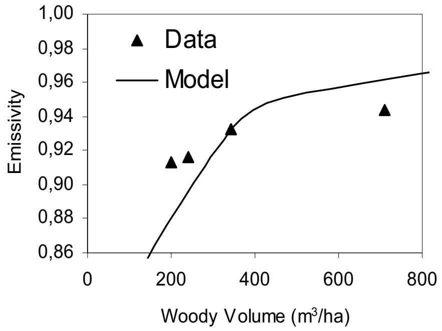

Figure 6. Comparison of L-band experimental data with model simulations. ($\vartheta = 30^o$, V pol)

5 CONCLUSIONS

The performed analysis of radiometric data has indicated a significant sensitivity of multi-frequency microwave emission to forest type and biomass. The most important interaction mechanism between microwaves and trees is absorption at low frequency or low biomass and scattering at high frequency and high biomass. The use of the highest frequencies (Ka and X) has been successful in distinguishing different forest types, whereas L- band has been found to be the most significant frequency channel for estimating woody volume and basal area of trees. Simulations performed at L-band with a discrete element radiative transfer model were found to be in reasonable agreement with experimental data. A model analysis showed that total emission from trees is mainly due to crowns and that the main contribution to crown emission is due to primary and medium branches.

REFERENCES

Calvet J-C., J-P.Wigneron, E.Mougin, Y.Kerr, J.Brito, 1994. Plant water content and temperature of the Amazon forest from satellite microwave radiometry, *IEEE Trans. Geosci Remote Sensing,* 32, 2, 397-408.

Ferraro R.R., Grody N.C., and Kogut J.A., 1986, Classification of geophysical parameters using passive microwave satellite measurements, *IEEE Trans. Geosci. and Remote Sensing* **24**, 1008-1013.

Ferrazzoli P., and L. Guerriero, 1996, Passive Microwave remote sensing of Forests: A model Investigation," *IEEE Trans. Geosci. Remote Sensing*, 34, pp. 433-443.

Fung A. K., *Microwave scattering and emission models and their applications*, Artech House Inc., Boston, 1994.

Hallikainen M.T, P.A. Jolma, J.M. Hyyppa, 1988, Satellite microwave radiometry of forest and surface types in Finland, *IEEE Trans. Geosci. Remote Sensing*, pp. 622-628.

Hallikainen M.T., V.S.Jääskeläinen, J.Pulliainen, J.Koskinen, 2000,Transmissivity of boreal forest canopies for microwave radiometry of snow, *Proc. of Intern. Geosc. Remote Sensing Symposium IGARSS 2000,* Hawaii, July 2000, pp. 1564-1566.

Hollinger, J., Lo R., Poe G., Savage R. and Peirce J., 1987, Special Sensor Microwave/Imager *User's Guide, Naval Research Laboratory*, Washington DC, 177 pp,

Karam M.A., 1994, The potential of microwave radiometers in monitoring forest biomass, *Proc. Geosc. Remote Sensing Symposium, IGARSS '94*, 3, pp. 1860-1862.

Kurvonen L., J. Pulliainen, and M. Hallikainen, 1998, Monitoring of boreal forests with multitemporal special sensor microwave imager, *Radio Science,* 33, pp. 731-744.

Lang R.H., P. de Matthaeis, D.M. Le Vine, S. Bidwell, M. Haken, N. Chauhan, 2000, L-band radiometer measurements of conifer forests, *Proc. Intern. Geosc. Remote Sensing Symposium, IGARSS 2000*, Honolulu, Hawaii, July 2000, pp 1930-1932.

Macelloni G., Paloscia S., Pampaloni P., Ruisi R., 2001, Airborne Multifrequency L- to Ka- band radiometric measurements over forests, *IEEE Trans. Geosci. Remote Sensing*, **39**, 2507-2513.

Neale C.M., McFarland M.J., Chang K., 1990, Land-Surface-Type Classification Using Microwave Brightness Temperatures from the Special Sensor Microwave/Imager, *IEEE Trans. Geosci. and Remote Sensing*, **28**, 829-838.

Paloscia S. and Pampaloni P., 1988, Microwave polarization index for monitoring vegetation growth. *IEEE Trans. Geosci. Remote Sensing*, **26**, 617-621.

Paloscia S. and P. Pampaloni, 1992, Microwave vegetation indexes for detecting biomass and water conditions of agricultural crops, *Remote Sens. Environ.* 40, pp.15-26.

Tsang L., J.A. Kong, R.T. Shin, 1985. *Theory of Microwave Remote Sensing*, J. Wiley & Sons, New York.

Vichev B.I, E.N.Krasteva, K.G.Kostov, 1995, Study of seasonal evolution of tree emission using zenith-looking microwave radiometers, *Proc. of Intern. Geosci. Remote Sensing Symposium IGARSS'95*, 10-14 July 1995, Florence (Italy), pp. 981-983.