Effect of soil moisture on microwave scattering for remote sensing

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Abstract. The main objective of remote sensing is to design space borne microwave sensors to sense a target and derive useful geophysical parameters. For this purpose, the knowledge of the target characteristics must be obtained through ground based remote sensing. In this paper, soil has been taken as the target. Various percentages of gravimetric soil moisture (m_g) have been taken for establishing its relation with the scattering coefficient (σ_0) for both like polarizations at X-band frequencies. A linear model has been developed for correlating these two variables (i.e. m_g and σ_0). Using this model, regression analysis has been done for obtaining different regression parameters and predicted values. Treating measurements from bare smooth soil fields with different soil moistures, the data were analysed to examine the effect of soil moisture on scattering coefficient (σ_0) at 9.50 GHz frequency in X-band. The scattering coefficient increases with increase in soil moisture content. Different regression parameters have been obtained, which show that the best look-angle is at 25° for HH-pol and 60° for VV-pol for observing σ_0 from bare moist soil. Data analysis indicated that the basic cause and effect relationship between the sensor measurements and soil moisture can be extrapolated from theory and small-scale tests to larger resolution elements observed by the sensing aircraft. These results indirectly provide reference data for a satellite-borne remote sensor. From the results, the look angles suitable for operation with radar antennas can be suggested.

Keywords. Remote sensing; microwave scattering; soil moisture; scattering coefficient.

1. Introduction

Forecasts related to hydrological and agricultural water management decisions can be improved by timely and accurate observations of soil moisture. However, conventional measurements are cumbersome and impractical, especially when frequent observations over large regions are required. Remote sensing techniques are ideal for such purposes and are being evaluated for increasing the precision in soil moisture sensing. Microwave systems appear to be the best suited for potential remote sensing applications because they

provide a direct estimate of soil moisture. They are extendable to satellite platforms and are weather independent. The principal advantage of remote sensing, as opposed to conventional data collection methods, is that spatially distributed and frequent observation of a phenomenon can be made rapidly over a large area. Microwave remote sensing holds great promise for hydrology because the primary physical property that affects the measurement is directly dependent on the amount of water present.

The dielectric properties of the target are some of the principal determinants of microwave-scattering coefficients. A soil target consists of air, water and varieties of soil constituents. At microwave frequencies, the real part of the complex numbers representing the dielectric constant are air, $K = 1$, soil, $K = 4$ and water, $K = 80$. These large contrasts in K make it possible to measure soil moisture.

Several researchers have used active microwave sensors in order to (i) test the capability of such equipment to measure the soil surface water content (Ulaby *et al* 1978; Le Toan *et al* 1981; Jackson & O'Neill 1985), and (ii) monitor the water budget at a field or regional scale (Bernard *et al* 1981; Pervot *et al* 1984). Consequently, to retrieve soil moisture from a radar scattering coefficient (σ_0) implies establishing relationships between the gravimetric water content (m_g) and σ_0 for all available combinations of look-angle. To fulfil the aim of the air-borne or space-borne mission using active microwave remote sensing for land applications, there is an urgent need for the development of numerical procedures comparable with existing technology which may be implemented to retrieve soil moisture information from remote data.

In this paper, an attempt has been made to highlight the effect of soil moisture on scattering coefficients for microwave response. For this purpose, we have developed a simple linear model with large sets of data (m_g , σ_0) and have established relationships for scattering coefficient with selected sets of look-angle (θ) for the X-band at different soil moistures.

2. Experimental technique

A bistatic scatterometer system is used for observing moist soil. Schematic representation of the bistatic scatterometer system employed for outdoor microwave remote sensing experiments is shown in figure 1. The system consists of two pyramidal horn antennas in which one was connected to the transmitter and the other to the receiver having half-power beam width equal to 23.5° in H-plane and 24° in E-plane, with a gain of 20.74 dB and 20.27 dB respectively and operated at 9.5 GHz. These antennas were mounted on wooden portable stands. The system had a facility to vary the height and the look-angle.

The polarization of the radiated signal was also changed by using 90° E-H twist. For each degree variation of look-angle, a particular height of the antenna and the separation of the antenna from the centre of the target were calculated. This technique helped us to calculate the far-field and near-field effects. The whole system was calibrated by noting the signal returned from a flat aluminium sheet placed between the transmitting and receiving antennas. The standard technique is discussed in detail by Singh & Jha (1987).

3. Theoretical approach

When electromagnetic waves are incident on a terrain, their reflection/scattering depends basically on two factors: (i) target parameters, and (ii) system parameters, where

Figure 1. Schematic diagram of bistatic scatterometer system.

the target parameters contain the surface geometry and subsurface characteristics of the target including complex dielectric properties and the system parameters include the properties of incident waves, i.e., wavelength, like- or cross-polarization and look-angle θ . The dielectric properties for soil are strongly dependent upon the amount of water/moisture in it as well as its texture and thus the amount of water/moisture added to dry soil increases the magnitude of its dielectric constant as well as its conductivity, which in turn affects the scattering and emission of electromagnetic waves.

