PROGRESS AND PROBLEMS IN MICROWAVE RADIOMETRIC REMOTE SENSING OF SOIL MOISTURE (INSTRUMENTS AND APPLICATION)

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Summary: This paper summarizes the results of work done by authors in the area of passive microwave soil moisture measurements in Germany, Hungary, India, Italy, the USA and the USSR. A discussion is given on models of interconnection between spectrum of microwave radiation at millimeter, centimeter, and decimeter wavelength with parameters of soil and vegetation. A comparison is undertaken to analyze the approches for describing the influence of different types of soil, soil bulk density, surface roughness, and temperature variations as well as crop type, biomass and canopy architecture at different stages of growth, leaf area index, and temperature on microwave radiation of the soil/canopy system. Experimental data of sensitivity of microwave radiation to soil moisture and some other mentioned above parameters are presented. A comparison is given between the experimental and the theoretical data. Some attention is put on the dependencies of spectrum data of microwave radiation and the characteristics of soil moisture profile on the rate of the data change during drying of the soil , and on the screening effect of vegetation at different frequencies. A description is presented of some of the main results obtained in several international experiments conducted during the last few years. Future steps and approaches in this area of passive microwave remote sensing as well as ideas and plans for new experiments and instruments are presented as a subject for discussion.

Key words: passive microwave radiometry, soil moisture estimation, vegetation screening, microwave radiation models

1. PHYSICAL BACKGROUND

The thermal radiation from canopies depends both on their temperature and emissivity; its intensity reaches a maximum in the 8 - 14 µm band where the emissivity is usually fairly constant and higher than 0.95 and the emission is dominated by the surface temperature. On the other hand, in the microwave region, emissivity plays the major role in that it changes over a wider range depending on soil and plant properties.

It is shown theoretically that the main parameters that affect the radiation of soil and vegetation canopies are (Shutko, 1982 and 1987, Reutov et al., 1990):

- the dielectric properties of the medium (including conductivity) that are dependent mainly on the moisture content of the object, the bulk density, the material properties of the medium and the types and quantity of dissolved matter (degree of mineralization or, in particular, salinity)
- the physical temperature of the medium
- the peculiarities of the vertical profile of the temperature and the dielectric properties within an effective emitting layer that varies from some parts of the observation wavelength for a good conductive medium to some wavelength for a nonconductive medium
- the peculiarities of a geometric structure on the surface (the presence or absence of large or small compared with the wavelength undulations)
- the presence or absence of a layered structure within the medium and the type of connections between these layers.

As the water content increases, microwave emissivity becomes lower, whereas infrared emissivity tends to increase. Also, due to evapotranspiration, an increase of water in soil and plants is generally accompanied by a surface temperature decrease; these combined effects are dimmed in the infrared band and enhanced in the microwave one.

The sources of information in microwave radiation are (Shutko, 1987):

- the data of temporal and spatial measurements of the contrasts in microwave radiation for certain types of polarization at the fixed wavelength and angles of observation;
- the peculiarities in a spectrum of intensity of radiation for certain types of polarization at fixed angles of observation and the pecularities in a spectrum of the degree of polarization (coefficient of polarization) at fixed angles of observation
- the pecularities in the angular dependences of the characteristics of radiation at certain wavelengths.

It is necessary to recognize the methods based on the analysis of the contrast and spectral peculiarities of radiation for observation angles between 0 to 50 degrees to be the mostly worked out and practically used by now for studying the waters and grounds.

2. PRACTICAL RESULTS AT THE INSTITUTE FOR RADIOENGINEERING AND ELECTRONICS MOSCOW

Hardware and software for the remote sensing of environmental parameters by measuring their natural radiation at microwave frequencies have been developed by the IRE AS USSR over the last 20 years through extensive scientific and technological research, studies, experimental tests, and practical application (Shutko, 1986 and 1991, Shutko et al., 1991)

Currently available instruments consists of several portable, stable and sensitive radiometers operating at different wavelength ranging from 0.5-2cm to 20-30cm (1-1.5 GHz to 15-60 GHz). A typical set consisting of two to three instruments may be packed into a briefcase. The characteristic antenna size is 60x60x3 cm^3. Instruments may be used under laboratory conditions as well as on mobile ground and aircraft platforms.

