EITN90 Radar and Remote Sensing
Lecture 4: Characteristics of Clutter

Daniel Sjöberg

Department of Electrical and Information Technology

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Outline

Learning outcomes of this lecture

In this lecture we will

- Characterize the clutter
- Observe orders of magnitude from different sources
- Have an initial discussion on clutter suppression
- See a few empirical models

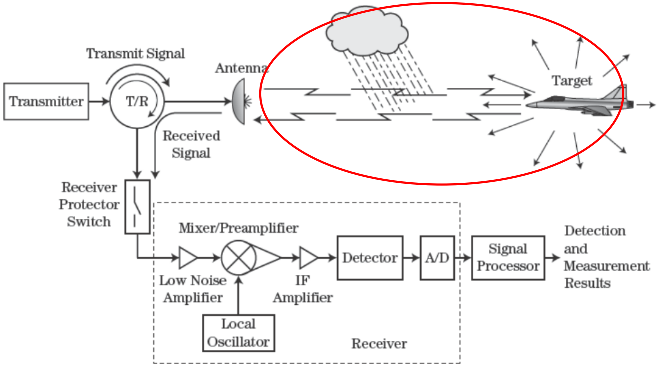

FIGURE 1-1 ■ Major elements of the radar transmission/reception process.

Outline

1. **Introduction and definitions**
2. **General characteristics of clutter**
   - Surface clutter
   - Atmospheric clutter
3. **Clutter modeling**
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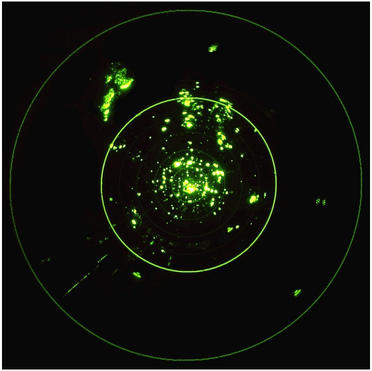
   - Atmospheric clutter
   - Summary of clutter results
4. **Conclusions**
5. **Lab on Friday**

What is clutter?

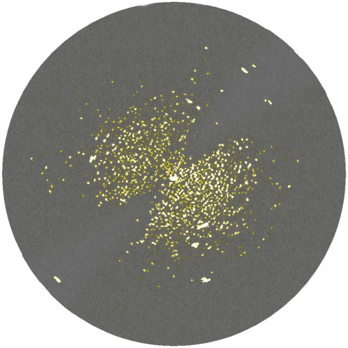
- Backscattering from natural objects, such as precipitation, vegetation, soil and rocks, or the sea.
- When trying to detect man-made object, it is considered an unwanted interference, masking the signal.
- When surveying natural processes (thickness of ice caps, weather etc), it may be the main signal of interest.

Examples of clutter

Images from http://www.radartutorial.eu/ (CC BY-SA 3.0).



PPI screen of an ATC-radar with targets and clutter.

