CHAPTER-5

SCATTERING BEHAVIOUR OF RED SOILS AT C- AND X-BAND MICROWAVE FREQUENCIES

5.1 Introduction

The study of soils using microwave remote sensing techniques can be done either by passive sensors or by active sensors [1]. The parameters measured in case of passive and active sensors are brightness temperature and the scattering coefficient respectively. The scattering coefficient is function of physical and electrical properties of soils [2]. Experimental studies related to the scattering coefficient of different soils as function of their type, texture, MC (%), frequencies, polarization and incidence angles have been attempted by several investigators [3-11]. Results of all these investigations confirm that the scattering coefficient increases with increase in MC (%) and incident angles but decreases with frequency. Thus natural objects have different scattering coefficients depending on their physical and electrical properties. The surface smoothness of the target is found to have a great effect in this case. If the surface is very smooth, the power will be highest in the direction of the reflection angle. On the other hand, if the surface is very rough, it will be scattered in all the directions. This roughness parameter is usually defined in relation to the wavelength.

In the present thesis, we have carried out the measurements on the dielectric constant of six red soil samples (S1-S6) collected from North Maharashtra, West Maharashtra and Konkan region of the Maharashtra state at C-Band (4.1, 5.1 and 5.7 GHz) and X-Band (8.2, 9.2, 10.5 and 11.7 GHz) microwave frequencies using waveguide cell method. However, in this chapter, out of the total six red soil samples, we have selected only three samples to discuss the scattering behavior. We have taken the red soil samples S5, S2 and S6 on the basis of their % sand content and hereafter, for convenience, these samples will be renamed as A (S5), B (S2) and C (S6) respectively. Further, this study is carried out only at two frequencies, viz., 5.1 GHz (C-Band) and 10.5 GHz (X-Band). Such study of scattering behavior of red soils at microwave frequencies will be helpful for designing of active microwave remote sensors.
5.2 Physico-chemical and dielectric properties of red soils

The physical and chemical properties of these three red soils are shown in Table 5.1. As mentioned earlier, the red soil samples are arranged in accordance with increase in their percentage of sand content. Sample B is alkaline in nature while the other two samples (B and C) are acidic. From their EC values, we see that all the three red soil samples are non-saline.

Table 5.1 Physical and Chemical Analysis of three Red Soil Samples

<table>
<thead>
<tr>
<th>Soil sample, Site (District)</th>
<th>Soil Texture</th>
<th>Soil Colour</th>
<th>pH (1:2.5)</th>
<th>EC (dSm⁻¹)</th>
<th>N</th>
<th>P</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Sai (Raigadh)</td>
<td>42.0 35.0 23.0 Loam Deep Red</td>
<td>5.90</td>
<td>0.03</td>
<td>301</td>
<td>22.73</td>
<td>42.56</td>
<td></td>
</tr>
<tr>
<td>B Parola (Jalgaon)</td>
<td>62.4 12.3 25.3 Sandy Clay Loam Light Red</td>
<td>8.10</td>
<td>0.21</td>
<td>255</td>
<td>13.77</td>
<td>425</td>
<td></td>
</tr>
<tr>
<td>C Mahabaleshwar (Satara)</td>
<td>90.0 9.0 1.0 Sand Deep Red</td>
<td>5.81</td>
<td>0.03</td>
<td>151</td>
<td>2.77</td>
<td>150.1</td>
<td></td>
</tr>
</tbody>
</table>

Variations of dielectric constant of red soil samples with different values of gravimetric moisture content are given in Table 5.2.