The instruments and the retrival algorithms have been successfully tested since 1975 in the USSR, since 1983 in Bulgaria, Poland, East Germany, Hungary, Cuba, Vietnam and since 1990 in the USA during the MONSOON'90 experiment in the USDA ARS Walnut Gulch experimental watershed in Arizona, where a strong relationship between remotely sensed data and in situ measurements of soil moisture related to the

meteorological conditions and the surface relief has been observed. Responsible for the IRE radiometer performance during that experiment was Dr. Thomas Jackson of the USDA, Beltsville Agricultural Research Center, Hydrology Lab.
In many areas in the world where these instruments have been used they provide information invisible to the eyes about the depth to a shallow water table; contours of water seepage from irrigation canals; soil moisture content, biomass of agricultural and wetland vegetation and have been put in practice for operational mapping of above mentioned parameters at the territory of more than 7 million hectares in 10 republics of the former USSR.

3. MULTITEMPORAL MAPPING OF SOIL MOISTURE AT USDA-ARS HYDROLOGY LABORATORY

A common factor in most applications of soil moisture data is the need for repetitive observations over large areas. Critical research areas such as the role of surface layer in modeling the surface fluxes in climate models require this type of information. For these reasons, considerable efforts have been made to develop and verify efficient passive microwave mapping radiometers. Since we are dealing with aircraft based systems at this stage, the key factor in determining efficiency is minimizing flight time which in turn means the use of multibeam radiometers. In the U.S. two systems developed by NASA have been used; a pushbroom microwave radiometer (PBMR) and the electronically steered thinned array radiometer (ESTAR). Both of these systems operate at L band (21 cm or 1.41 GHz). The PBMR provides data at four beam positions over a range of plus and minus 32^{o}. This instrument has been extensively tested and found to be very reliable (Jackson et al., 1986 and Wang et al., 1989). Additional details on the PBMR can be found in Harrington and Lawrence (1985).
The ESTAR instrument being used can provide data for eight beam positions over a range of plus and minus 45^{o}, thus offering a significant improvement in mapping capabilities. In addition, the ESTAR approach has the potential to solve the resolution-antenna size problem inherent in using long wavelength systems at spacecraft altitudes. The verification program for ESTAR has only recently been initiated. Additional details on the ESTAR instrument can be found in Ruf et al., 1988 and Le Vine et al., 1989 and 1990.
These radiometer systems have been sucessfully used in several recent large scale hydrologic-meteorological experiments that illustrate both the efficiency of this approach to mapping soil moisture and the potential new information that may be obtainable through the careful study of the temporal changes.

HAPEX. This was the first multitemporal mapping experiment. The overall experiment objective was to improve the parametrizations of the land surface processes in atmospheric general circular models (GCM's). The study was conducted in southwestern France during the summer of 1986. A relatively small site was flown with the PBMR at total 13 times during a six week period. Brightness temperatures over the area ranged from 230^{o} K to 280^{o} K. Additional information on this experiment can be found in Andre et al. (1988). Analyses of these data is still ongoing.

FIFE. The objectives to FIFE were similar to those of HAPEX. The data collected in HAPEX was primarily over agricultural fields whereas the FIFE site was grassland located in Kansas. Microwave brightness temperatures were obtained with the PBMR over a 7 by 15 km area during 12 days in 1987. Preliminary flights had been conducted in 1986 and follow-up flights were made in 1989. Data from these experiments have been extensively analyzed and used to produce soil moisture maps. Additional information on FIFE can be found in Hall et al. (1989) and Wang et al. (1989) and (1990).

MONSOON'90. The purpose of this multidisciplinary experiment was to observe the moisture fluxes in an arid climate during a drydown and the role of remote sensing in determining these fluxes. The test site was a 5 by 20 km area of the Walnut Gulch rangeland watershed in Arizona. A series of 6 PBMR flights were made over a 10 day period in 1990. Conditions prior to the first flight were quite dry. This was followed by a heavy rain, which is clearly reflected in the image produced for the following day. The patterns observed in that image dramatically illustrate the variability of surface moisture in time and space. More details on MONSOON'90 can be found in Kustas et al. (1991). A multifrequency radiometer package developed by the USSR Academy of Sciences Institute of Radioengineering and Electronics was also flown as a part of this mission (Jackson et al., 1991).