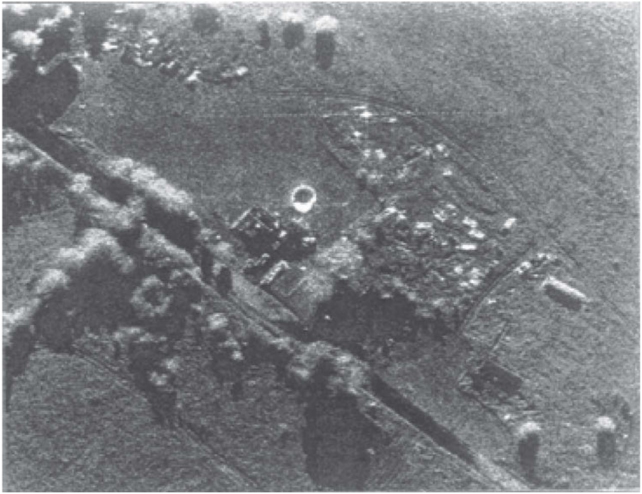


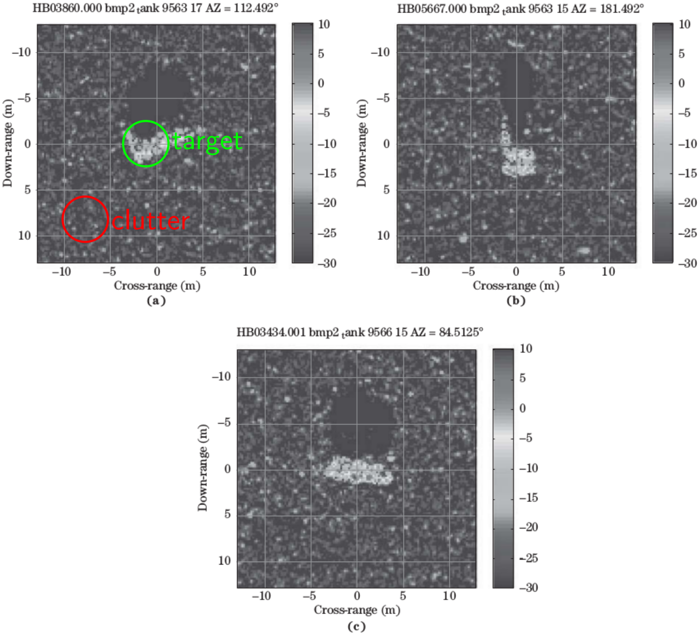
Sea-Clutter on a PPI-Scope. Wind from 310° or 130°.

By observing how the image evolves with time gives further information. Clutter can fluctuate and move.

Radar imaging

FIGURE 5-1 ■ Synthetic aperture radar image of suburban terrain. (From Novak and Owirka [1]. With permission.)





(a)

(b)

(c)

FIGURE 21-32 ■ Three SAR images of an armored vehicle with radar at the bottom of each image and the vehicle (a) at a non-cardinal pose angle, (b) broadside to the radar, and (c) end-on to the radar.

Clutter vs noise

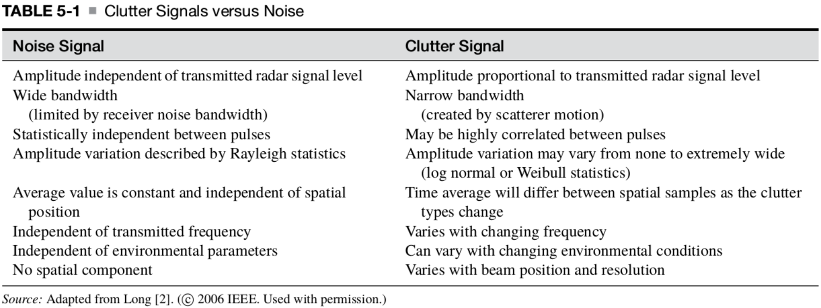


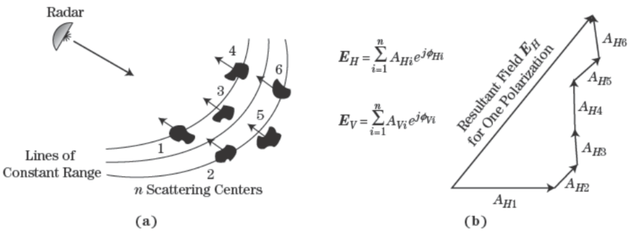
TABLE 5-1 ■ Clutter Signals versus Noise

Noise Signal	Clutter Signal
Amplitude independent of transmitted radar signal level	Amplitude proportional to transmitted radar signal level
Wide bandwidth (limited by receiver noise bandwidth)	Narrow bandwidth (created by scatterer motion)
Statistically independent between pulses	May be highly correlated between pulses
Amplitude variation described by Rayleigh statistics	Amplitude variation may vary from none to extremely wide (log normal or Weibull statistics)
Average value is constant and independent of spatial position	Time average will differ between spatial samples as the clutter types change
Independent of transmitted frequency	Varies with changing frequency
Independent of environmental parameters	Can vary with changing environmental conditions
No spatial component	Varies with beam position and resolution

Source: Adapted from Long [2]. (© 2006 IEEE. Used with permission.)

