Measurement of forward scattering coefficient of different water bodies at different frequencies

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The thrust of this study is to analyse the effect of scattering of electromagnetic waves on microwave links and tracking of low flying objects in the presence of strong ground bounce return from water bound areas. For this purpose, a ground based bi-static forward scatterometer has been used to generate co-polarized specular data at CJ, X, and Ku bands. The measurements are carried out on three types of water surfaces, i.e. tap water, natural lake water and saline water. All the three water surfaces are assumed to be slightly rough surfaces at the frequency of interest. Therefore, small perturbation model of slightly rough surface for forward scattering is a good selection to analyse data. The scattered microwave power from the terrain measured for 25° - 70° scattering angle ($\theta_s$) with an interval of 5° in specular direction with transmitting antenna placed at an incidence angle ($\theta_i$) of 45° from nadir illuminates the terrain keeping $\phi_i = \phi_s = 0°$ at 5.825, 9.472 and 13.4 GHz in CJ, X and KU bands, respectively for $vv$ and $hh$ polarization with different antenna heights. The forward scattering coefficient computed with the help of experimental geometry parameters, which then compared with estimated value of scattering coefficient obtained from small perturbation model of slightly rough surface. A good agreement between observed and estimated scattering coefficient for horizontal ($hh$) and vertical ($vv$) polarization has been found in X and KU bands with a polarization reversal in CJ band. It is also observed that dissolved salt or impurities increase the value of scattering coefficient. The basic purpose of this study is to map and monitor the natural resources and to provide timely inputs for the planners to develop appropriate strategies for optimum utilisation of the resources.

Keywords: Forward scattering coefficient, Water resources, Dielectric coefficient

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1 Introduction

The basic aim of using remote sensing technique is to study, map and monitor the natural resources and provide timely inputs to the planners for developing appropriate strategies for optimum utilization of the available resources of the country. The most important characteristic of microwaves is their penetration through clouds and rain. Sensors used in microwave remote sensing are of two types: passive and active. Passive sensors are those which do not have their own source of illumination. Active sensor uses the scattered power from the terrain, which gives its characteristics in the form of scattering coefficient, transmissivity and reflectivity.

An attempt is made in the present study to analyse the effect of ground scattering of electromagnetic waves on microwave links, design of radar systems intended to sense land based targets, tracking of low flying objects, particularly smart weapons engaging ground based targets and land combat missiles engaging ground based targets affected by a strong ground bounce return from water bound areas. The forward scatter returns from these extended target also has important applications to environmental engineering, hydrology, geology, soil physics, civil engineering, planetary sciences, etc. The forward surface scattering is valuable in the prediction of performance of line-of-sight system in the presence of water bound areas.

Surface roughness plays an important role in the prediction of scattered field and is given by Rayleigh criterion$^1$. The experimental investigations on bistatic forward electromagnetic scattering from terrain have been few because the application of forward scattering is not as straight forward as for backscattering. An attempt is made on bistatic scattering from controlled sea surface by Smith et.al.$^2$ in which the experimental result are validated on controlled sea surface at low grazing angles in X band. The purpose of this work is to suggest a new way of measurement that might be a realistic scenario, in which the transmitting antenna of scatterometer is placed at 45° incidence angle and the receiving antenna varies from 25° to 80° with 5° interval for different water
bodies at varying height of antenna operated in three different bands of frequencies for both like polarization.

Water is essential substance of life on earth and it is most abundant natural resource available on the earth. It is colourless, odourless and tasteless liquid consisting of hydrogen and oxygen molecules, which give it a polar property and the molecule orients itself in the direction of applied electric field\textsuperscript{3,4}. The relaxation time is the time required by the molecules to align them in the direction of electric field. The water molecules have large dipole movement and hence, the high dielectric constant. The relation between the dipole movement and the frequency in terms of dielectric constant is given by Debye\textsuperscript{4} as:

\[
\varepsilon\left(\omega\right) = \varepsilon_{\infty} + \frac{\varepsilon_0 - \varepsilon_{\infty}}{1 + 2\pi f \tau} \left[1 - \cos(\omega \tau)\right]
\]

where, \(\varepsilon_{\infty}\) is static dielectric constant of pure water; \(\varepsilon_0\), high-frequency (or optical) limit of \(\varepsilon\); \(\tau\), relaxation time of pure water; and \(f\), electromagnetic frequency (Hz).

