Figure 10-1: Scattering from a random surface, a vegetation canopy, and snow-covered soil.
Figure 10-2: Two configurations of height variations: (a) random height variations superimposed on a periodic surface, and (b) random height variations superimposed on a flat surface.
Figure 10-3: Random, isotropic surface $z(x,y)$: (a) pictorial view, (b) measured height profile $z(x)$, (c) pdf of digitized height profile, and (d) autocorrelation function $\rho(\xi)$, where $\xi$ is the displacement between two points on the surface.
Figure 10-4: Measured dielectric constant as a function of volumetric moisture content for a loamy soil at four microwave frequencies [Hallikainen et al., 1985].
Figure 10-5: Variation of reflectivity $\Gamma$ with $\theta$ and $m_v$ for a loamy soil at 1.5 GHz.
Figure 10-6: At (a) normal incidence, the phase difference between the rays reflected from A and B is $\Delta \phi = 2kh$ and at (b) oblique incidence $\Delta \phi = 2kh \cos \theta$. 
Surface parameters

- Dielectric constant $\varepsilon = \varepsilon' - j\varepsilon''$
- Height pdf $p(z)$ → rms height $s$
- Height correlation function $\rho(\xi)$ → correlation length $l$
- $\text{rms slope } m = [-s^2 \rho''(0)]^{1/2}$

Radar wave parameters

- Frequency $f$ (or wavelength $\lambda$)
- Incidence angle $\theta$
- Receive / transmit polarization configuration $rt$

Figure 10-7: Block-diagram representation of the surface and radar input parameters for the I²EM model in the backscatter mode. For bistatic scattering, $\theta$ becomes $\theta_i$ and the scattered direction is specified by $\theta_s$ and $\phi$, where $\phi$ is the azimuth angle between the incident and scattered directions.
\[ \rho(\xi) = e^{-\left(\frac{\xi}{l}\right)^x} \]

Figure 10-8: (a) The $x$-exponential correlation function and (b) three-scale random surface.
Figure 10-9: In backscattering, the effective wavelength is $\lambda_e = \lambda / (2 \sin \theta)$. As $\lambda_e$ is shortened due to an increase in either frequency or angle, the smaller roughness scales become more effective in scattering. The surface has three roughness scales: large-scale with $(s_1, l_1) = (0.4 \text{ cm}, 7 \text{ cm})$, medium-scale with $(s_2, l_2) = (0.25 \text{ cm}, 3 \text{ cm})$, and small-scale with $(s_3, l_3) = (0.13 \text{ cm}, 1.5 \text{ cm})$. The plots show the individual contributions of the three roughness scales, as well as the total.
Figure 10-10: $I^2$EM comparison of the backscattering coefficients for two surfaces with identical surface parameters, but different correlation functions.
Figure 10-11: $I^2$EM backscatter response to two surfaces with different rms heights.
Figure 10-12: The role of the correlation length $l$ is demonstrated by three surfaces with $l = 2$ cm, 8 cm, and 16 cm, all computed using $I^2$EM.
Figure 10-13: The role of soil moisture: (a) angular response of $\sigma^0$ for three surfaces with different soil moisture content, (b) $\sigma^0$ versus $m_v$ at $30^\circ$. 
Figure 10-14: I²EM-computed plots of (a) the co-pol ratio $p$(dB) and (b) the cross-pol ratio $q$(dB) as a function of $ks$. 

(a) $p$(dB) versus $ks$

(b) $q$(dB) versus $ks$
Figure 10-15: Comparison of I$^2$EM-calculated values of $\sigma^0$ with experimental data measured for a smooth surface with $s = 0.4\,\text{cm}$.
Figure 10-16: Comparison of $I^2$EM-calculated values of $\sigma^0$ with experimental data measured for a rough surface with $s = 1.12$ cm.
$\theta_i = \theta_s, \phi = 0$

Model: I^2EM

Data: De Roo and Ulaby (1994)

$s = 0.246$ cm

$l = 2.578$ cm

$\varepsilon = 3$

$s = 0.663$ cm

$l = 5.06$ cm

$\varepsilon = 3$

$s = 0.926$ cm

$l = 5.63$ cm

$\varepsilon = 3$

**Figure 10-17:** Comparison of I^2EM-computed bistatic scattering coefficient with measurements made in the incidence plane ($\theta_i = \theta_s$ and $\phi = 0$) for three surfaces with different roughnesses.
Figure 10-18: Comparison of $I^2$EM-computed bistatic scattering coefficient with measurements made as a function of the azimuth angle $\phi$ for $\theta_i = \theta_s = 45^\circ$. 

Model: $I^2$EM
Data: Hauck et al. (1998)
Figure 10-19: Comparison of $I^2$EM-computed bistatic scattering coefficients with measurements as a function of the scattering angle $\theta_s$. 