Scattering coefficients

FIGURE 5-3 ■ Vector summation of scatterers at different positions and ranges. (a) Geometry of multiple scatterers. (b) Vector summation forms resultant E-field amplitude.



The received electric field strength from the i-th scatterer is proportional to (k collects factors common to all scatterers)

$$|E_\mathrm{i}| \sim \left[\frac{P_\mathrm{t} G^2 \lambda^2 \sigma_i}{(4\pi)^3 L_\mathrm{s} R^4}\right]^{1/2} = k\frac{\sqrt{\sigma_i}}{d_i^2}, \quad \arg\{E_i\} = -\left(\theta_i + \frac{4\pi}{\lambda} d_i\right)$$

$$E = \sum_i E_i = \sum_i k\frac{\sqrt{\sigma_i}}{d_i^2} \exp\left[-\mathrm{j}\left(\frac{4\pi}{\lambda} d_i + \theta_i\right)\right] = \frac{k}{d^2}\sqrt{\sigma}\mathrm{e}^{\mathrm{j}\phi}$$

The complex number $\sqrt{\sigma}\mathrm{e}^{\mathrm{j}\phi}$ is the *backscatter coefficient* and d is the nominal distance to the clutter.

Clutter polarization scattering matrix

Taking polarization effects into account, the concept of the backscatter coefficient can be extended to the polarization scattering matrix (PSM).

$$\boxed{\mathbf{S} = \begin{pmatrix} \sqrt{\sigma_{\mathrm{HH}}}\mathrm{e}^{\mathrm{j}\phi_{\mathrm{HH}}} & \sqrt{\sigma_{\mathrm{HV}}}\mathrm{e}^{\mathrm{j}\phi_{\mathrm{HV}}} \\ \sqrt{\sigma_{\mathrm{VH}}}\mathrm{e}^{\mathrm{j}\phi_{\mathrm{VH}}} & \sqrt{\sigma_{\mathrm{VV}}}\mathrm{e}^{\mathrm{j}\phi_{\mathrm{VV}}} \end{pmatrix}}$$

The PSM could also be expressed in circular polarization (right hand CP and left hand CP). Additional information on the scatterer can be obtained by considering, for instance,

- Parallel/cross polarization ratio: $\sqrt{\sigma_{\mathrm{HH}}}/\sqrt{\sigma_{\mathrm{VH}}}$.
- Vertical/horizontal polarization ratio: $\sqrt{\sigma_{\mathrm{VV}}}/\sqrt{\sigma_{\mathrm{HH}}}$.
- Polarimetric phase: $\phi_{\mathrm{HH}} - \phi_{\mathrm{VV}}$.

These measurements require a radar capable of transmitting and receiving individually in all polarizations, which is expensive.

Surface and volume reflectivity

The absolute square of the complex backscatter coefficient $\sqrt{\sigma}\mathrm{e}^{\mathrm{j}\phi}$ is the radar cross section σ of the clutter.

To characterize clutter originating from a surface, use the *surface reflectivity*

$$\boxed{\sigma^0 = \frac{\sigma}{A}} \quad [\sigma^0] = \frac{\mathrm{m}^2}{\mathrm{m}^2} = \text{unitless}$$

where A is the illuminated clutter area.

