PREFACE

Over the last few decades, use of microwave energy has become the emerging field for variety of applications. Different aspects of microwaves have been applied in various branches of science and technology like industrial measurements, space research, military, medical, agricultural, and domestic applications, etc. Thus, microwaves play an ever increasing role in modern life. The electromagnetic spectrum from 300MHz to 300GHz is called the microwave spectrum. This corresponds to the range of wavelength from 1m to 1mm in the free space. Microwaves occupy relatively very small region in the EM spectrum that is bounded by radio waves on the side of longer wavelength and infrared waves on the side of shorter wavelengths. However, they have several interesting and unusual features which are not found in other portion of the electromagnetic spectrum. These interesting properties of microwave radiations have variety of applications;

- Microwave radiation does not alter nor contaminate the material under test, enabling fast, nondestructive and continuous monitoring.
- Microwave can propagate through the free space allowing remote sensing to be accomplished, where lower frequency signals gets reflected from the ionosphere.
- Relatively insensitive to environmental conditions like darkness, fog, clouds in contrast to IR/optical radiation.
- Most of solid dielectric materials and atmosphere are transparent to microwaves.
- Microwaves are absorbed by the water and thus can be used to dry, heat and cook food. Their absorption can be used to sense/determine the amount of moisture content within the materials.

Microwaves can penetrate deep in the soil in comparison to visible and infrared radiations, and the microwave sensors can operate in all weather conditions. Hence microwave remote sensing technique is used to estimate the moisture content in the soil has gained considerable attention. The technique involves either measurement of emissivity of soils using radiometers, or back scattering coefficient using an active sensor. Both the emissivity and back scattering coefficient depend on
the complex dielectric constant of the soils, which is considerably affected by the moisture content in the soil.

One very important property of microwave is that its energy is almost equal to rotational energy of water molecule. The microwave dielectric measurement uses the absorption of microwave energy corresponding to the rotational energy of water molecules. Microwave remote sensing of natural earth materials such as soil and water has a very close dependence on their electrical parameters. The most important parameter is the dielectric constant. The knowledge of dielectric constant helps in the study of dry and wet soils using microwave sensors.

Soil is composed of minerals, soil organic matter, water and air. Soil colour is influenced by the content of organic matter and water as well as the presence and oxidation state of iron and magnesium. The red colour soil indicates good drainage. Iron found within the red soil is oxidized more readily due to the higher oxygen content. This causes the soil to develop a 'rusty' colour. The colour can be darker due to organic matter in the soil. The dependence of emissivity and scattering coefficient of the soil on dielectric constant is used for designing the passive and active microwave sensors respectively. This will give knowledge of variability of soil moisture, which is important for agriculture.

However, to our knowledge, almost no or very little experimental data on dielectric, emissive properties and scattering coefficient of soils have been reported similar to the present investigations on red soils from Northern Maharashtra, Western Maharashtra and Konkan region. So, the main aim of the present research work is to provide the detailed ground truth experimental data on the dielectric, emissive properties and scattering behavior of dry and wet red soils of these regions at microwave frequencies. This gives the relevance and importance of our experimental studies in agriculture and remote sensing applications.

For this purpose, we have selected six different suitable locations for collecting red soil samples, representing the Northern Maharashtra, Western Maharashtra and Konkan region. At each location or site, the soil samples collected have a depth about 0cm to 20cm(topsoil). These topsoil samples are then scientifically processed and sieved to get soil particle sizes around 425 µm. Then a sample of desired gravimetric MC (%) is prepared by adding exact amount of distilled water.
Samples are then carefully inserted into the solid dielectric cell for measuring their
dielectric properties.

Waveguide cell method is used for determination of dielectric properties of
red soil samples at microwave frequencies. An automated C-band and X-band
microwave set-up in the TE\textsubscript{10} mode with Gunn oscillator/source, PC-Based slotted
line control and data acquisition system are used for this purpose. From the measured
values of the dielectric constant (\(\varepsilon'\)) of these red soil samples the emissivity \(\varepsilon_p(\theta)\) and
scattering coefficient (\(\sigma^0\)) for horizontal and vertical polarizations at different
incidence angle, Brewster's angle (\(\Phi_B\)), microwave conductivity (\(\sigma\)), relaxation time
(\(\tau\)), etc. are then estimated by using suitable computer programs based on appropriate
relations. Such studies on dielectric, emissive and scattering behavior of red soils at
different microwave frequencies will be helpful for designing of passive and active
microwave remote sensors. Results may also useful in correlating the available
satellite data of this region. Statistical correlation studies of measured values of
dielectric constant and electrical conductivity with physico-chemical parameters of
red soils are useful in predicting the texture and nutrient content of these soils.