The scattering coefficient (σ_0) of the target has been computed using the radar equation given by Singh & Jha (1987).

$$\sigma_0 = R^1 |R_0|^2 / I_0, \quad (1)$$

where, R_0 is the reflection coefficient, σ_0 is scattering coefficient, R^1 is the distance of the transmitting and receiving antennas from the centre of the illuminated area and I_0 is the illuminated area of the target.

In (1), σ_0 is directly related to reflectivity, whereas reflectivity depends upon target characteristics (i.e. dielectric constant of soil). Therefore σ_0 is directly related to soil moisture and can be related to a general form

$$\sigma_0 = \frac{d\sigma_0(\theta, p)}{d(m_g)} \times m_g + K_1, \quad (2)$$

where, m_g is gravimetric soil moisture, $d\sigma_0(\theta, p)/d(m_g)$ is slope and K_1 is a constant, which depends upon the target characteristics and sensor parameters.

Figure 2. Angular variation of scattering coefficient as a function of soil moisture by weight (gravimetric) for VV- and HH-polarizations at 9.5 GHz, temp. = 23°C and surface roughness = 0.4 cm.

4. Results and discussion

The soil surface from which the data were obtained had 6% gravel, 55% sand, 35% silt and 4% clay. The ground surface was taken as smooth (as the roughness parameter was equal to 0.4 cm) and the soil moisture content had varying values. Figure 2 shows the angular variation of scattering coefficient for bare smooth moist soil at various moisture contents for VV- and HH-polarisations respectively.

The curves plotted for VV-polarization show that different soil moisture contents (10, 12, 15 and 19%) give 20 dB variations of scattering coefficient for the observed range of look-angles i.e. 20° to 70°. The highest percentage of gravimetric soil moisture gives maximum scattering coefficient. From the curves plotted for HH-polarization it is seen that the behaviour of the curve is approximately opposite to the VV-polarization. The variation of scattering coefficient is approximately 10 dB for HH-polarization. In this case also, the maximum scattering coefficient is at the highest soil moisture content (i.e. 19%).

The variations in percentage of gravimetric soil moisture (m_g) with scattering coefficient measured in the top 5-centimetre layer for look-angles 60° and 25° for VV-pol and HH-pol respectively at X-band (9.5 GHz) are shown in figures 3 and 4. In both the figures, it is observed that the scattering coefficient increases as the percentage of soil moisture increases. Similar results have been obtained by Ulaby *et al* (1982), Dobson & Ulaby (1981) and Bertuzzi *et al* (1992) for C- and L-bands. These results at the X-band complement earlier research efforts at other bands. For the X-band, the intercept changes as compared to those for the C- and L-bands.

The slope obtained in our case for the X-band is different from those reported at both the C- and L-bands, given by Bradley & Ulaby (1980). For the sake of comparison, the equations of regression lines given by Schmugge *et al* (1980) are compared with our

Figure 3. Variation of scattering coefficient with percentage of soil moisture (gravimetric) for VV-pol. Frequency = 9.5 GHz, look-angle = 60°, $\sigma_0 = -5.356 + 0.96m_g$, regression line.

X-band as below:

$$\sigma_0 = -10.9 + 0.33m_v, \quad (3)$$

for C-band (4.75 GHz, HH-pol, 15°),

$$\sigma_0 = -15.5 + 0.35m_v, \quad (4)$$

Figure 4. Variation of scattering coefficient with percentage of soil moisture (gravimetric) for HH-pol. Frequency = 9.5 GHz, look-angle = 25°, $\sigma_0 = -2.984 + 0.683m_g$, regression line.

for L-band (1.6 GHz, HH-pol, 15°),

$$\sigma_0 = -2.984 + 0.683m_g, \quad (5)$$

for X-band (9.5 GHz, HH-pol, 25°).

Comparing (5) with (3) and (4), it is inferred that the slope of the X-band is greater because gravimetric soil moisture has been considered here, instead of the volumetric soil moisture taken by others. It also depends upon frequency. Similarly, the equation for VV-pol for the X-band at 60° is

$$\sigma_0 = 5.356 + 0.96m_g. \quad (6)$$

Now, comparing (5) and (6) for HH- and VV-pol, it is observed that the slope is larger for VV-pol than for HH-pol. The slope defines the sensitivity of the scattering coefficient to the soil moisture. It is found that the sensitivity to soil moisture is better with VV- than with HH-pol.

Tables 1 and 2 show various regression parameters. The slope of the regression line, which shows the sensitivity of the relation between scattering coefficient and soil moisture, decreases with the look-angle for both HH-pol and VV-pol, and the constants of the intercept increase as the look-angle increases. The intercept refers to attenuation. The most suitable result for the regression line is found at look-angle 25° for HH-pol and 60° for VV-pol. From the same table, it is observed that variation in correlation coefficient (r) changes with look-angle, which shows the strength of the relationship between σ_0 and m_g . It is found that, for HH-pol, r continuously decreases with respect to θ while r decreases up to 50° and then increases for VV-pol. The best value of r for HH-pol is 0.842 at look-angles of 25° and 0.95 for VV-pol at 60°. However the 60° angle is not preferred due to problems in radar remote sensing. It is clear that the VV-pol gives much better performance in comparison to HH-pol as expected.