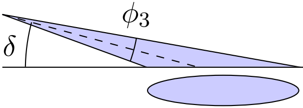
For clutter scatterers in a volume, use the *volume reflectivity*

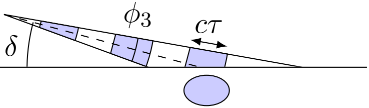
$$\boxed{\eta = \frac{\sigma}{V}} \quad [\eta] = \frac{\mathrm{m}^2}{\mathrm{m}^3} = \mathrm{m}^{-1}$$

where V is the illuminated clutter volume.

Beam limitation vs pulse limitation

Depending on pulse length $c\tau$, the illuminated clutter area is limited by the projected beam or the projected pulse (θ_3 and ϕ_3 are the 3 dB azimuth and elevation beam widths, respectively):

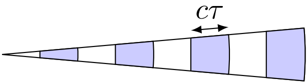




$$A = \frac{\pi R^2 \tan\left(\frac{\theta_3}{2}\right) \tan\left(\frac{\phi_3}{2}\right)}{\sin\delta} \approx \frac{\pi R^2}{4}\,\frac{\theta_3\phi_3}{\sin\delta}$$

$$A = \frac{c\tau R \tan\left(\frac{\theta_3}{2}\right)}{\cos\delta} \approx \frac{c\tau R\theta_3}{2\cos\delta}$$

The illuminated clutter volume is restricted by the pulse length



$$V = \frac{\pi R^2 \theta_3 \phi_3}{4}\,\frac{c\tau}{2}$$

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Dependence on grazing angle

The surface reflectivity depends on the grazing angle.

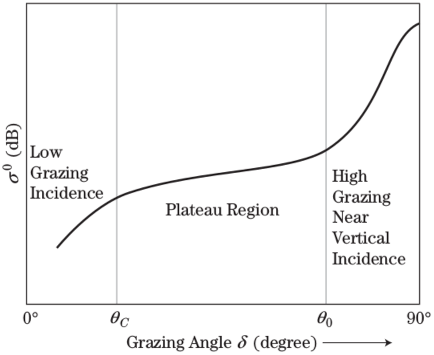


FIGURE 5-4 ■ General dependence of σ^0 on grazing angle. (Adapted from [6]. With permission.)

Based on theory and measured data for land and sea. The behavior at low grazing angles is motivated by the surface becoming smoother (less backscattering). Rayleigh's definition of a smooth surface is

$$\boxed{\sigma_\mathrm{h} \sin\delta < \frac{\lambda}{8}}$$

Random nature of clutter

The clutter response varies with time and space due to motion of the radar or the scatterers, for instance due to wind. A statistical approach is necessary, for instance using the Weibull distribution

$$p_\sigma = \begin{cases} \frac{b\sigma^{b-1}}{\alpha} \exp\left(-\frac{\sigma^b}{\alpha}\right) & \sigma \geq 0 \\ 0 & \sigma < 0 \end{cases}$$

where $\alpha = \sigma_\mathrm{m}^b / \ln 2$ and σ_m is the median of the distribution.

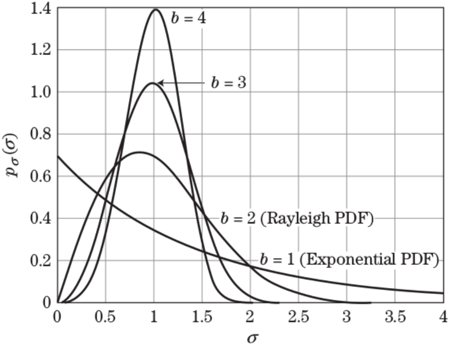


FIGURE 5-7 ■ Weibull distributions for $\sigma_m = 1$ and several values of b.