4. MICROWAVE EMISSION FROM VEGETATION

Emission features of several types of natural surfaces have been investigated since 1980 by means of two microwave (10 GHz and 36 GHz) and one infrared (8-14 µm) radiometers used both from ground based (Pampaloni et al., 1983) and aircraft platforms (Bonsignori et al., 1987). Quantitative relationships between microwave emission, and some biomass parameters have been obtained for several crop types (Pampaloni et al. 1985b). These relations have shown that, although bare and vegetated soils generally show different values of brightness temperature, a single frequency and single polarization observation is generally of little use for investigating the biophysical characteristics of a surface. More information can be obtained by combining brightness temperatures measured at two frequencies and polarizations and by adding information taken in the thermal infrared band (Paloscia & Pampaloni, 1984; Pampaloni & Paloscia, 1985).
Accordingly, we defined the following microwave vegetation indexes: the Normalized Temperature (T_n, i.e. the ratio between the microwave "brightness" and infrared "radiance" temperatures), the Normalized Temperature Difference (T_n, namely the difference between T_n at 36 GHz and 10 GHz), and the Polarization Index ($PI = [T_{bv} - T_{bh}] / \{[T_{bv} + T_{bh}] / 2\}$, i.e. the difference between the vertical and horizontal components of T_b divided by their sum). These indexes were found to depend on plant biomass and they could be related to some crop parameters such as the plant water content per square meter (Q in kg/m^2) and the leaf area index (LAI in m^2/m^2).
The use of normalized temperature (T_n)at 10 and 36 GHz allows discrimination among different crops. Indeed in this frequency range, emissivity seems to be affected by the morphology of canopies: plants characterized by broad and almost horizontal leaves, such as sugar beet and sun flower, have a lower value of normalized temperature both at 10 GHz and 36 GHz, whereas plants with small and randomly oriented leaves, such as alfalfa and wheat, show higher T_n mainly at 36 GHz. Corn, which is characterized by large but not fully horizontal leaves, especially in the upper part of the plant, has intermediate values of normalized temperature at both frequencies. The wide range of variability of alfalfa normalized temperature at 10 GHz seems to be due to the growth stage of the crop. The T_n of alfalfa crops over a moist soil is in fact linearily dependent on crop LAI.

Since the normalized temperatures at both frequencies are almost similar on fully grown plants, whereas they show a different value on agricultural bare soil, one could take advantage of this behaviour and use the difference between the two emissions at 36 GHz and 10 GHz to detect crop growth. However the most promising microwave parameter to detect vegetation biomass seems to be the polarization index. Experimental data have shown that, as expected, the PI at both frequencies, measured at incidence angles higher than 40^{o}, shows very different values between bare and vegetated soil. The result is understandable assuming that the V polarized emission from soil is attenuated by vegetation which in turn emits unpolarized radiation. Although the trend is similar at both frequencies, the range of variation is wider at 10 GHz than at 36 GHz. Moreover, PI at 10 GHz gradually changes according to the developement stage of plants, whereas at 36 GHz it only seems to be able to separate bare soil from vegetation. Finally, it has been observed that, at 10 GHz, the polarization index of some fully developed crops is negative.
An analysis of experimental data can be carried out on the basis of the Radiative Transfer Theory. In a very simplified approach vegetation has been modelled as a uniform absorbing and scattering medium over the soil surface (Mo et al., 1981). Computations, carried out on the basis of this model, have shown that at 36 GHz as well as at 10 GHz the scattering effects seem to be very low (Pampaloni & Paloscia, 1986). This result is probably influenced by the strong simplification introduced in the model. Assuming that scattering is negligible and that the brightness temperature $T_b(\tau,\mu)$ of a vegetated surface can be expressed as follows:

$$T_b(\tau,\mu) = (1 - e^{-\tau/\mu})\, T_c + \varepsilon_s T_s e^{-\tau/\mu} \qquad (1)$$

where τ is the equivalent optical depth; T_c is the vegetation temperature; T_s is the soil temperature; ε_s is the soil emissivity; $\mu = \cos\theta$ is the radiation direction.

