Soil Moisture Measurements by Means of a Portable Dielectric Probe

Luzzi G., Chiarantini L., Coppo P., Gagliani S.

Science for Environment Foundation
Viale Galileo, 32 - 50125 Firenze

ABSTRACT

Soil moisture content is a fundamental parameter for Remote Sensing observations mainly at microwave frequencies. Conventional methods of soil moisture measurements, are often too time consuming for large area investigations and the attainable accuracy is not very high mainly because of the difficulty to obtain an unobstructed and representative sample. In the microwave spectrum, the dielectric behavior of the soil is strongly related to the degree of soil wetness because of the high value of the Dielectric Constant of water. Some measurements were carried out with a commercial probe working at 1.42 GHz, at the same time as the gravimetric moisture sampling, during a remote sensing campaign (MAC EUROPE 91) carried out with microwave and optical sensors, over agricultural fields located in the Chianti area near Florence. In this paper some preliminary results of data collected during this campaign are shown; also results of further measurements carried out in laboratory, aimed at the retrieval of the soil moisture content values from dielectric constant data are presented. Even if the field measurements are widely spread with respect to laboratory data, the accuracy achieved is good.

INTRODUCTION

The measurement of the Soil Moisture Content (SMC) is critical for many agricultural and geological applications and in particular it is also of fundamental importance for agrometeorological studies. Its role in various research fields (e.g. evapotranspiration studies, hydrology, phytopathology investigations) is well known. Remote Sensing is a good tool for the estimation of SMC over large areas; on land studies the calibration and interpretation of microwave and optical Remote Sensing (RS) data are strongly related to soil moisture and for this reason it is one of the most important “ground truth” data in RS campaign. The most common measuring method is the gravimetric one which suffers some disadvantages like the difficulty of collecting many data in a short time, or because it is often destructive and not very representative of the actual soil condition; so, several new techniques have been developed in the last few years to try to avoid these problems; among these, the Dielectric Constant (DC) measurement method seems to be a good alternative.

The dielectric behaviour of the soil is strongly related to its water content and an inversion relationship must be used to convert DC data in SMC data; different approaches were followed to find the DC-SMC relationship: some based on empirical or semiempirical formulae (e.g. Hallikainen et al. 1985, and Wang and Schmugge 1980) and others on detailed physical analysis (Dobson et al. 1985). In this paper the results of a data collection carried out with a commercial DC probe on an Italian agricultural site within the MAC Europe 91 campaign (Canuti et al., 1992) are shown; DC data have been converted into SMC by using an empirical relationship obtained with a laboratory calibration. A detailed analysis of the probe method suggests some considerations about limitations and advantages with respect to the standard gravimetric method.

1. THE DIELECTRIC BEHAVIOUR OF THE SOIL

The response to an incidence electromagnetic field of a homogeneous and isotropic medium under the influence of an electromagnetic field, (magnetic permeability $\mu_r \sim 1$), can be described by its dielectric constant (DC), usually referred to the free space permittivity $\varepsilon_0$. The relative DC is a complex number which is related in the microwave region of the spectrum to changes in the rotational energy levels of the molecule. The DC of the solid component of the dry soil is very low (real part = 2-4, imaginary part $\sim 1$) while the DC of liquid water is very high (e.g. at the 1.4 GHz frequency $\varepsilon = 79.6 - 62.2$ J, after Stogryn, 1971). The presence of a small quantity of water
in the soil can largely affect its DC. Wet soil is a heterogeneous medium made up of parts with different DC values; to represent it with an equivalent homogeneous medium, with a single representative DC value, mixture formulae can be used.

It is a well established result found by various researchers that, in order to adequately represents critical aspects of soil modeling, wet soil must be considered a mixture of four components: air voids, solid part of the soil, free water and bound water, the last being represented by water molecules tightly held to particles and lattice structure of the soil; these two different phases of water have dissimilar DC values, and their relative fraction is related to soil texture. Furthermore the actual value of the bound water DC is very difficult to evaluate and to measure too.

In order to retrieve the SMC from the measured DC values, many formulae and models have been proposed: as an example in fig. 1 the results of three different approaches are shown: an empirical fitting depending only on the clay and sand volume fractions of the soil (Hallikainen et al., 1985), and two models with some empirical parameters (Wang and Schmugge, 1980 and Dobson et al., 1985); for these last two functions dummy values of some semiempirical parameters have been used. The presence of water in the soil to study the dielectric behaviour must be quantified through the volumetric soil moisture content and the present study will always refer to the volumetric soil moisture using the acronym SMC. In short at a given frequency the DC of soil is strongly affected by its texture, through the specific area, by the bulk density and for the lower frequencies also by the salinity of the soil, while other parameters of usually subordinate importance are temperature, specific density, and presence of organic matter.