Spatial statistics for ground clutter

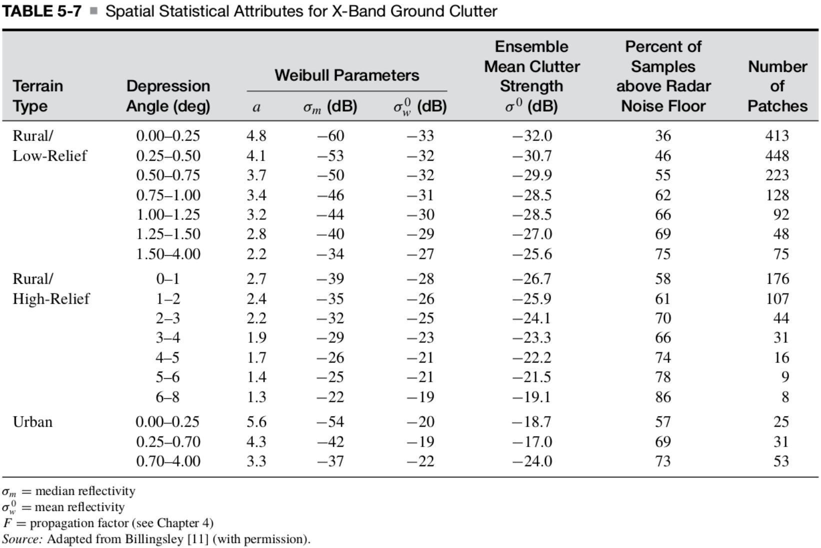


TABLE 5-7 ■ Spatial Statistical Attributes for X-Band Ground Clutter

Terrain Type	Depression Angle (deg)	Weibull Parameters			Ensemble Mean Clutter Strength σ^0 (dB)	Percent of Samples above Radar Noise Floor	Number of Patches
		a	σ_m (dB)	σ_w^0 (dB)			
Rural/ Low-Relief	0.00–0.25	4.8	−60	−33	−32.0	36	413
	0.25–0.50	4.1	−53	−32	−30.7	46	448
	0.50–0.75	3.7	−50	−32	−29.9	55	223
	0.75–1.00	3.4	−46	−31	−28.5	62	128
	1.00–1.25	3.2	−44	−30	−28.5	66	92
	1.25–1.50	2.8	−40	−29	−27.0	69	48
	1.50–4.00	2.2	−34	−27	−25.6	75	75
Rural/ High-Relief	0–1	2.7	−39	−28	−26.7	58	176
	1–2	2.4	−35	−26	−25.9	61	107
	2–3	2.2	−32	−25	−24.1	70	44
	3–4	1.9	−29	−23	−23.3	66	31
	4–5	1.7	−26	−21	−22.2	74	16
	5–6	1.4	−25	−21	−21.5	78	9
	6–8	1.3	−22	−19	−19.1	86	8
Urban	0.00–0.25	5.6	−54	−20	−18.7	57	25
	0.25–0.70	4.3	−42	−19	−17.0	69	31
	0.70–4.00	3.3	−37	−22	−24.0	73	53

σ_m = median reflectivity
σ_w^0 = mean reflectivity
F = propagation factor (see Chapter 4)
Source: Adapted from Billingsley [11] (with permission).

Land reflectivity: grass and crops

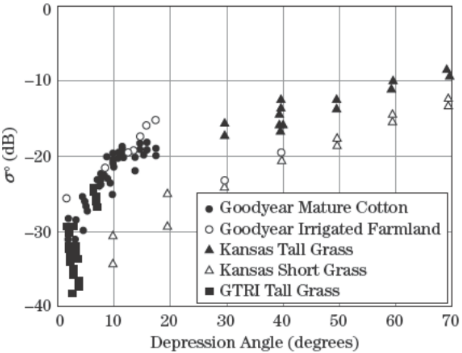
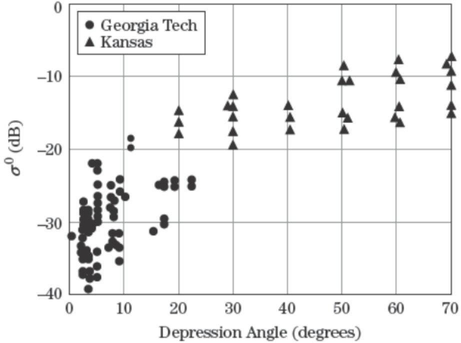


FIGURE 5-9 ■ σ^0 data for grass and crops from several sources at X-band. (Data from [16–18]. With permission.)

