Depolarization of Electromagnetic Waves By Sea Surface

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***Abstract*— An improved Two Scale Model (TSM) has been investigated for the depolarization of electromagnetic waves from sea surface. Classical TSM produce depolarized results due to the tilt of reflecting plane. To include the contribution of actual phenomenon we add the second order scattering effects at small scale and develop an improved TSM. Numerical results are obtained for both backscattering and bistatic scattering using Gaussian spectrum for different roughness levels and compared with those of SPM2 and classical TSM. It is observed that as the roughness of the surface increases the intensity of depolarized scattered power increases.**

I. INTRODUCTION

Depolarization in a radar return results in a corruption of the desired signal. It is an undesired effect, for a given transmitter, limiting the useful radar coverage distance, just like receiver noise and interference from multipath propagation or undesired signals limit usable distances of communications systems. However, the cross-polarization in conjunction with co-polarization information can be used to retrieve the surface roughness parameters (rms height, correlation length, soil moisture content, wind speed and wind direction etc.), the geometrical configuration of scatterers and gives important clues to the electrical properties of surfaces etc. Hence the study of depolarization can not be used to discriminate unwanted reflections only but also used to the identification and optimization purposes and permits deeper insight into physical phenomena. Due to this reason the cross-polarized radar returns are of interest to some EMC engineers, hydrologists, meteorologists and agriculturists.

Cross polarization in a radar return from a rough surface [1]-[3] has been observed experimentally. First order Small Perturbation Method (SPM1) [4] and Kirchhoff Approximation (KA) [5] does not predict this phenomenon. In order to account for observed cross polarization most theoreticians have used the methods of (AIEM) , Second order Small Slope Approximation (SSA2), Second order Small Perturbation Method (SPM2) , Two Scale Model (TSM), and Empirical models etc.

In the classical TSM it is assumed that the short wave length waves are riding on the larger waves and thus tilted with respect to the horizontal surface [2]. It uses SPM1 at small scale i.e., for short wavelength waves and the effect of long wavelength part is taken into account by averaging over tilt angles. Hence by using the classical TSM based on first order theory, depolarization is basically due to the tilt of reflecting plan and needs to be improved.

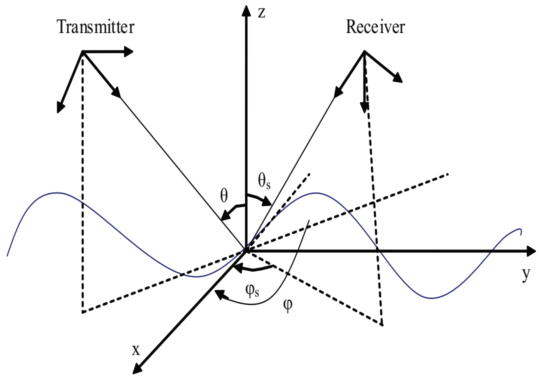

Fig. 1. Geometrical representation of bistatic configuration

Since the mechanism of multi-scattering due to target surface roughness also causes depolarization and second order scattering from rough surface is a type of multiple scattering [1] so we consider the contribution of second order scattering calculations at small scale and develop an improved TSM [6]. In this paper we study and analyze this improved model for cross polarization case. Surface roughness is characterized as a Gaussian random process with an isotropic Gaussian correlation function. The simulation results are obtained for two roughness levels, both for backscattering and bistatic scattering and compared with those of SPM2 and classical TSM.

The rest of the paper is organized as follows: in section II after taking a small review of SPM up to second order we briefly introduce the theoretical development of improved TSM. The simulation results are presented in section IV. Finally, the conclusions and prospectives of this work are reported.

II. MATHEMATICAL MODELS

This section contains a small review of SPM up to second order and then an improved two scale model is presented. The geometry of the surface scattering reflection is shown in Figure 1.

A. Small Perturbation Method (SPM)

The scattering of electromagnetic waves from a slightly rough surface can be studied using a Small Perturbation Method. In this method it is assumed that the surface variations are much smaller than the incident wavelength and the slopes of the rough surface are relatively small. This method has been studied and applied extensively to problems in optics, remote sensing, and propagation and yields the Bragg scatter phenomenon of rough-surface scattering when only first-order terms are considered. Depolarization of electromagnetic waves was obtained by Valenzuela [1] while studying this method upto second order, where he inferred that depolarization from slightly rough surface is due to multiple scattering because the expression for the depolarized scattered power he obtained is of the form obtained in multiple scattering investigations.