The dielectric constant and relaxation time of water is a function of physical temperature of water. The pure water having dissolved salts is called saline water. The salinity is defined in parts per million (‰), as the total mass of solid salt in grams dissolved in one kg of the solution. The dielectric constant of saline water is also a function of frequency and physical temperature. The real and imaginary parts of the dielectric constant of a saline water solution are given by:

\[
\varepsilon_\text{sw} = \varepsilon_{\text{sw}} + \frac{\varepsilon_{\text{sw}} - \varepsilon_{\text{sw}}}{1 + 2\pi f \tau}\left[1 - \cos(\omega \tau)\right]
\]

where, the subscript sw refers to saline water; \(\sigma\) is the ionic conductivity of the aqueous saline solution (S*m\textsuperscript{-1}); and \(\varepsilon_0\), permittivity of free space.

2 Methodology

The measurements are carried out on three types of water terrain: tap water pond, natural storage of water (lake) and pond of saline water with a salinity of 32 k PPM (approximate salinity of sea water). All the three surfaces are assumed to be calm surfaces, which seem like slightly rough surface with the scatterometer as shown in Fig. 1.

When electromagnetic radiation is incident on a surface of the target, the radiation gets scattered depending on the surface roughness of the target. The two fundamental parameters commonly used to characterize surface roughness are standard deviation of the surface height variation \((k \sigma)\) and surface correlation length \((kl)\), where, \(k=2\pi/\lambda\) is the wave number.

Considering a surface in the x-y plane whose height at a point \((x, y)\) is \(z(x, y)\) above the x-y plane. For a statistically representative segment of the surface of dimensions \(L_x\) and \(L_y\) centered at the origin, the mean height of the surface is\textsuperscript{3}:

\[
\bar{z} = \frac{1}{L_x L_y} \int_{-L_x/2}^{L_x/2} \int_{-L_y/2}^{L_y/2} z(x, y) \, dx \, dy
\]

and the second moment is:

\[
\overline{z^2} = \frac{1}{L_x L_y} \int_{-L_x/2}^{L_x/2} \int_{-L_y/2}^{L_y/2} z^2(x, y) \, dx \, dy
\]

The standard deviation of the surface height \(\sigma\) is given by:

\[
\sigma = \left(\overline{z^2} - \overline{z}^2\right)^{1/2}
\]

If \(z(x, y)\) is statistically independent of the azimuth \(hh\) and \(vv\) angle in the x-y plane, the above formulation can be reduced to one dimension. The normalized auto correlation for a one-dimensional surface profile \(z(x)\) is defined as:

\[
\rho(x') = \frac{\int_{-L_x/2}^{L_x/2} z(x)z(x + x') \, dx}{\int_{-L_x/2}^{L_x/2} z^2(x) \, dx}
\]

As all the three surfaces are assumed as calm water\textsuperscript{3,5}, then the validity conditions for these Gaussian surfaces confirm the validity conditions of Small perturbation model of slightly rough surface, in which the surface height variations are small in comparison to the wavelength, i.e. \(k \sigma < 0.3\) with rms slope, \(m=(\sqrt{2} \pi \sigma / l) < 0.3\) and \(kl = 3\). The test bed selected for water body is such that the

![Fig. 1 — Different water terrains used for measurement](image-url)
measurement is confined to the terrain surface for most of the scattering angles.

2.1 Experimental setup

A gunn source, with a pyramidal horn antenna of 17 dB gain having 10 dB down beam width of 30°, is used as transmitting antenna and a similar horn is used as receiving antenna with a power meter as receiver, which shows the power emitted from target material having frequency range 10 MHz - 18 GHz with input sensitivity of -70 dBm to 20 dBm, and calibrated with 1 mW of power at 50 MHz before taking measurements. The practical experimental setup is shown in Fig. 2.

In this forward scattering facility, two identical horn antennas (transmitter and receiver) are pointed at the target terrain by using a laser beam to avoid associated measurement errors and assume that their footprints overlap according to measurement geometry (Fig. 3). The scatterometer parameters are listed in Table 1.