Follows the general trend shown before. Depression angle is an angle relative to the radar system, same as grazing angle for level surface. This is easier to control in an experiment.

Land reflectivity: trees

FIGURE 5-10 ■ σ^0 data for trees from two sources for X-band. (Data from [16,18]. With permission.)



Land reflectivity: frequency

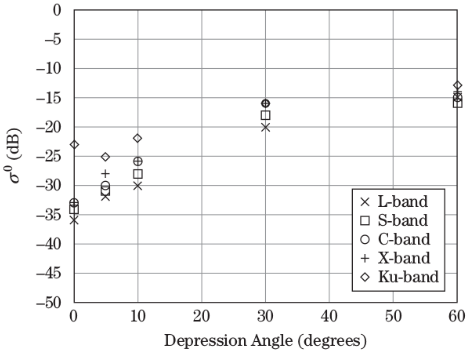


FIGURE 5-12 ■ Averaged reflectivity data for rural farmland as a function of frequency. (Adapted from Nathanson [15]. With permission.)

Higher frequency implies higher reflectivity.

Sea reflectivity: affecting factors

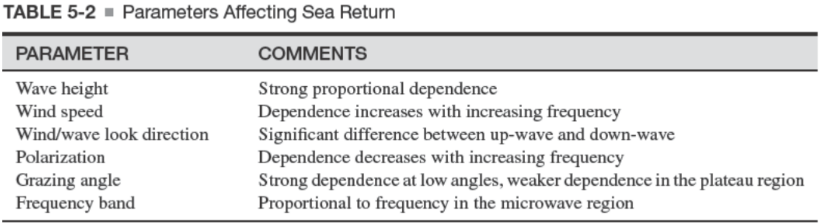


TABLE 5-2 ■ Parameters Affecting Sea Return

PARAMETER	COMMENTS
Wave height	Strong proportional dependence
Wind speed	Dependence increases with increasing frequency
Wind/wave look direction	Significant difference between up-wave and down-wave
Polarization	Dependence decreases with increasing frequency
Grazing angle	Strong dependence at low angles, weaker dependence in the plateau region
Frequency band	Proportional to frequency in the microwave region

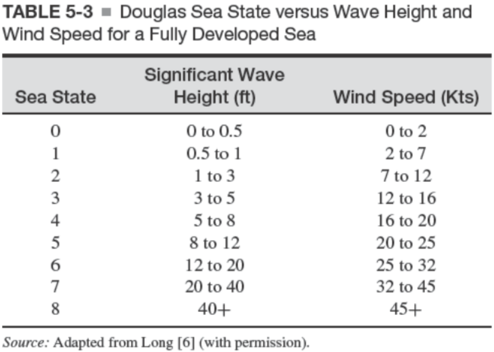


TABLE 5-3 ■ Douglas Sea State versus Wave Height and Wind Speed for a Fully Developed Sea

Sea State	Significant Wave Height (ft)	Wind Speed (Kts)
0	0 to 0.5	0 to 2
1	0.5 to 1	2 to 7
2	1 to 3	7 to 12
3	3 to 5	12 to 16
4	5 to 8	16 to 20
5	8 to 12	20 to 25
6	12 to 20	25 to 32
7	20 to 40	32 to 45
8	40+	45+

Source: Adapted from Long [6] (with permission).