Model: $I^2$EM

Data: JRC

Gaussian correlation $\varepsilon = 5.5 - j2.1$

$\theta_i = 20^\circ$

$\phi = 0^\circ$

$s = 0.4$ cm

$l = 6$ cm

$f = 11$ GHz
Figure 10-20: Measured backscattering coefficient of a dry asphalt surface at three microwave frequencies. The estimated value of the rms height is $s = 0.5$ cm.
Figure 10-21: Measured backscattering coefficient of loose dirt with $s \approx 1.5$ cm at three microwave frequencies.
Figure 10-22: Measured 1.5 GHz response of $\sigma^0_{hh}$ to $m_v$ for a smooth surface with $k_s = 0.35$ and a rougher surface with $k_s = 1.3$ [from Ulaby et al., 1978].
Figure 10-23: Parallel-look direction corresponds to $\phi_0 = 0$, and perpendicular-look direction corresponds to $\phi_0 = 90^\circ$. 
Figure 10-24: Area as observed by (a) a pencil-beam scatterometer and (b) a high-resolution imager.
Figure 10-25: Angular plots of $\sigma_{hh}^s(\theta')$ for smooth and rough random surfaces in the absence of the periodic surface.
Figure 10-26: Periodic surface with relatively smooth random undulations. (a) Variation of the scattering coefficient $\sigma_{hh}^{0}(\theta_0, \phi_0)$ as a function of the beam angle of incidence $\theta_0$ for several values of the azimuth angle $\phi_0$, and (b) variation of $\sigma_{hh}^{s}(\theta_0, \phi_0)$ with the azimuth angle $\phi_0$. 

- $\epsilon = 3.6 - j0.2$
- $\psi = 29.68^\circ$
- $ks = 0.2$
- $kl = 9.0$
- hh polarization
Figure 10-27: Periodic surface with rough random undulations. (a) Variation of the scattering coefficient $\sigma^0(\theta_0, \phi_0)$ as a function of the beam angle of incidence $\theta_0$ for several values of the azimuth angle $\phi_0$, and (b) variation of $\sigma^0_{\text{hh}}(\theta_0, \phi_0)$ with the azimuth angle $\phi_0$. 

---

Scattering coefficient $\sigma^0(\theta_0, \phi_0)$ and $\delta(\theta')$ (dB)

Beam and local angle of incidence $\theta_0, \theta'$ (degrees)

---

$\epsilon_s = 3.6 - j0.2$

$m = 0.3$, rms surface slope $k_s = 2$

---

Parallel to rows

Perpendicular to rows

Parallel to rows
Figure 10-28: Scatterometer time response for a wheat-stubble field [Ulaby et al., 1982c].
Figure 10-29: Graphic illustration of the difference between Seasat SAR returns as influenced by tillage direction [from Blanchard and Chang, 1983].
Figure 10-30: Measured backscattering coefficient of (a) a smooth surface with \( s = 0.32 \text{ cm} \) at 1.5 GHz and (b) a rough surface with \( s = 3.02 \text{ cm} \) at 9.5 GHz.
Figure 10-31: Measured and modeled variation of the co-pol ratio $p$ with EM roughness $ks$. 

$p = \sigma_{hh}^0 / \sigma_{vv}^0$ (dB)

Wet ($\varepsilon = 15.0 - j3.0$), model

Wet, measured

$\theta = 50^\circ$
\[ q = 0.23\Gamma^{0.5}(1 - \exp(-ks)) \]

\[ \varepsilon_{\text{soil}} = 6.58 - j1.55 \]

\[ m_v = 0.15 \text{ g/cm}^3 \]

\[ \theta = 40^\circ \text{ data} \]

\[ q = 0.23\Gamma^{0.5}(1 - \exp(-ks)) \]

\[ \varepsilon_{\text{soil}} = 15.34 - j3.66 \]

\[ m_v = 0.30 \text{ g/cm}^3 \]

\[ \theta = 40^\circ \text{ data} \]

**Figure 10-32:** Measured and modeled variation of the cross-pol ratio \( q \) with EM roughness \( ks \) for (a) a dry and (b) a wet soil surface [Oh et al., 1992].
The PRISM-1 uses the co-pol ratio $p$ and cross-pol ratio $q$ at any specified frequency/angle combination to estimate the values of the rms height $s$ and volumetric moisture $m_v$. This algorithm is for $f = 1.25$ GHz and $\theta = 30^\circ$. 
Figure 10-34: Comparison of radar-estimated values (based on PRISM-1) of $k_s$, $\varepsilon'$, $\varepsilon''$, and $m_v$ with corresponding values measured directly [Oh et al., 1992].
Figure 10-35: PRISM-2 plots of (a) the cross-pol ratio $q$ as a function of $ks$ at $\theta = 45^\circ$, (b) $\sigma_{hv}^0$, and (c) co-pol ratio $p$. 
Figure 10-36: Comparison of radar-estimated values of $s$ and $m_v$ using PRISM-2 with corresponding values measured directly. Each data point represents a single frequency/angle combination [Oh, 2004].
Figure 10-37: To reduce the scattering in Fig. 10-36 due to intercalibration among the various radars and measurement campaigns, multifrequency/angle radar estimates are averaged together [Oh, 2004].
Figure 10-38: SMART model algorithm.
Figure 10-39: Plot of $10 \log \left( \sigma_{0}^{0} \lambda^{-0.7} \frac{\sin^{5} \theta}{\cos^{1.5} \theta} \times 10^{-0.028 \varepsilon' \tan \theta} \right)$ as a function of $\log(k_{s} \sin \theta)$ for the POLARSCAT and RASAM scatterometer data [Dubois et al., 1995a, b].
Figure 10-40: Estimated (a) soil moisture versus *in-situ* measured soil moisture and (b) rms height versus *in-situ* measured rms height [Dubois et al., 1995a].
Figure 10-41: Radar-estimated soil moisture versus *in-situ* measured soil moisture for bare-soil fields imaged by the JPL AIRSAR and SIR-C [Dubois et al., 1995a].
Figure 10-42: Comparison of numerical 3-D computed values with I²EM, PRISM-1, and SMART models for (a) vv polarization and (b) hh polarization.

θ = 40° 
ε_soil = 5.46 − j0.37
Figure 10-43: Comparison of numerical 3-D computed values with I²EM, PRISM-1, and SMART models for (a) vv and (b) hh polarizations.