The thesis is divided into seven chapters. The contents of each chapter are
summarized below.

Chapter-1 gives the introductory information, objectives and importance of
the present research work. In microwave remote sensing the role of microwaves is
important and the need of designing precise and reliable soil moisture sensor is
discussed. The use of microwave techniques in determining the dielectric, emissive
and scattering properties of soils is specified. Detailed inclusive review of the relevant
literature based on the dielectric, emissive and scattering characteristics of soils is
presented and the necessity of the present research work is clearly outlined.

Chapter-2 deals with theoretical background of the dielectric constant (\(\varepsilon'\)) and
dielectric loss (\(\varepsilon''\)) for dielectric materials. The effect of electric field on polar and
non-polar molecules is explained. The basic concept and theory of dielectrics,
dielectric polarization and its types, dielectric constant, dielectric loss, emissivity,
scattering coefficient etc., are discussed. Soil physical properties like composition,
texture, structure, porosity, wilting point, etc. and chemical properties pH, Electrical
Conductivity (EC), Organic Carbon (OC), various micronutrients and macronutrients
are also elaborated. The need of soil testing process is emphasized. Particularly, soil testing helps in getting idea about nature of soil (acidic or basic) and also status of the nutrient levels and thereby helps to estimate soil fertility.

Chapter-3 describes an automated C-Band and X-Band microwave set-up and also other experimental details used to measure the dielectric properties of dry and wet red soil samples. The main microwave components/parts used in the set-up such as Gunn oscillator, pin modulator, isolator, frequency meter, tunable probe, PC-based slotted line control and data acquisition system are described and their functions are explained. The C and X-Band microwave bench are automated having the automation software consists of microcontroller (8051), ADC-12 bit-MCP (3202) visual based software.

The sample collection and preparation techniques for topsoil samples are described. Different methods used for measuring dielectric parameters are also discussed in this chapter. The detailed description of waveguide cell method and its brief comparison with other three methods for measurement of dielectric constant of materials is also provided. It also included the various formulae to determine various dielectric, emissive and scattering properties of red soil samples.

Chapter-4 reports the results on the dielectric constant ($\varepsilon'$), dielectric loss ($\varepsilon''$), emissivity ($\varepsilon_p(\theta)$), Brewster’s angle ($\Phi_B$), a. c. conductivity ($\sigma$), relaxation time ($\tau$), etc. and their variations with gravimetric MC(%) and microwave frequencies for six red soil samples (S1-S6). All these experiments are performed for MC variations of soil samples ranging from 0% to 30 % and at seven different microwave frequencies in the C-band (4.1, 5.1 and 5.7 GHz), and X-band (8.2, 9.2, 10.5 and 11.7 GHz).

In general, the dielectric constant and loss factor for red soil samples, S1-S6 are found to increase with increase in gravimetric MC for all seven microwave frequencies. However, this variation is nonlinear and the general trend is almost similar for all the samples, except little differences in their magnitudes. Further, both these parameters for all soil samples show little decrease in their values upon increase in frequencies for the same values of gravimetric MC. Further, we observed higher values of dielectric constant for oven- dry (0% MC) soil samples which possess greater sand percentages. As we increase the MC (%) of soil samples, the rate of increase of dielectric constant is found higher at or near transition moisture Wt for
soils having relatively greater sand percentages (S4 and S6). This indicates that the sensitivity of soil texture to $\varepsilon'$ is higher in wet soils and lower in dry soils and our results find close agreement with the studies reported by several earlier investigators.

The results on the emissivity ($e_p(\theta)$), show decrease in emissivity of the red soils with increase in MC / dielectric constants for both vertical and horizontal polarizations at microwave frequencies. It is further observed that at constant value of MC, emissivity of all the red soil samples increases with increase in the incident angle for vertical polarization, and this increase continues up to a certain incident or look angle referred to as ‘Brewster’s angle’, at which it reaches maximum value equal to unity; and beyond this particular angle, emissivity decreases sharply. Further, for vertical polarization, at constant value of incident angle, emissivity of all the red soil samples is found to decrease significantly with increase in the values of its MC (%). In case of horizontal polarization, emissivity of soils is found to decrease with the increase in incident angle. It is further observed that the magnitudes of emissivity of soils at same incident angle are greater for vertical polarization rather than for horizontal polarization.