It has been found (Pampaloni & Paloscia, 1986) that the relation between optical depth r and plant water content Q or leaf area index LAI of corn and alfalfa can be approximated by the equations:

$$r = (k/\sqrt{L})\ln(1+Q) = (k / y\sqrt{L})\ \mathrm{LAI} \qquad (2)$$

where Q is in kg/m^2, LAI in m^2/m^2, L is the wavelength in m, k is a crop factor which was found to be $0.16\sqrt{m}$ for corn and $0.25\sqrt{m}$ for alfalfa, and y (=3.3) is an experimental correlation factor between LAI and Q (Paloscia et al., 1988).

From eqs. 1 and 2, assuming $T_c = T_s = T_{IR}$ (infrared temperature), we can relate the normalized temperature T_n to LAI. Comparing the results with experimental data, we see that the model represents experimental data fairly well when LAI is higher than 1. To fit the points at LAI < 1, a soil emissivity higher than 0.82 (about 0.9) would be necessary. On the other hand, it is rather reasonable that soil moisture and then emissivity change during to crop growth, due to irrigations and rainfalls. At 36 GHz the sensitivity of T_n was found to be much lower, because, at this frequency, emissivity of soil is generally higher than at 10 GHz and near to the one of well developed vegetation. Notwithstanding the strong simplification introduced in this analysis, the model seems to be able to reproduce experimental data fairly well, provided adequate values of soil emissivity are choosen.
In the model taken into consideration, the emission from vegetation is assumed to be unpolarized, whereas the radiation

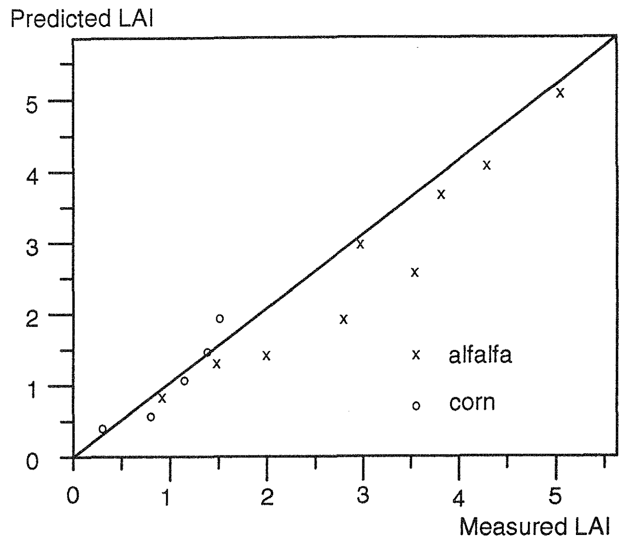

fig.1: Predicted LAI extracted from polarimetric measurements at 10 GHz ($\theta = 50^{o}$) as a function of measured LAI (after Paloscia & Pampaloni, 1988)

emitted by the whole canopy-soil system is polarized. Assuming that $T_s \sim T_c$,using eqs. 1 and 2, and since the average emissivity of agricultural soil is in the range of 0.85 - 0.95, we obtain (Paloscia et al., 1988):

$$PI(Q,\mu) = PI(O,\mu) / (1 + Q)^{k/\mu\sqrt{L}} \qquad (3)$$

$$PI(LAI) = PI(O,\mu)\, e^{-LAI\, k/y\mu\sqrt{L}} \qquad (4)$$

We see that LAI can be estimated from the Polarization Index when crop type (k) is known. The LAI predicted values from 10 GHz data are represented in fig. 1 as a function of the measured ones. Once crop type and $PI(O,\mu)$ are known (Paloscia et al., 1988) the model predicts with some underestimation the LAI of corn and alfalfa during the first growth phase, when LAI is lower than 5 for corn and 2 for alfalfa.
In a more sophisticated approach vegetation may be represented as alternate layers of randomly oriented dielectric disks and needles overlying an infinite halfspace (soil) with a rough boundary (Ferrazoli et al., 1992). This model generally confirms a negative trend of PI at 100 GHz versus vegetation growth and is able to predict a slightly negative value of PI observed on some well developed crops. The agreement with experimental results is better in the case of crops characterized by small leaves.