Table 5.2 Variation of dielectric Constant for different moisture content of red soils at 5.1 GHz and 10.5 GHz frequencies

<table>
<thead>
<tr>
<th>Moisture Content (%)</th>
<th>Soil Sample A Site: Sai (Raigadh)</th>
<th>Soil Sample B Site: Parola (Jalgaon)</th>
<th>Soil Sample C Site: Mahabaleshwar (Satara)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dielectric Constant (ε⁺)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.1GHz 10.5GHz 5.1GHz 10.5GHz 5.1GHz 10.5GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3.37 2.81 3.73 3.01 3.79 3.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.1 4.84 4.05 4.75 5.43 5.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>8.5 8.7 8.4 7.65 8.72 9.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>11.7 11.8 10.01 12.79 11.8 12.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>16.06 17.09 15.54 15.9 15.9 17.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>23.4 19.8 23.1 18.7 23.02 20.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>24.01 20.6 23.5 19.76 24.04 21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Following conclusions can be drawn from the results reported in Table 5.2.

- Dielectric constant of soil increases with increase in its percentage moisture content.
- Dielectric constant of soil decreases upon increasing the microwave frequency.
- Dielectric constant of oven dry soils decreases upon increasing the percentages of their sand content. This confirms the textural dependence of dielectric properties of soils.

These experimentally measured values of dielectric constant of three red soil samples are used to estimate the corresponding values of their scattering coefficients.

5.3 Scattering behavior of the surface

When an electromagnetic wave is incident on the boundary surface between two semi-infinite media, a portion of the incident energy is scattered backward and the rest is transmitted into the second medium. Scattering coefficient ($\sigma_o$) is the characteristics of the material of the target at a given frequency, incident angle and polarization and is defined directly in terms of the incident and scattered fields. The natural objects have different scattering coefficients depending on their physical and electrical properties. One can identify them and study their behavior by knowing scattering coefficient. In a special case when the lower medium is homogeneous, the phenomenon of scattering is called surface scattering. Again if the lower medium is inhomogeneous, the scattering takes place from within the volume of the lower medium and is called volume scattering.

For estimation of scattering coefficient the surface pattern plays an important role. For an optical wave a surface may appear very rough, but the same surface may be very smooth to a microwave signal. The two fundamental parameters commonly used to characterize surface roughness are the standard deviation of the surface height variation called as r.m.s. height ($\sigma$) and the surface correlation length ($l$) in terms of wavelength. As the surface correlation length increases the surface becomes smoother and hence the radiation pattern becomes more directional.

5.4 Scattering models

Depending upon the nature of surface pattern, three different models which are commonly used for the estimation of scattering coefficient [4-8] are, namely,
(i) Physical optics model
(ii) Geometric optics model
(iii) Perturbation model

Besides these models, the forth model called as ‘Integral equation model’ may also be used in some occasions. However, validity conditions and the outcome from this model are very much similar to the Perturbation model. Selection of any model for estimation of scattering coefficient will depend on the roughness of the surface and the validity conditions, both of which must be satisfied. Any surface can be distinguished as rough surface, smooth undulating surface and two scale composite rough surface. For undulating surface with small slopes and a medium small standard deviation of heights as compared to wavelength incident, a scalar approximation in the field expression or physical optic model is used.

If the surface has larger standard deviation of surface heights, the surface is considered as rough and the stationary phase approximation or geometric optics model is used. Perturbation model is used for a slightly rough surface, physical optic model for a medium rough surface and geometric optics model for undulating surface. Selecting a model for computation for a particular surface will depend upon the validity of a model for the surface concerned. The limitation of physical optics model and geometric optics methods is expressed as \( kl \leq 6 \). When both the surface standard deviation and the correlation length are smaller than wavelength, then the surface is slightly rough and small perturbation model is used. The validity condition for this model is given in the Table 5.3 which are based on the values of standard deviation of surface height or r.m.s. surface height (\( \sigma \)), surface correlation length (\( l \)), value of wave number \( k = \frac{2\pi}{\lambda} \) and r.m.s. surface slope (m).