By using extended boundary condition method, the first and second order bistatic scattering coefficient σ_{pq} as a function of the transmitter polarization q and receiver polarization p is given by

$$\sigma_{pq}^{(1)} = 16\pi \left| k^2 \cos\theta_i \cos\theta_s \alpha_{pq}^{(1)} \right|^2 W\left(k_{s\perp} - k_{i\perp}\right) \quad (1)$$

$$\sigma_{pq}^{(2)} = 4\pi k^6 \cos^2\theta_i \cos^2\theta_s \int dk_\perp \Big[W\left(k_{s\perp} - k_\perp\right) W\left(k_\perp - k_{i\perp}\right) \alpha_{pq}^{(2)} \left(\alpha_{pq}^{*(2)} + \beta_{pq}^{*(2)} \right) \Big] \quad (2)$$

where $k_\perp = k_x \mathbf{x} + k_y \mathbf{y}$ denotes vector in (x-y)-plane, $W(k.)$ is the spectrum and $\alpha_{pq}^{(1)}$, $\alpha_{pq}^{(2)}$, $\beta_{pq}^{(2)}$ are the first and second order polarization dependent coefficients given in [11].

Since SPM is used to obtain the scattering coefficients of a slightly rough surface such as its vertical roughness scale is small compared to the transmitted wave length, therefore this approach is well adapted to small sea amplitude which is the case for low wind driven waves. The computation of the SPM is based on a spectral description of the sea surface. Actually, the first order SPM approach provides an estimation of the diffuse component of the electromagnetic scattered wave. For monostatic case it does not predict the cross-polarized components. Its development to the second order gives estimation of co- and cross-polarized components in all directions. We exploit this property to get better estimates for depolarizations.

B. Improved Two-scale Model

The classical two-scale model, introduced by Fuks [7] and Fung et al. [8] in backscattering configuration and extended by Khenchaf et al. [9], [10] in bistatic configurations, approximate the sea surface as a two-scale surface with small-scale ripples or capillary waves riding on the top of large-scale surfaces or gravity waves. Then scattering coefficients are estimated in two steps. Firstly, the classical TSM uses SPM1 on small scale waves and then determine the diffuse component in the global reference by a tilting process. The geometry of the surface scattering problem is shown in Fig. 2 . The transmitter and the receiver are located in a reference (x, y, z) by the angles θ, ϕ, θ_s and ϕ_s.

The 2×1 complex element vectors E^i and E^s describe the polarizations of the incident and scattered electric fields, respectively. Assume the incident wave $\mathbf{E}^i$ to be

$$\mathbf{E}^i = \widehat{\mathbf{a}} E_0 \quad (3)$$

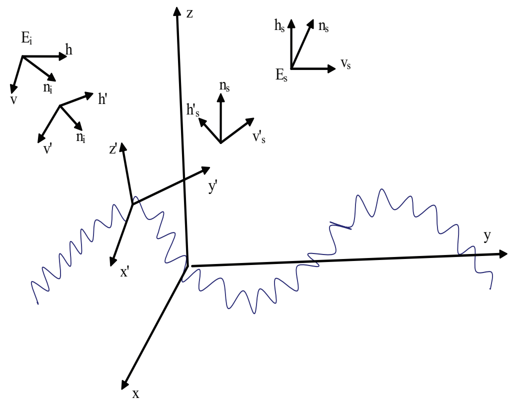

Fig. 2. Geometry of a surface bistatic scattering in the two-scale model

with

$$E_0 = |E_0| \exp\left\{-jk\left(\widehat{\mathbf{n}}_i.\mathbf{r}\right)\right\} \quad (4)$$

where $\widehat{\mathbf{a}}$ is the unit polarization vector (vertical polarization $\widehat{\mathbf{v}}$ or horizontal polarization $\widehat{\mathbf{h}}$), k is the wave number of transmitted wave and $\widehat{\mathbf{n}}_i$ is the unit vector in the incident direction.