5. SOIL MOISTURE ESTIMATION USING TRUCK MOUNTED L, S MICROWAVE AND THERMAL INFRA BAND RADIOMETERS AND DIFFERENT THEORETICAL MODELS

Series of radiometer measurements were carried out in August 1990 in Taksony at the great plan of Hungary. The main aim of these measurements was to check the accuracy of the applied radiometers and theoretical models for soil moisture estimation.
The soil moisture estimations based on the measurements of truck mounted L- (1.41 GHz), S- (2.695 GHz) band microwave and thermal-infra radiometers. Tree test plots with a size of $12x12\ m^2$ each were prepared, removing the

vegetation cover and smoothing the surface with a grader. The first one was kept dry, the second one was artificially irrigated till saturation.
For comparison with the microwave measurements, a great number of soil samples were taken. At the corners of the test plots, soil moisture profile measurements were taken at the depth 0-2.5, 2.5-5, 5-10, 10-15, 15-20, 30-35 and 40-45cm, additional 32 surface soil samples were taken at the depth 0-2.5 and 2.5-5cm. The soil temperature was determined at the depth 0, 2, 5, 10, 15, 20, 30 and 40cm. The soil moisture was determined by the gravimetric method.
The calibration measurements were carried out from 6 m height at look angles of -5, 0, 5, 10 and 20 degrees, over calm water body and using 11cm thick Eccosorb sheets close to the antenna system (AN79). Based on the results of these measurements, the radiometer characteristics were determined. At all test areas, five microwave measurements were carried out before and after taking the soil samples. The observation angle was 5 degree with horizontal polarization. For the calculation of soil moisture values, two different theoretical models have been used: the first one publisched by Wang and Schmugge (1980), the second by Dobson et al. (1985). Both models based on a mixing equation which considers the contributions of the rock, air and water in the soil.
It has been concluded that the comparison of the gravimetric and estimated soil moisture values gave an error less than 5% at smooth surface. Also the roughness effect on microwave emission were studied, carrying out radiometer measurements before and after ploughing of the test plots. Different roughness correction models have been used and the results of the calculations are presented in Ijjas et al. (1991).