The transmitting horn antenna fixed at an angle of 45° from nadir illuminates the terrain and the power reflected from the terrain is measured by the receiver. The scattering geometry of the system is shown in Fig. 3 (Ref. 7).

The scattered microwave power from the terrain measured for 25° - 70° scattering elevation angle ($\theta_s$) with an interval of 5°, keeping azimuthal angle ($\phi_t = \phi_r$) at 0° for both polarization with different antenna heights of 30 - 40 cm, and the common illuminated area calculated with the help of antenna geometry parameters, then the forward scattering coefficient computed using popular radar range equation:

$$\sigma^o = \left(\frac{4\pi}{\lambda}\right)^2 \frac{R_r^2 R_t^2 P_r}{G_t G_r P R^2 \Lambda^2}$$ … (8)

where, $R_r$ is target distance; $P_r$, received power; $P_t$, transmitted power; $G_t$, $G_r$, gain of transmitting and receiving antenna; $A$, common illuminated area; $\lambda$, wavelength; and $R_r$, $R_t$, the distance of point of reflection from transmitter and receiver, respectively.

2.2 Estimation of scattering coefficient

When both the surface height standard deviation ($\sigma$) and correlation length ($l$) are smaller than the wavelength, the small perturbation model can be used. The scattered fields can be solved by using the extended boundary condition method with the perturbation method and the bistatic scattering coefficient has been expressed by the first order solution as:

<table>
<thead>
<tr>
<th>Centre frequency</th>
<th>5.82 GHz</th>
<th>9.47 GHz</th>
<th>13.4 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band width</td>
<td>Approx 500 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna type</td>
<td>Pyramidal horn for Tx and Rx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna gain</td>
<td>18 dB</td>
<td>21 dB</td>
<td>21 dB</td>
</tr>
<tr>
<td>10 dB down antenna beam width</td>
<td>19°</td>
<td>19°</td>
<td>19°</td>
</tr>
<tr>
<td>Polarization (linear)</td>
<td>hh and vv</td>
<td>hh and vv</td>
<td>hh and vv</td>
</tr>
<tr>
<td>Antenna height</td>
<td>$h_t = h_r = 30, 35$ and $40$ cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Far field</td>
<td>81.65 cm</td>
<td>83.7 cm</td>
<td>69.45 cm</td>
</tr>
<tr>
<td>Cross-pol isolation</td>
<td>$&gt; 35$ dB</td>
<td>$&gt; 35$ dB</td>
<td>$&gt; 35$ dB</td>
</tr>
<tr>
<td>Incident angle</td>
<td>$\theta_i = 45^\circ$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scattering angle</td>
<td>$\theta_s = 25^\circ$ to $75^\circ$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuthal angle</td>
<td>$\phi_i = \phi_r = 0^\circ$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bore-sight range</td>
<td>90 cm</td>
<td>94 cm</td>
<td>95 cm</td>
</tr>
<tr>
<td>Calibration accuracy</td>
<td>±5%</td>
<td>±5%</td>
<td>±5%</td>
</tr>
<tr>
<td>Measurement precision</td>
<td>±4%</td>
<td>±4%</td>
<td>±4%</td>
</tr>
</tbody>
</table>
\[
\sigma_{pq} = 4k^4 \sigma^2 l^2 \cos^2 \theta_s \cos \theta_i f_{pq} \exp[-k_{d\rho}^2 l^2 / 4]
\]

where,
\[
k_{d\rho} = k^2 \{ \sin^2 \theta_s + \sin^2 \theta_i - 2 \sin \theta_s \sin \theta_i \cos (\varphi_s - \varphi_i) \};
\]
and \(f_{pq}\) term, is the functions of the wave numbers \(k\) in free space and in the medium, the \(z\) components of incident and transmitted propagation vectors, and the incident and scattering angles (azimuthal \(\phi_i\), \(\phi_s\) and elevation \(\theta_i\), \(\theta_s\)).