In the local reference frame

$$\mathbf{E}^i = E_{h'}^i \widehat{\mathbf{h}}' + E_{v'}^i \widehat{\mathbf{v}}' = \left[\left(\widehat{\mathbf{h}}'.\widehat{\mathbf{a}} \right) \widehat{\mathbf{h}} +' \left(\widehat{\mathbf{v}}'.\widehat{\mathbf{a}} \right) \widehat{\mathbf{v}}' \right] E_0 \quad (5)$$

and the locally scattered field due to incident waves are:

$$\begin{bmatrix} E_{h'_s}^s \\ E_{v'_s}^s \end{bmatrix} = \begin{bmatrix} S_{h'_s h'}^{(1)} + S_{h'_s h'}^{(2)} & S_{h'_s v'}^{(1)} + S_{h'_s v'}^{(2)} \\ S_{v'_s h'}^{(1)} + S_{v'_s h'}^{(2)} & S_{v'_s v'}^{(1)} + S_{v'_s v'}^{(2)} \end{bmatrix} \begin{bmatrix} E_{h'}^i \\ E_{v'}^i \end{bmatrix} \quad (6)$$

where $S_{p'q'}^{(1)}$ and $S_{p'q'}^{(2)}$are the first and second order scattered field for unit incident fields.

The scattered field can be written as

$$\mathbf{E}^s = S\mathbf{E}^i \quad (7)$$

Where S is the scattering matrix, expressed in the global frame of reference by

$$S = \begin{bmatrix} \widehat{\mathbf{h}}_s.\widehat{\mathbf{h}}'_s & \widehat{\mathbf{h}}_s.\widehat{\mathbf{v}}'_s \\ \widehat{\mathbf{v}}_s.\widehat{\mathbf{h}}'_s & \widehat{\mathbf{v}}_s.\widehat{\mathbf{v}}'_s \end{bmatrix} \begin{bmatrix} S_{h'_s h'}^{(1)} + S_{h'_s h'}^{(2)} & S_{h'_s v'}^{(1)} + S_{h'_s v'}^{(2)} \\ S_{v'_s h'}^{(1)} + S_{v'_s h'}^{(2)} & S_{v'_s v'}^{(1)} + S_{v'_s v'}^{(2)} \end{bmatrix} \begin{bmatrix} \widehat{\mathbf{h}}'.\widehat{\mathbf{h}} & \widehat{\mathbf{h}}'.\widehat{\mathbf{v}} \\ \widehat{\mathbf{v}}'.\widehat{\mathbf{h}} & \widehat{\mathbf{v}}'.\widehat{\mathbf{v}} \end{bmatrix} \quad (8)$$

Now by using scattered field, the scattering coefficients σ_{pq} as a function of the transmitter polarization q ($\widehat{\mathbf{h}}$ or $\widehat{\mathbf{v}}$) and the receiver polarization p ($\widehat{\mathbf{h}}_s$or $\widehat{\mathbf{v}}_s$) are given by