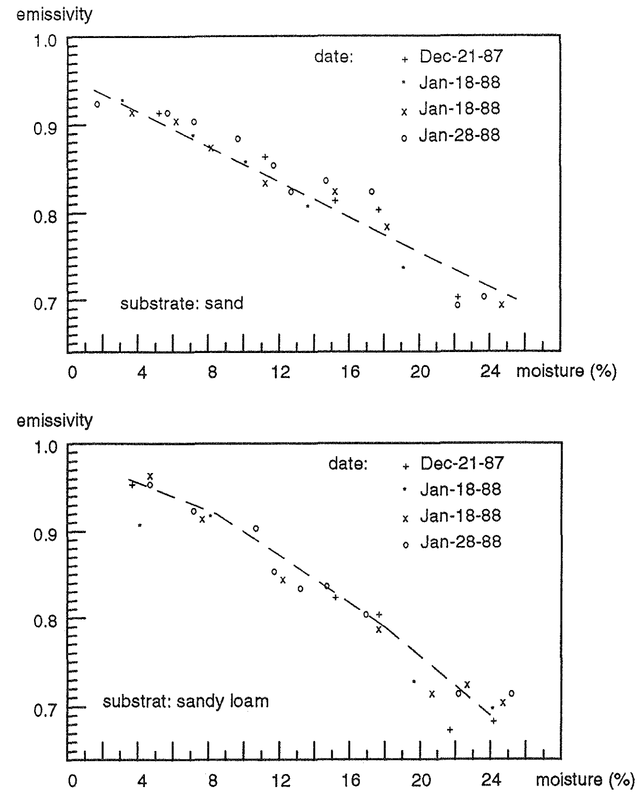

fig.2: Calibration results of the microwave passive radiometer at 10 GHz

6. SOME RESULTS OF PASSIVE MICROWAVE MEASUREMENTS IN EAST GERMANY; POLAND AND CUBA

In East Germany some research in the field of passive microwave radiometry was performed during the multistage experiments from 1986 to 1990 under of the INTERCOSMOS cooperation. In these experiments, carried out on test sites in East Germany 1986 (experiment GEOEX), Poland 1987 (experiment TELEGEO), Cuba 1988 (experiment CARIBE) and Mongolia 1990 (experiment GEOMON) we used the radiometer facilities of the former Central Institute for Physics of the Earth Potsdam, the Remote Sensing Centre in that time was a part of. Integrated in this radiometer system was a X-band microwave radiometer, designed and manufactured by the Technical Highschool Ilmenau, which could be operated either with the mobile ground station in connection with the other radiometers in the optical and infrared spectral bands, or in an aircraft or helicopter together with the multiband radiometer covering the Landsat-TM bands. The microwave radiometer is sensitive at a frequency of 10.4 Ghz with a half width of 500 Mhz, the aperture angle is about 15^{o}.For the calibration of the microwave radiometer as well as for the basic understanding of the physical background and interdependences connected with the microwave radiometry we performed some experiments under determined conditions. Several mixtures of sand and loam, homogeneus as well as layered, with variing temperature, moisture and surface roughness were measured from a distance of about 1-2 m and view angels of $0\text{-}40^{o}$ from nadir (fig.2). The drying out of the irrigated test plots with bare soil as well as the influence of several types of vegetation, in particular vital and dryed leaves of different size, layered as well as randomly oriented, was observed. More details on these experiments can be found in Söllner et al. (1988) and Weichelt (1988).
The experiments in Central Europe (East Germany and Poland) were carried out in agricultural test sites with typical landscape features of the Central-European internal lowland. In the southern part the groundwater is elevated up to near the surface level, marshy soils and humus gleys could be found. On ground moraine plateaus loamy underlaid sands are encountered that are partly slack or ground water influenced and have a different top sand layer thickness. Because of the strongly changing thickness of this top sand layer the soil moisture regime is a decisive yield factor.
On two days with an interval of one week during the GEOEX-experiment airborne radiometer missions with six tracks per flight were carried out. Dry weather conditions between the two flight dates leads to a decrease of the top soil moisture at the total of 32 ground control points of 2-5%, while the temperature of the top soil at noon increases from 25^{o} to 30^{o} C. Also the plant moisture during this time period decreased, nevertheless for the microwave signal of the given wavelength the corn and grassland vegetation was nearly opaque. So a direct differentiation of soil moisture over these fields could not be expected, the only way to expect the extraction of moisture information from the microwave measurements was a multitemporal analysis. Comparing the microwave signals of the two flights, a different increase of the brightness temperature over the test areas could be observed, indicating the decrease of moisture on major parts of the test site, with only exceptions near the Havel river channel.
On the sugar beets the results of the microwave measurements showed a decrease of the brightness temperature, which could be explained by an increase of the plant cover in conjunction with the plant growth. Previous investigations on sugar beet

leaves gave an emissivity value about 0.86, the soil emissivity was in contrary about 0.97 for the presumed water content. Based on this emissivity values and on the field measurements of the temperature and moisture for plants and soil during the airborne missions the plant coverage could be estimated from the microwave signals (tab. 1).

date	temperature (^{O}K) soil	vegetation	plot	field. estimation	microwave estimation
8. july	305	291	K_1	0.50	0.45
8. july	305	291	K_2	0.50	0.52
8. july	305	291	M_1	0.65	0.63
8. july	305	291	M_2	0.65	0.67
15. july	312	294	K_1	0.60	0.55
15. july	312	294	K_2	0.60	0.62
15. july	312	294	M_1	0.75	0.68
15. july	312	294	M_2	0.75	0.65

Tab. 1: Comparison of sugarbeet ground cover evaluated from microwave radiometric measurements and field estimation.

During the TELEGEO-experiment in Poland in addition to our microwave radiometer a Soviet microwave radiometer of the Moscow Institute of Radioengineering and Electronics (IRE) with a wavelength of about 30 cm was available. The results obtained there supported the expected wavelength-dependency of the vegetation influence on the microwave measurements at different bands: at greater wavelength the screening of the soil moisture signal by corn plants and pasture was significantly lower. This was obviously connected with the leave size and orientation. The higher soil moisture in the depressions and with decreasing distance to the Narev river was clearly detectable in the 30 cm microwave signal, while it was masked by the vegetation in the 3 cm band. Trees on the other hand could be detected in the 3 cm band while being not identified in the 30cm band. For the 3 cm band a classification of the profile across the lowland meadows to the river results only in open water places whereas for the 30 cm band the different soil moisture content in several parts of the meadows clearly could be recognized.