2. CHARACTERISTICS OF THE MEASURING APPARATUS

The measuring apparatus is a commercial one manufactured by the Applied Microwave Corporation of Lawrence, Kansas - USA; this kind of probe has already been tested in laboratory conditions (Jackson, 1990). It consists mainly of three parts: the MW probe, the measuring system and the acquisition and processing units. It is a two channel reflectometer which measures the impedance variation of a line (a terminated coaxial cable) due to the presence of a dielectric medium on the surface of an open end capacitance: the probe’s tip. It is completely battery operated.

Under the assumption that the fields are not propagating in the medium and that fringing fields are negligible, the relations relating the amplitude and phase of the reflection coefficient and the DC of the contact medium are simple and allow an easy determination of the DC. To fulfil these conditions for a wide range corresponding to dry and very wet soils, tips of different geometries are need. For this reason four different tips are available. Anyhow a small volume of the medium is sampled and its extent varies with the tip geometry and with the loss tangent of the medium (Swicord and Davis, 1981). For this reason in

![Fig. 1: Real (a) and imaginary (b) part of the DC of the soil obtained from three different models (After Dobson et al, 1985, Hallikainen et al., 1985 and Wang and Schmugge 1980) as a function of the volumetric soil moisture (SMC).](image-url)
order to associate DC data to a value measured with the gravimetric method, in the case of inhomogeneous soil can cause a certain inaccurate: if the sampled depth does not concur in both cases some indetermination in the comparison between DC and SMC values can arise.

An aspect which can cause the goodness of the DC measure to degenerate and can be a little destructive for the sample is that a full contact is needed between the tip’s and the sample’s surface; to secure this condition the probe must be firmly placed on the soil surface with the not rare consequence of altering the bulk density of the upper layer of the sample. The calibration of the probe, which consists in the calculation of two constants related to the amplitude and phase of the measuring system can be made with some media of known DC and a metal plate reflecting surface; particularly useful are liquids for which contact problems between the probe tip and the sample are practically avoided.

3. THE DATA COLLECTION

The experimental apparatus was used directly in field during a RS campaign, to collect data in a real operational configuration, and in the laboratory to obtain the inversion relationship and retrieve and to check the accuracy of the method.

3.1 In field campaign

Within the Mac Europe 91 RS campaign, organized by NASA and Italian Space Agency (ASI), several ground data collection activities were carried out in an agricultural area near Florence. The aim of this campaign was the study and interpretation of SAR and optical sensors data for hydrological and agricultural applications (Coppo et al., 1992). Measurements at different depths, simultaneously to gravimetric sampling on the same plot of land, were carried out on 21st 22nd and 29th of June and 7th of July 1991 in an agricultural part of the Chianti region, along the Pesa river (Montespertoli). The wettest day was the 21st of June because of a rain storm during the previous night, while on the other dates typical sunny summer condition were present without further rain events; all the fields showed a good moisture uniformity with a depth profile increasing down to 10-15 centimeters where the SMC became steady. For each field four points were selected where depth profiles of DC and corresponding gravimetric sampling were carried out: three to five data were collected and the measuring steps were chosen according to the general moisture conditions.

Volumetric soil moisture was measured by weighing samples of soil collected with samplers of known, constant, volume (62.5 cm$^3$ for 2.5 cm step and 125 cm$^3$ for the 5 cm step: Fig.2 shows how DC (a) and gravimetric (b) values were collected; for the drying procedure a MW oven was used. A first analysis of the relationship between DC data and SMC measured with the gravimetric method showed a great dispersion, probably due to measurement problems on both DC and gravimetric data such as the difficulties due to the roughness of the soil surface: an average over the four points of each field was made, obtaining a single value for each field and soil layer.

Fig. 2 - Geometry of DC measurements (a) and of the corresponding sampled volume for gravimetric measurements (b); the semicircle gives an impression of the volumes (A, B, C) sampled in DC measure.

After that, the results showed a good correlation from which a simple relationship was obtained by means of the least square regression method. In fig. 3 the average values of the measured real (a) and imaginary part (b) of the DC as a function of the SMC measured with the gravimetric method are plotted: the points correspond to three fields with three different surface roughnesses (roller packed, ploughed and harrowed) at different soil depths. The range of soil temperature over the four days and over the different depths was 23-32 °C; bulk density variations over the three fields and at the different depths, from 0 (surface value) to 15 cm, were around 1.3 g/cm$^3$, so that within these ranges the effects of their variations are negligible: data collected during all the campaign can be analyzed together.
3.2 Laboratory measurements

Some laboratory measurements were also carried out by using samples of soil taken from the field, with the aim of obtaining an empirical relationship between DC and SMC, to retrieve from the DC data the estimated SMC values. In lab conditions obviously the experimental accuracy can be increased. Different SMC values were obtained both by wetting a dry soil sample with different quantities of water and vice versa by drying wet samples: no appreciable difference was noted in these two different procedures. In fig. 4 the results of the laboratory DC measurements versus SMC are shown.