$$
\begin{aligned}
\sigma_{pq}^{s} &= \frac{4\pi R^{2}}{A}\frac{\left\langle \left|E_{pq}^{s}\right|^{2}\right\rangle}{\left|E_{q}^{i}\right|^{2}} \\
&= \Bigg\langle \left(p.\widehat{\mathbf{h}}_{s}'\right)^{2}\left(\widehat{\mathbf{h}}'.q\right)^{2}\left(\sigma_{h_s'h'}^{(1)}+\sigma_{h_s'h'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{h}}_{s}'\right)^{2}\left(\widehat{\mathbf{v}}'.q\right)^{2}\left(\sigma_{h_s'v'}^{(1)}+\sigma_{h_s'v'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{v}}_{s}'\right)^{2}\left(\widehat{\mathbf{h}}'.q\right)^{2}\left(\sigma_{v_s'h'}^{(1)}+\sigma_{v_s'h'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{v}}_{s}'\right)^{2}\left(\widehat{\mathbf{v}}'.q\right)^{2}\left(\sigma_{v_s'v'}^{(1)}+\sigma_{v_s'v'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{v}}_{s}'\right)^{2}\left(\widehat{\mathbf{h}}'.q\right)\left(\widehat{\mathbf{v}}'.q\right)\left(\sigma_{v_s'h'v_s'v'}^{(1)}+\sigma_{v_s'h'v_s'v'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{v}}_{s}'\right)^{2}\left(\widehat{\mathbf{h}}'.q\right)\left(\widehat{\mathbf{v}}'.q\right)\left(\sigma_{v_s'v'v_s'h'}^{(1)}+\sigma_{v_s'v'v_s'h'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{h}}_{s}'\right)\left(p.\widehat{\mathbf{v}}_{s}'\right)\left(\widehat{\mathbf{v}}'.q\right)^{2}\left(\sigma_{h_s'v'v_s'v'}^{(1)}+\sigma_{h_s'v'v_s'v'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{h}}_{s}'\right)\left(p.\widehat{\mathbf{v}}_{s}'\right)\left(\widehat{\mathbf{v}}'.q\right)^{2}\left(\sigma_{v_s'v'h_s'v'}^{(1)}+\sigma_{v_s'v'h_s'v'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{h}}_{s}'\right)^{2}\left(\widehat{\mathbf{h}}'.q\right)\left(\widehat{\mathbf{v}}'.q\right)\left(\sigma_{h_s'h'h_s'v'}^{(1)}+\sigma_{h_s'h'h_s'v'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{h}}_{s}'\right)^{2}\left(\widehat{\mathbf{h}}'.q\right)\left(\widehat{\mathbf{v}}'.q\right)\left(\sigma_{h_s'v'h_s'h''}^{(1)}+\sigma_{h_s'v'h_s'h'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{h}}_{s}'\right)\left(p.\widehat{\mathbf{v}}_{s}'\right)\left(\widehat{\mathbf{h}}'.q\right)^{2}\Big(\sigma_{h_s'h'v_s'h'}^{(1)} \\
&\quad +\sigma_{h_s'h'v_s'h'}^{(2)}\Big)+\left(p.\widehat{\mathbf{h}}_{s}'\right)\left(p.\widehat{\mathbf{v}}_{s}'\right)\left(\widehat{\mathbf{v}}'.q\right)\left(\widehat{\mathbf{h}}'.q\right) \\
&\quad \left(\sigma_{h_s'v'v_s'h'}^{(1)}+\sigma_{h_s'v'v_s'h'}^{(2)}\right)+\left(p.\widehat{\mathbf{h}}_{s}'\right)\left(p.\widehat{\mathbf{v}}_{s}'\right)\left(\widehat{\mathbf{v}}'.q\right) \\
&\quad \left(\widehat{\mathbf{h}}'.q\right)\left(\sigma_{v_s'h'h_s'v'}^{(1)}+\sigma_{v_s'h'h_s'v'}^{(2)}\right)+\left(p.\widehat{\mathbf{h}}_{s}'\right)\left(p.\widehat{\mathbf{v}}_{s}'\right) \\
&\quad \left(\widehat{\mathbf{h}}'.q\right)\left(\widehat{\mathbf{v}}'.q\right)\left(\sigma_{h_s'h'v_s'v'}^{(1)}+\sigma_{h_s'h'v_s'v'}^{(2)}\right)+\left(p.\widehat{\mathbf{h}}_{s}'\right) \\
&\quad \left(p.\widehat{\mathbf{v}}_{s}'\right)\left(\widehat{\mathbf{h}}'.q\right)\left(\widehat{\mathbf{v}}'.q\right)\left(\sigma_{v_s'v'h_s'h'}^{(1)}+\sigma_{v_s'v'h_s'h'}^{(2)}\right) \\
&\quad +\left(p.\widehat{\mathbf{h}}_{s}'\right)\left(q_{s}.\widehat{\mathbf{v}}_{s}'\right)\left(\widehat{\mathbf{h}}'.q\right)^{2}\left(\sigma_{v_s'h'h_s'h'}^{(1)}+\sigma_{v_s'h'h_s'h'}^{(2)}\right)\Bigg\rangle
\end{aligned} \tag{9}
$$