Figures 5 and 6 show the correlation between observed and calculated values. These values are best-fitted at look-angles 25° and 60° for HH-pol and VV-pol, respectively. Tables 1 and 2 also show the angular variation of coefficient of determination (r^2) which shows the dependence of scattering coefficient on soil moisture. The maximum value of r^2 is 0.71 at look-angle 25° and, with further increase in the value of look-angle,

Table 1. Linear regression results of scattering coefficient vs. gravimetric soil moisture at different look-angles for HH-pol.

Angle (deg.)	Slope	Intercept	r^2	r	SE*	SE of estimate
20	0.696	2.182	0.682	0.826	0.168	1.515
25	0.683	2.984	0.710	0.842	0.154	1.391
30	0.620	6.620	0.637	0.789	0.166	1.493
35	0.565	8.809	0.554	0.744	0.179	1.616
40	0.513	10.018	0.449	0.706	0.182	1.639
45	0.521	12.178	0.489	0.699	0.188	1.695
50	0.461	13.575	0.440	0.664	0.184	1.657
55	0.431	13.555	0.447	0.669	0.169	1.526
60	0.372	14.929	0.283	0.619	0.167	1.503
65	0.205	15.715	0.149	0.385	0.174	1.566
70	0.130	16.003	0.127	0.356	0.178	1.820

* SE -- standard error

Table 2. Linear regression results of scattering coefficient vs. gravimetric soil moisture at different look-angles for VV-pol.

Angle (deg.)	Slope	Intercept	r^2	r	SE	SE of estimate
20	1.11	-8.90	0.81	0.90	0.18	1.68
25	1.10	-9.90	0.82	0.906	0.37	2.51
30	1.12	-9.75	0.79	0.89	0.40	2.71
35	1.10	-10.00	0.77	0.877	0.42	2.87
40	1.17	-11.82	0.76	0.872	0.45	3.10
45	1.25	-13.85	0.74	0.86	0.51	3.49
50	1.27	-15.33	0.71	0.84	0.56	3.81
55	0.95	-15.23	0.81	0.90	0.34	2.18
60	0.96	-5.35	0.91	0.95	0.20	1.41
65	0.85	-1.42	0.43	0.65	0.28	1.85
70	0.33	-0.42	0.37	0.61	0.30	2.04

the r^2 value decreases for HH-pol. Similarly, for VV-pol the maximum value of r^2 is 0.918 at 60°.

In these tables, the angular variation of standard error (SE) of scattering coefficient is also shown. The value of SE varies throughout. Standard error provides an idea about the unreliability of a sample. The greater the standard error, the greater the departure of the actual value from that expected and hence the greater is the degree of unreliability in the measurements. The SE also determines the limit within which the scattering coefficient and soil moisture values are expected to lie. The minimum value of SE is 0.154 at 25° and 0.20 at 60° for HH- and VV-pol respectively. It means that the SE of the scattering coefficient depends upon look-angle and the best look-angles are 25° and 60° for HH-pol and VV-pol respectively for observing bare smooth soil moisture.

5. Conclusion

In this paper an attempt has been made to correlate the relationship between soil moisture and scattering coefficient. This can be done by using a linear regression equation to explain

Figure 5. Calculated vs observed values for scattering coefficients at best suitable look-angle (25°) for HH-pol, $r^2 = 0.710$, SE = 0.168, SE of estimate = 1.301.

Figure 6. Calculated vs observed values for scattering coefficients at best suitable look-angle (60°) for VV-pol, $r^2 = 0.918$, SE = 0.108, SE of estimate = 1.414.

the relationship. From the results obtained and regression analysis, the following conclusions can be drawn.

- (i) The scattering coefficient increases with increase in soil moisture content of the ground surface.
- (ii) The best fit regression line is at look-angle 25° , $r^2 = 0.710$, standard error = 0.154, and standard error of estimate = 1.391 for HH-pol, whereas, for VV-pol the corresponding best look-angle = 60° , for $r^2 = 0.91$, standard error = 0.20 and standard error of estimate = 1.41.
- (iii) The slope of regression is higher for larger frequency which in turn means that the higher frequency is more suitable for the study of σ_0 from the upper surface. This was concluded after analysing the results of both L- and C-bands (Schmugge *et al* 1980) and our own results of the X-band.
- (iv) It was further observed that while the VV-pol was more sensitive to soil moisture at higher look-angles, the HH-pol was more sensitive at lower look-angles. Therefore, depending on the need and the facility available, proper system parameters can be predecided for space-borne applications.

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