\[
f_{hh} = \left[ \frac{k_1^2 - k_2^2}{(k_z + k_{1z})(k_{2z} + k_{1z})} \right]^2 \cos^2 (\varphi_s - \varphi_i)
\]

\[
\cdots (10)
\]

\[
f_{vv} = \left[ \frac{k_2^2 k_z + k_1^2 k_{1z}}{k_1^2 k_z + k_2^2 k_{1z}} \right]^2 \times \left[ k_1^2 k_2 \sin \theta_s \sin \theta_i - k_2^2 k_{1z} \cos (\varphi_s - \varphi_i) \right]
\]

\[
\cdots (11)
\]

The polarization term \(f_{hh}\) is associated with horizontal polarization and is given by Eq. (10), whereas the term \(f_{vv}\) is associated with vertical polarization and is given by Eq. (11). The first order solution gives the lowest order incoherent scattered intensities.

Wave number in medium 1 is given by \(k_1 = \frac{2\pi}{\lambda_i}\); and the wavelength by \(\lambda_i = \frac{\lambda}{\sqrt{\varepsilon_i}}\). The propagation vectors in \(x\), \(y\) and \(z\) direction is given by:
\[
k_i = k \sin \theta_i \cos \theta_i; \quad k_z = k \sin \theta_i \sin \theta_i;
\]
\[
k_{1z} = \sqrt{k_1^2 - k_z^2 - k_{1z}^2}; \quad k_{2z} = \sqrt{k_2^2 - k_z^2 - k_{2z}^2};
\]
\[
k_y = k \sin \theta_i \cos \theta_i; \quad k_{2} = k \sin \theta_i \sin \theta_i;
\]
\[
k_{1} = k \cos \theta_i; \quad k_{2z} = k \cos \theta_i
\]

In this study, the geometry suggests \(\phi = \phi_i = 0^\circ\); \(\theta_i = 45^\circ\); \(\theta_s = 0^\circ\) to \(70^\circ\)

The scattering angles are considered up to \(70^\circ\) to ensure that the reflections come only from the ground, at higher angles the direct wave might interfere with scattered waves.

Therefore,
\[
k_{1z} = \sqrt{k_2^2 - k_z^2}; \quad k_{1z} = \sqrt{k_1^2 - k_{1z}^2}
\]

and \(f_{hh}\) and \(f_{vv}\) becomes:
\[
f_{hh} = \left[ \frac{k_1^2 - k_2^2}{(k_z + k_{1z})(k_{2z} + k_{1z})} \right]^2
\]

\[
f_{hv} = f_{vh} = 0
\]

\[
\cdots (13)
\]

\[
f_{vv} = \left[ \frac{k_2^2 k_z + k_1^2 k_{1z}}{k_1^2 k_z + k_2^2 k_{1z}} \times \left[ k_1^2 k_2 \sin \theta_s \sin \theta_i - k_2^2 k_{1z} \cos (\varphi_s - \varphi_i) \right] \right]^2
\]

\[
\cdots (14)
\]

Putting these values in Eq. (9), one can get the values of scattering coefficients in \(hh\) and \(vv\) polarization. Using Eq. (9), the ensemble average of all the point targets in the area of interest, the scattering coefficient is computed and the results are compared with the measured data.

3 Results and Discussion

The dielectric constant of the sample is measured\(^6\) using waveguide cell method at various frequency of interest shown in Fig. 4. From the scatterometer operating over rocky terrain at different frequencies, with different antenna heights and incidence angles, the ground truth data collected from these experiments is shown with their similar regression equations and r-square coefficient for different measurement conditions.

The variations in measured and estimated scattering coefficient with scattering angle in KU band in \(vv\) and \(hh\) polarization at antenna height of 30, 35 and 40 cm

![Fig. 4 — Variations in dielectric constant with frequency](image)
are shown for tap water in Figs 5a and b, respectively with linear regression equation and R-squared value depicted in Table 2. Similarly, the variations in measured and estimated scattering coefficient with scattering angle are plotted in Figs 6a and b, respectively in X band in \textit{vv} and \textit{hh} polarization at antenna height of 30, 35 and 40 cm are shown for natural water with linear regression equation and R-squared value shown in Table 3. Likewise the variations in measured and estimated scattering coefficient with scattering angle plotted in Figs 7a and b in CJ band in \textit{vv} and \textit{hh} polarization at antenna height of 30, 35 and 40 cm are shown for natural lake water, respectively with linear regression equation and R-squared value shown in Table 4. The variations in measured and estimated scattering coefficient for saline water at X-band with scattering angle plotted in Figs 8a and b, respectively and linear regression equation with R-squared value in Table 5.