As we expect in this case data are less spread; the volume sample, taken from the roller packed field, was about 100g (dry) at a soil temperature of about 20°C and the sample was prepared maintaining a bulk density of 1.4 g/cm³; its texture has been measured and roughly estimated to be 24% of sand and 76% of clay and silt. After every drying or wetting phase, the sealed samples were allowed to reach thermal equilibrium and moisture homogeneity. Calibration checks during the experiment were made with solids and liquids of known DC.

4. DATA ANALYSIS

To derive the SMC from the measured values of DC an empirical method has been used. A similar approach is used in Hallikainen et al., 1985, where quadratic functions were obtained over different soil samples and at three different frequencies; the coefficients of these functions depend on the texture of the soil and on the measuring frequency. In our case the soil textures of the three fields did not differ significantly, so we calculate the empirical function only on one field and then extend the result to the others. In this case texture variations have not been investigated and the polynomial coefficients have fixed values; only the real part of the DC was used. The function obtained through the lab measurements, which were inverted to obtain the SMC vs DC real part relationship is a second order polynomial function with the coefficients shown in fig. 4.

Comparing figs. 3a and 4a it can be noted that both in field and laboratory data are fitted practically by the same function. A test of the accuracy of the method has been made using the polynomial function obtained from the fit of the laboratory data. Fig. 5 shows the comparison between the values of the in field measurements retrieved from the DC data and by using the laboratory relationship, and the values measured at the corresponding depth with gravimetric technique. The result is good even if some spread of the data is present; in fact the regression coefficient is $R = 0.942$ and this value over 28 data guarantees a good correlation. The three points located between 16% and 18% of measured SMC, depart from the regression; because these three data were collected on the same day this can be due to a systematic, temporary, instrument
malfunctin. To estimate the accuracy of the method the mean square error defined by the expression:

\[ \Delta = \sqrt{ \frac{\sum (\text{SMC}_{\text{calc}} - \text{SMC}_{\text{meas}})^2}{(Np - 1)}} \]

has been calculated; \text{SMC}_{\text{calc}} is the SMC derived from the measured real part of the DC value, \text{SMC}_{\text{meas}} is the in field data measured with the gravimetric technique and \(Np\) the number of data (28); a value lower than 3% was obtained. This value can be regarded as sufficiently accurate compared to the accuracy of the gravimetric method, and good for SAR applications use.

Regarding the direct measurements of the DC it must be observed that the values obtained at higher SMC both in field and in laboratory, are greater than the one obtained by other researchers in U.S. agricultural fields (e.g. Hallikainen et al., 1985). This can be due only partially to the measurement procedure that, because of contact problems, can determine an overestimation due to an increase of the density of the sample. Besides, a wide spread of the imaginary part values for higher SMC can be noted in from fig. 4b. This may be due to some inhomogeneities caused by the fact that the time waited for to reach sample uniformity and stability was too short, or by contact problems; these two aspects can affect more specifically the phase measurements. Anyhow it is a fact that the measurement of the imaginary part is very difficult (e.g. Jackson, 1990). The study of the effect of the sample texture and of other parameters needs further investigations.

**Fig. 4 -** Real (a) and imaginary (b) parts of the DC data collected in laboratory as a function of the volumetric soil moisture (SMC); the solid line represents the fitting polynomial function.

**Fig. 5 -** Comparison between the SMC calculated by using the laboratory retrieval function (real part) of the in field measured data and the corresponding values measured with the gravimetric method.
CONCLUSIONS

A DC measurement system working at L band has been tested both in agricultural fields and in laboratory. The results obtained with a simple empirical method, using the real part of the soil DC, show that it is possible to obtain an adequate accuracy in SMC estimation and good operational for Remote Sensing applications too; the ready use of the probe allows to collect many data in a short time and hence reduces the error due to soil surface roughness. The better accuracy attainable in laboratory studies of the DC - SMC relationship is also shown. Some difficulties related to the use of the contact probe which determine a loss of unobtrusiveness of the method have been confirmed and show that great care is needed in the measurement of the dielectric properties themselves. Further studies aimed at understanding the influence of the soil characteristics are necessary.

ACKNOWLEDGMENTS

This work was partially supported by the EC EPOCH-RIVET Project under contract n.EPOC-CT90-0027 and by Italian Space Agency (ASI)

REFERENCES