During the CARIBE experiment in April 1988 in the Republic of Cuba measurements with the microwave radiometer were carried out on flooded rice fields. The test site near Bayamo in the Eastern part of Cuba contained fields of rice aged 1 month in the northern part and about 2 month in the southern part. The top water level differed from 5 cm to 10 cm depending on the microrelief of the fields. Differences in the plant densities, which are characteristic for sown rice, were detected by microwave ground based measurements (from a height of about 10 m above ground) as well as from airplane measurements. Comparing the microwave measurements with the field investigations a definite relationship to the plant cover degree could be established. The results supported the expected behavior, that the differences in the plant cover and hence in the plant density decreases with increasing age and growth of the rice plants.

As the differences of the plant cover degree also influence other vegetation indicators like NDVI or VM2 (spectral curvature index), which has often been used by us, the common interpretation of multisensor results can give, for example, the possibility to identify dry and, for the rice planting, unproductive areas. While normally flooded areas can be characterized by a strong positive correlation between vegetation indexes and brightness temperature, dry areas have high brightness teperatures and a low vegetation index (fig. 3).

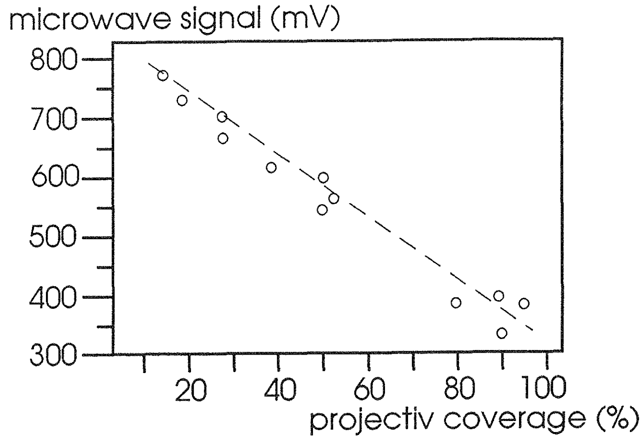

fig. 3: Microwave radiometer signal as function of the ground coverage on flooded rice fields.

More information about these experiments are given in Barsch et al. (1989) and Weichelt et al. (1990b).

A terrestrical application of the possibilities to extract soil moisture information from the passive microwave signal was developed for the investigation of the excavation materials of an open-cast mine of lignite in the state of Brandenburg (East Germany). For this purpose the microwave radiometer was equipped with a scanning device and mounted on the excavator near the operators cabin. According to the perpendicular scan and the horizontal movement of the excavator a two-dimensional pixel raster of the actual excavation plane has been measured. The microwave brightness temperature in every pixel position was measured by the radiometer, while the real physical surface temperature was determined by a parallel mounted thermal infrared radiometer. The stepwise scanning of the sequential excavation planes led to a three-dimensional emissivity model of the excavation body. In the experimental phase about 25 soil samples were taken and analyzed regarding their soil texture. For the interpretation of the microwave measurements they were divided into three groups with weak, medium and strong binding forces.

Typical for the investigated samples was the observed correlation between the binding force category and the soil moisture. Samples of the first group with a weak binding force had moisture values ranging from 2.4% to 5%, the second from 3.8% to 16% and the third from 16% to 31.2%. The observed emissivities were ranging from 0.99 to 0.92, 0.99 to 0.90 and 0.93 to 0.89, respectively. Without knowledge of the soil typ it is obviously impossible to determine the moisture content only from microwave and infrared measurements.

Nevertheless, considering the emissivity of this sediments as a function of the plastic and the flow limit a practical way for the diagnosis of the mechanical material behavior has been developed. While emissivities for materials with stronger binding forces decreases more slowly, also the limits for the plastic or flow behavior of these materials are reached at greater moisture contents. Therefore it is possible to determine a certain value of the emissivity where the plastic limit or the flow limit is reached or even exeeded independent from the material typ. Of course these emissivity values must be understand as inexact because of the influence of several minor effects. Nevertheless a procedure may be developed to establish an automatic alert system capable of warning the operator in case of sudden and uncontrolled moisture increase in the material to be excavated and to avoid hazards for the excavator. More details can be found in Weichelt et al. (1990a) and Schmidt et al. (1990).

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