where

$$
\begin{aligned}
\sigma_{p'q'}^{(1)} &= 16\pi\left|k^{2}\cos\theta_{i}'\cos\theta_{s}'\alpha_{p'q'}^{(1)}\right|^{2}W\left(k_{s\perp}-k_{i\perp}\right) \\
\sigma_{p'q'm'n'}^{(1)} &= 16\pi k^{2}\left|k^{2}\cos\theta_{i}'\cos\theta_{s}'\right|^{2}\alpha_{p'q'}^{(1)}\alpha_{mn}^{(1)*} \\
&\quad .W\left(k_{s\perp}-k_{i\perp}\right) \\
\sigma_{p'q}^{(2)\prime} &= 4\pi k^{6}\cos^{2}\theta_{i}'\cos^{2}\theta_{s}'\int dk_{\perp}\big[W\left(k_{s\perp}-k_{\perp}\right) \\
&\quad W\left(k_{\perp}-k_{i\perp}\right)\alpha_{p'q'}^{(2)}\left(\alpha_{p'q'}^{*(2)}+\beta_{p'q'}^{*(2)}\right)\big] \\
\sigma_{p'q'm'n}^{(2)\prime} &= 4\pi k^{6}\cos^{2}\theta_{i}'\cos^{2}\theta_{s}'\int dk_{\perp}\big[W\left(k_{s\perp}-k_{\perp}\right) \\
&\quad W\left(k_{\perp}-k_{i\perp}\right)\alpha_{p'q'}^{(2)}\left(\alpha_{m'n'}^{*(2)}+\beta_{m'n'}^{*(2)}\right)\big]
\end{aligned}
$$

θ_i' is a local incidence angle, θ_s' is a local scattering angle and $*$ denotes the complex conjugate. The average $\langle . \rangle$ in the scattering coefficients may then be calculated by using any model of surface slopes distribution.

Since for backscattering case $\alpha_{hv}^{(1)} = \alpha_{vh}^{(1)} = 0$ so in classical TSM all the terms involving first order cross polarized factors become zero. While $\alpha_{pq}^{(2)}$ & $\beta_{pq}^{(2)} \neq 0$ for all p and q, hence the knowledge of second order polarization dependent coefficients can be useful not only for the exact estimation of depolarized scattering coefficients but also for the better predictions at grazing angles . In this paper we explore this improved model for depolarized coefficients and its applications are considered for sea surface. Note that for the sake of simplicity in (9) we ignore the terms involving the product of first and secong order fild.

C. Mathematical Spectrum

The first time obtained depolarization results by using improved TSM are based on Gaussian probability density function and Gaussian spectrum. The expression of slope pdf is given by

$$
P\left(Z_x, Z_y\right) = \frac{1}{2\pi m^2}\exp\left(-\frac{Z_x^2 + Z_y^2}{2m^2}\right) \tag{10}
$$

where Z_x and Z_y are slopes in x and y direction and $m = \sqrt{2}h/l$. The expression of Gaussian spectrum is given by

$$
W\left(k_\perp\right) = \frac{h^2 l^2}{4\pi}\exp\left(-\frac{\left(k_x^2 + k_y^2\right) l^2}{4}\right) \tag{11}
$$

where k_x and k_y are components of wave vector h is the rms height and l is the correlation length of rough surface.

III. Numerical Results

In this section, initially we illustrate the numerical simulation results of the cross polarized coefficient (σ_{hv}) in backscattering case. The bistatic case is considered afterward.

Figures 1 and 2 illustrate the effect of incidence angle on σ_{hv} in the $kh = 0.5$, $kl = 3$ and $kh = 1$, $kl = 6$ cases, respectively. The value of dielectric constant is taken as $4 + i$. The results are compared with SPM2 and classical TSM.

It can be observed that new model gives improved results. The difference between classical TSM and improved TSM increases with the increase in incident angle and roughness level. The same type of observation can be done in bistatic case. Figures 3 and 4 are plotted against observed angle by taking the incident angle $\theta_i = 30°$ and received azimuth $\phi_s = 45°$. The rest of the parameters are same as taken above.

IV. Conclusion

The development of an improved two-scale model describing bistatic reflectivity is presented and explored for depolarization case. For the first time the numerical results are computed for the backscattering and bistatic scattering using Gaussian spectrum for two roughness levels and compared with SPM2 and classical TSM. The applications of new model for depolarization and on grazing angles using more realistic sea spectrum developed by Elfouhaily et al. are under computation and will be reported later on.