To validate the trends in the graph of CJ band (Figs 7a and b), Fig. 9 is a result of estimating scattering coefficient in S band of frequency 2.5 GHz for the natural water in \textit{vv} and \textit{hh} polarization at antenna height of 30, 35 and 40 cm with linear regression equation and R-squared value in Table 6. Figures 10a and b show variations in measured and

![Fig. 5](image1)

![Fig. 6](image2)

<table>
<thead>
<tr>
<th>S No</th>
<th>Band-polarisation</th>
<th>Height, cm</th>
<th>Type</th>
<th>Equation</th>
<th>R-square</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KU-\textit{vv}</td>
<td>30</td>
<td>Measured</td>
<td>( y = -0.0524x + 5.219 )</td>
<td>0.545</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>( y = -0.0252x + 0.602 )</td>
<td>0.935</td>
</tr>
<tr>
<td>2</td>
<td>Tap water</td>
<td>35</td>
<td>Measured</td>
<td>( y = -0.051x + 4.3537 )</td>
<td>0.621</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>( y = -0.018x - 0.31 )</td>
<td>0.9878</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>40</td>
<td>Measured</td>
<td>( y = -0.042x + 3.278 )</td>
<td>0.6096</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>( y = -0.0205x - 0.7744 )</td>
<td>0.9731</td>
</tr>
<tr>
<td>4</td>
<td>KU-\textit{hh}</td>
<td>30</td>
<td>Measured</td>
<td>( y = -0.0686x + 0.809 )</td>
<td>0.7031</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>( y = -0.0498x - 3.052 )</td>
<td>0.9443</td>
</tr>
<tr>
<td>5</td>
<td>Tap water</td>
<td>35</td>
<td>Measured</td>
<td>( y = -0.0599x - 2.1774 )</td>
<td>0.6449</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>( y = -0.0466x - 3.7916 )</td>
<td>0.9987</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>40</td>
<td>Measured</td>
<td>( y = -0.0506x - 3.326 )</td>
<td>0.6739</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>( y = -0.0224x - 5.5092 )</td>
<td>0.9731</td>
</tr>
</tbody>
</table>
Table 3 — Regression equations and R-square value for X-vv-hh Measured – Estimated

<table>
<thead>
<tr>
<th>S No</th>
<th>Band-polarisation</th>
<th>Height, cm</th>
<th>Type</th>
<th>Equation</th>
<th>R-square</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X-vv</td>
<td>30</td>
<td>Measured</td>
<td>$y = -0.198x + 9.34$</td>
<td>0.6993</td>
</tr>
<tr>
<td></td>
<td>Natural water</td>
<td></td>
<td>Estimated</td>
<td>$y = -0.073x + 2.975$</td>
<td>0.9968</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>35</td>
<td>Measured</td>
<td>$y = -0.2083x + 7.0948$</td>
<td>0.6253</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>$y = -0.0726x + 2.412$</td>
<td>0.9882</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>40</td>
<td>Measured</td>
<td>$y = -0.2086x + 4.3252$</td>
<td>0.5521</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>$y = -0.0709x + 1.8667$</td>
<td>0.9847</td>
</tr>
<tr>
<td>4</td>
<td>X-hh</td>
<td>30</td>
<td>Measured</td>
<td>$y = -0.21x + 1.65$</td>
<td>0.6203</td>
</tr>
<tr>
<td></td>
<td>Natural water</td>
<td></td>
<td>Estimated</td>
<td>$y = -0.0558x + 0.173$</td>
<td>0.9917</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>35</td>
<td>Measured</td>
<td>$y = -0.076x - 10.92$</td>
<td>0.6278</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>$y = -0.0564x + 0.878$</td>
<td>0.9696</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>40</td>
<td>Measured</td>
<td>$y = -0.0895x - 7.5629$</td>
<td>0.5826</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>$y = -0.0963x + 1.7642$</td>
<td>0.9954</td>
</tr>
</tbody>
</table>