**Table 5.3 – Validity conditions for three different scattering models**

<table>
<thead>
<tr>
<th>Model</th>
<th>Validity condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical optics model</td>
<td>( m &lt; 0.25 ) and ( kl &gt; 6 )</td>
</tr>
<tr>
<td>(Kirchoff’s model with scalar approximation)</td>
<td></td>
</tr>
<tr>
<td>Geometrical optics model</td>
<td>(2( k\sigma \cos \theta )^2 &gt; 10 ( \text{and} ) ( l^2 = 2.76 \sigma \lambda ))</td>
</tr>
<tr>
<td>(Kirchoff’s model with stationary phase approximation)</td>
<td></td>
</tr>
<tr>
<td>Perturbation model</td>
<td>( k\sigma &lt; 0.3 ) and ( m &lt; 0.3 )</td>
</tr>
<tr>
<td>Here ( \theta = \text{Angle of incidence} )</td>
<td></td>
</tr>
</tbody>
</table>
5.5 Estimations of scattering coefficient by using perturbation model

For waveguide cell method, the surface of the soil inside the waveguide is smooth; hence the perturbation model is quite suitable [12-13]. The perturbation method requires the surface standard deviation to be less than about 5% of the electromagnetic wavelength. Accordingly, in the present case, the surface standard deviations for C- and X-bands are about 1.8 mm and 0.92 mm respectively. The corresponding surface correlation lengths are around 12.7 mm and 6.5 mm respectively. In order to apply perturbation model, the necessary conditions to be satisfied are

\[ k\sigma < 0.3, \quad \text{and} \quad \frac{\sqrt{2}}{l}\sigma < 0.3 \]

Where,
\[ k = \text{Wave number} = 2\pi/\lambda \]
\[ \sigma = \text{Surface standard deviation} \]
\[ l = \text{Surface correlation length} \]

In the present case
\[ k\sigma = 0.2 \quad \text{and} \quad kl = 1.0 \]

The backscattering coefficient is given by

\[ \sigma_{ppn}(0) = 8K^{4}\sigma^{2}\cos^{4}\theta|a_{ppn}(0)|^{2}W(2K\sin\theta) \] .... (5.1)

\[ p = v \text{ or } h \]

where,
\[ |a_{th}(0)|^{2} = \Gamma_{h}(0) \] .... (5.2)

\[ a_{rr}(\theta) = \left( e^{-1} \right) \frac{\left[ \sin^{2}\theta - e^{-1} \sin^{2}\theta \right]}{\left[ \sin^{2}\theta + e^{-1} \sin^{2}\theta \right]} \] .... (5.3)

\[ |a_{th}(0)|^{2} = \Gamma_{h}(0) \text{ is the Fresnel reflection coefficient for horizontal polarization.} \]

\[ a_{th}(\theta) = \frac{\sin^{2}\theta}{\sin^{2}\theta + e^{-1}} \] .... (5.4)

and \( W(2K\sin\theta) \) is the normalized roughness spectrum, which is the Bessel transform of the correlation function \( \rho(\zeta) \), evaluated at the surface wave number of \( 2K\sin\theta \).
The normalized roughness \( W(2K\sin\theta) \), is given by the following equation

\[
W(2K\sin\theta) = 0.5l^2 \exp[(kl\sin\theta)^2] \quad \text{.... (5.5)}
\]

Eqs. (5.1)-(5.5), are used to estimate the scattering coefficients for red soil samples having different moisture contents are carried out at C and X-Band microwave frequencies taking different values of angle of incidence (0° to 80°) for both horizontal and vertical polarizations.

### 5.6 Results and discussion

The three red soil samples (A, B, C) used in this study were collected from North Maharashtra, West Maharashtra, Konkan region of Maharashtra and arranged according to the percentages of their sand content in increasing order. The scattering coefficients for these red soil samples have been estimated using the corresponding values of their dielectric constant obtained by using Waveguide Cell Method with Gunn oscillator operating at C-band (5.1 GHz) and X-band (10.5 GHz) frequencies. Estimations of scattering coefficients of dry and moist red soils are carried out by using the perturbation model for both vertical and horizontal polarizations with different incident angles (0° to 80°) and at 5.1 GHz and 10.5 GHz microwave frequencies. The results are summarized and represented graphically in Figs. 5.1-5.3.