Brewster’s angle ($\Phi_B$) increases over the range from about $59.17^\circ$ to $78.55^\circ$ for MC variations from 0 % to 30 % of the red soil samples studied for seven different frequencies. This indicates that the variation of angle $\Phi_B$ has same trend as that of dielectric constant and inverse to the emissivity of soils. Our results also show a little decrease in $\Phi_B$ with increase in frequency for the same values of MC (%). However, the curves for different frequencies are very close to each other showing relatively less dependence of Brewster’s angle on the frequency variation as compared with dielectric constant for dry and wet soils. Utility and importance of these results in remote sensing and agricultural applications is outlined.

Chapter-5 describes the results on scattering behavior of red soils having various moisture contents (0% to 30%) at 5.1 GHz (C-Band) and 10.5 GHz (X-Band) microwave frequencies. Measured values of dielectric constant are used to estimate the scattering coefficient by using perturbation model for vertical and horizontal polarization at different incident angles ($0^\circ$ to $80^\circ$) for three red soil samples. The selection of these samples is made on the basis of their increasing order of sand percentages. The important conclusions obtained from this study are summarized below:
At constant value of MC, scattering coefficient of soil sample increases with increase in the incident angle for vertical polarization, and this increase continues up to angles between 55° to 65°, at which it reaches maximum value and beyond this, it decreases sharply.

In case of horizontal polarization, at constant value of MC, scattering coefficient of soils decreases with the increase in incident angle.

For vertical and for horizontal polarization, at constant value of incident angle, scattering coefficient of soil sample is found to increase significantly with increase in its MC (%). However, the magnitudes of scattering coefficient of soils at same incident angle are greater for vertical polarization than for horizontal polarization.

Scattering coefficient of soils decreases upon increase in the microwave frequency.

Variations of emissivity and scattering coefficient of soil samples with MC% show inverse trends.

These results on the scattering properties of dry and moist red soils are quite useful in designing active microwave sensors. Such sensors are very much needed for the study and interpretation of data of soils obtained by remote sensing satellites.

Chapter-6 presents detailed report on the measured values of electrical conductivity and dielectric constant of the red soils and their statistical correlations with physico-chemical properties of red soils. Dielectric constant of dry soils is measured at C-band (5.1 GHz) and X-band (10.5 GHz) microwave frequencies. Our results give negative correlation of dielectric constant with electrical conductivity and also with physical constituents like clay, silt and positive correlation with sand, pH and bulk density of red soils. Results also show a positive correlation of dielectric constant of soils with available macronutrients (P, K) and negative correlation with N. Further, dielectric constant of red soils shows negative correlation with micronutrients (Fe, Mn, Zn, Cu). Moreover, these relationships of dielectric constant of dry soils with its physical constituents and nutrient concentrations have frequency dependence. Our results also indicate comparatively higher values of correlation factor for dielectric constant of dry soils with their physical constituents except for sand content and macronutrients concentrations with exception for phosphorus studied at C-band frequency as compared to that X-band frequency. We have also obtained the regression equations
for each of these physico-chemical constituents in terms of dielectric constant and electrical conductivity. These equations are useful in predicting the texture and nutrient content of soils by simply knowing measured values of dielectric constant and electrical conductivity of red soils.

Chapter-7 summarizes the conclusions of the important findings of present research work. Our results indicate that the variations of dielectric properties are not only depend on the MC but also on the soil texture. Further, results also give little higher rate of increase in the $\varepsilon'$ for sandy soil in comparison to sandy loam and loamy red soils at relatively higher MC levels. The important role played by the ‘transition moisture values’ is emphasized. Frequency dependence of statistical correlation factors between dielectric constant and electrical conductivity of dry soils and its physical constituents and nutrient concentrations is also discussed. Result of this study is also useful in predicting the texture and nutrient content of soils by using regression equations and by knowing measured values of dielectric constant and electrical conductivity of red soils. Moisture, incident angle and frequency dependent studies of emissivity and scattering coefficient provide many possible applications and importance in the production of soil moisture sensors and hence in remote sensing and agriculture. Possible extensions / future scope for research of the present studies in this and similar areas are also outlined.