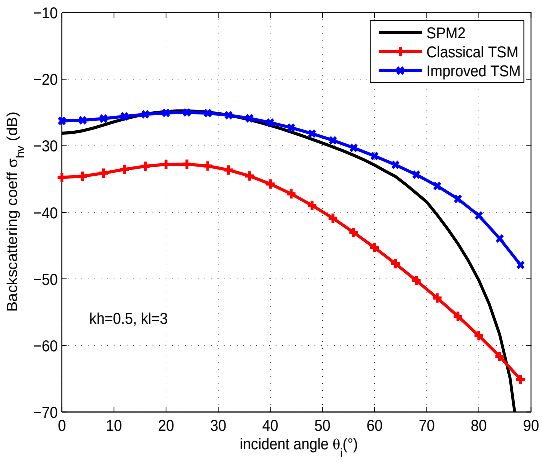

Fig. 3. Backscattering coefficient (σ_{hv}): Comparison of Improved TSM with SPM2 and classical TSM, where $kh = 0.5$ and $kl = 3$.

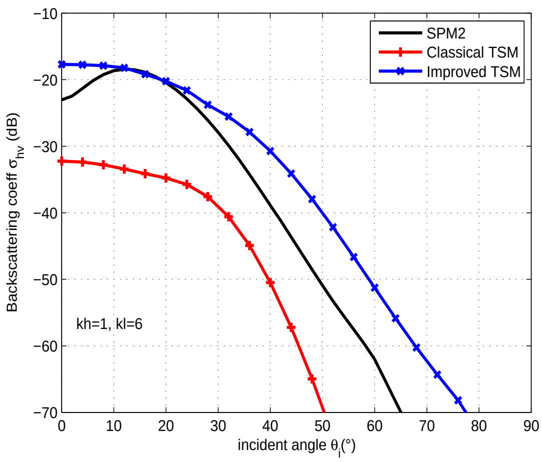

Fig. 4. Backscattering coefficient (σ_{hv}): Comparison of Improved TSM with SPM2 and classical TSM, where $kh = 1$ and $kl = 6$.

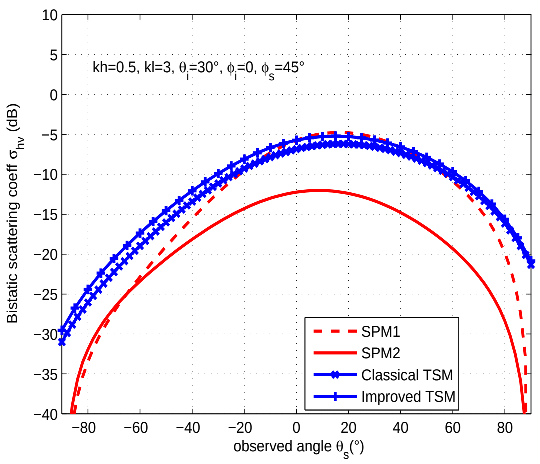

Fig. 5. Bistatic scattering coefficient (σ_{hv}): Comparison of Improved TSM with SPM2 and classical TSM, where $kh = 0.5$ and $kl = 3$.

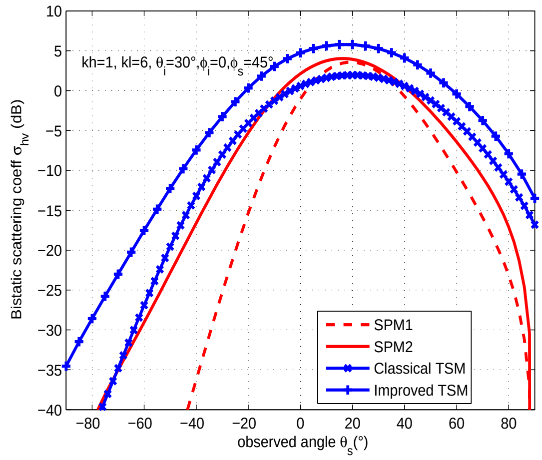

Fig. 6. Bistatic scattering coefficient (σ_{hv}): Comparison of Improved TSM with SPM2 and classical TSM, where $kh = 1$ and $kl = 6$

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