Table 4 — Regression equations and R-square value for CJ-vv-hh Measured – Estimated

<table>
<thead>
<tr>
<th>S No</th>
<th>Band-polarisation</th>
<th>Height, cm</th>
<th>Type</th>
<th>Equation</th>
<th>R-square</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CJ-vv</td>
<td>30</td>
<td>Measured</td>
<td>$y = -0.118x + 1.19$</td>
<td>0.5787</td>
</tr>
<tr>
<td></td>
<td>Natural water</td>
<td></td>
<td>Estimated</td>
<td>$y = -0.064x - 5.7$</td>
<td>0.7529</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>35</td>
<td>Measured</td>
<td>$y = -0.067x + 2.526$</td>
<td>0.9957</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>$y = -0.118x + 1.19$</td>
<td>0.5787</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>40</td>
<td>Measured</td>
<td>$y = -0.067x + 3.7634$</td>
<td>0.9999</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>$y = -0.067x + 2.526$</td>
<td>0.9957</td>
</tr>
<tr>
<td>4</td>
<td>CJ-hh</td>
<td>30</td>
<td>Measured</td>
<td>$y = -0.07x + 2.06$</td>
<td>0.5746</td>
</tr>
<tr>
<td></td>
<td>Natural water</td>
<td></td>
<td>Estimated</td>
<td>$y = -0.0687x + 4.382$</td>
<td>0.9688</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>35</td>
<td>Measured</td>
<td>$y = -0.0554x + 5.3145$</td>
<td>0.4461</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>$y = -0.0712x + 5.0671$</td>
<td>0.988</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>40</td>
<td>Measured</td>
<td>$y = -0.07x + 2.06$</td>
<td>0.5746</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Estimated</td>
<td>$y = -0.0687x + 4.382$</td>
<td>0.9688</td>
</tr>
</tbody>
</table>
estimated scattering coefficients for different water bodies with scattering angle in X-band with \( vv \) and \( hh \) polarization at antenna height of 35 cm with their linear regression equation and R-squared values in Table 7.

It is found that the value of dielectric constant reduces slightly with increase in the frequency (Fig. 4), which is also verified by Eq. (1). It is also confirmed that as the impurities (dissolved salt) in the water increases, the value of the dielectric constant reduces for a particular frequency.

The graphs of measured scattering coefficient with scattering angles in KU band (Fig. 5a) for tap water, and by observing the value of regression coefficient of respective tables, the trend confirms the small perturbation model of slightly rough Gaussian surface, i.e. as the scattering angle increases the value...
of the scattering coefficient reduces. The values of scattering coefficient for $vv$ polarization is higher than that of $hh$ polarization, which is also confirmed by the estimated value of the scattering coefficient by computing the ensemble average of all the points of the illuminated area of interest with the Eq. (9) (Fig. 5b). Similar trends are observed at KU and X band of frequencies for tap water, natural water and saline water. It is also observed that the value of scattering coefficient reduces as antenna height increases.

Apart from these, the polarization reversal is being observed in CJ band, i.e. the values of scattering coefficient in $hh$ polarization are higher than $vv$ (Fig. 7a), which is also verified by the estimated scattering coefficient (Fig. 7b) obtained from calculating ensemble averages, which is further confirmed by the estimation graphs of Fig. 9 for scattering coefficient in S band (2.5 GHz). The value of dielectric constant and wavelength plays a vital role in this polarization reversal and the values are 65.58 and 3.80 cm (7.89 GHz), respectively for natural water.

4 Conclusions

It is concluded that at a particular height of an antenna (e.g. 35 cm), the value of the scattering coefficient is higher for saline water as compared to natural and tap water, i.e. due to the lower value of dielectric constant, which is also confirmed by the estimation trends (Figs 10a and b). It is, further, concluded that even when the parameters of the observed surface are well determined and known, some discrepancy exists between models and measurements due to temperature difference in terrains, angle subtended on terrain is large relative to antenna beam width, non-uniform illuminated area, and the phase and range associated with the point targets of interest. This discrepancy is quite small and may be insignificant for many practical applications.

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References