Fig.5.1 (a) - (c) and Fig.5.2 (a - c) show the variation of Scattering Coefficient (vertical and horizontal polarization) with angle of incidence for three red soil samples (A, B and C) having different moisture content (0%, 10%, 20% and 30%) at C-band (5.1 GHz) and X-band (10.5 GHz) microwave frequencies respectively.
Fig. 5.1 (a) - (c): Variation of Scattering Coefficient (for vertical and horizontal polarization) with angle of incidence for three red soil samples (A, B and C) having different moisture content at 5.1 GHz.

Fig. 5.1 (a)

Fig. 5.1 (b)

Fig. 5.1 (c)
Fig. 5.2 (a - c): Variation of Scattering Coefficient (for vertical and horizontal polarization) with angle of incidence for three red soil samples (A, B and C) having different moisture content at 10.5 GHz.

From Figs. 5.1 and 5.2, it is observed that 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 particular angle, scattering coefficient decreases sharply. Value of this angle is found slightly more for higher MC. Further, for vertical polarization, at constant value of incident angle, scattering coefficient of soil sample is found to increase significantly with increase in the values of its MC (%).
In case of horizontal polarization, the value of scattering coefficient for soil sample almost remains constant up to incident angles about 40-50° and then starts decreasing slowly. Beyond 50°, it decreases significantly with increase in the incident angle and at about 70-80° and, thereafter values of scattering coefficient becomes almost equal for all four MC. Thus, in general, for horizontal polarization, scattering coefficient decreases with the increase in incident angle. It is further observed that the magnitudes of scattering coefficient of soils at same incident angle are greater for vertical polarization than for horizontal polarization. However, for horizontal polarization, at constant value of incident angle, scattering coefficient of soil sample is also found to increase significantly with increase in the values of its MC (%), similar to vertical polarization. Thus, results presented here show fairly good agreement with the experimental results and theoretical predictions of earlier investigators [3-11].

The results presented on scattering coefficients for vertical and horizontal polarization in Figs. 5.1 and 5.2 for dry and moist red soil samples (A, B and C) studied at different incidence angles have more or less similar trends in their variations. The small deviations observed in these results may be due to differences in the texture, other physico-chemical properties of these three soil samples and the microwave frequency used.

In order to understand the possible dependence of scattering coefficient on microwave frequency of operation, we have studied the variation of scattering coefficient of red soils having 15% constant value of MC with incidence angle for 5.1 GHz and 10.5 GHz. The results of this study are shown in Fig.5.3 (a, b and c). In each these three graphs, we see two distinct curves for each type of polarization (vertical and horizontal polarization) corresponding to C-band and X-band frequencies. For all the three red soil samples, the value of scattering coefficient is found higher at lower frequency (5.1 GHz) than that for relatively higher frequency (10.5 GHz). From these results, we conclude that scattering coefficient decreases upon increase in the microwave frequency. This trend in variations of scattering coefficient with microwave frequencies is similar to the dielectric constant but inverse or opposite to that of emissivity variations as discussed in chapter 4.

After careful observation of Fig. 5.3 (a-c), we see relatively smaller departures in the values of scattering coefficient with frequency for red soil sample B
Fig. 5.3 (b) than for rest of the two samples A and C (Fig. 5.3 a and b). This may be because soil sample B has the lighter red colour, highest pH and highest clay percentage in comparison with other samples A and C. This also confirms possible role of physical and chemical properties of soils on its dielectric and scattering properties.

Fig. 5.3 (a, b and c): Variation of Scattering Coefficient (vertical and horizontal polarizations) with angle of incidence at 15% gravimetric moisture content for three red soil samples (A, B and C) at 5.1GHz and 10.5GHz microwave frequencies.

The results of this study 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. Hence the reported study may find uses in various fields mainly in agriculture.
5.7 Conclusions

- Dielectric constant of soil samples increases with increase in the MC (%) and this variation is non-linear.

- 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.

The studies on the variations of dielectric constants of dry soils with their physico-chemical constituents at C-band and X-band microwave frequencies are given in Chapter 6. Results on statistical correlation factor of dielectric constant of red dry soils with their physical constituents and nutrient concentrations at microwave frequencies are also presented.


References