Sea reflectivity: measurements

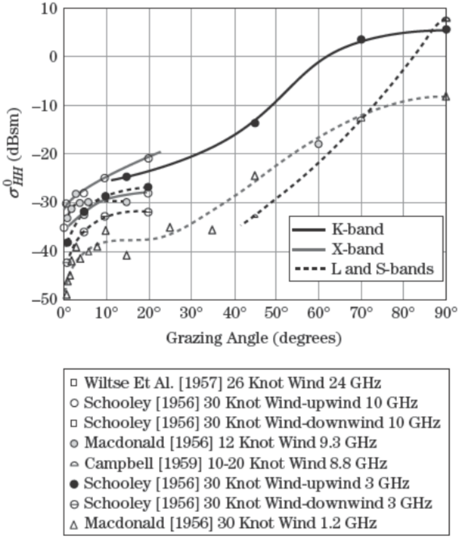


FIGURE 5-17 ■ Sea return as a function of grazing angle for four radar bands. (From Long [6]. With permission.)

Sea reflectivity: range dependence

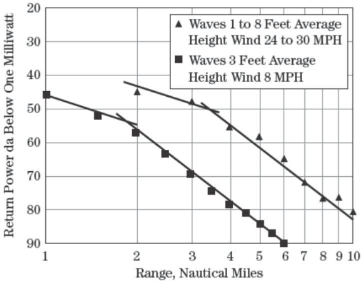


FIGURE 5-21 ■ Range dependence of sea return for two wave conditions, X-band, HH polarization. (From Dyer and Currie [19]. With permission.)

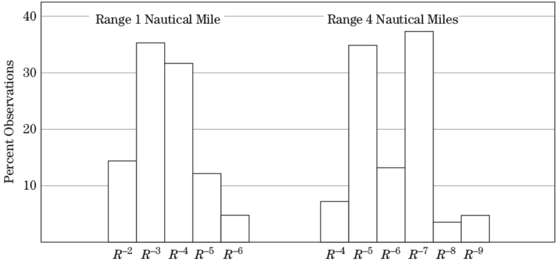


FIGURE 5-23 ■ Measured range dependencies above and below the critical grazing angle as a percentage of total measurements. (From Dyer and Currie [19]. With permission.)

Theoretically, sea clutter should decrease as R^{-3}, but may decrease faster.

Clutter suppression, decorrelation time

- The clutter decorrelation time τ_0, is the time over which the clutter response is coherent (stable phase and amplitude). This is frequency dependent.
- If the target signal is stable over longer time than τ_0, the signal-to-clutter ratio can be improved by averaging.
- If $\mathrm{PRI} > \tau_0$, each clutter sample is uncorrelated.

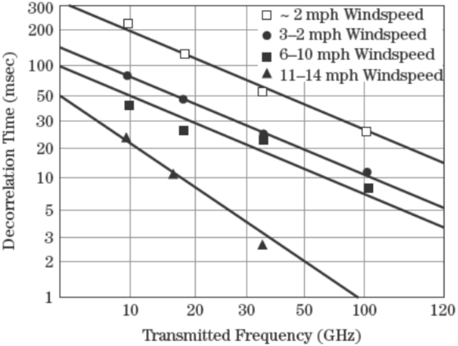
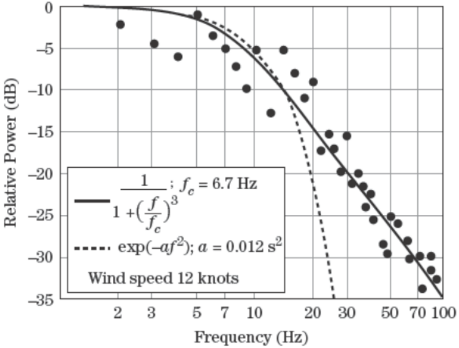


FIGURE 5-27 ■ Decorrelation time for windblown trees as a function of wind speed. (From Currie et al. [21]. With permission.)

Clutter frequency spectra

FIGURE 5-28 ■ Spectral data from trees at X-band with Gaussian and power function curve fits. (From Fishbein et al. [22]. With permission.)



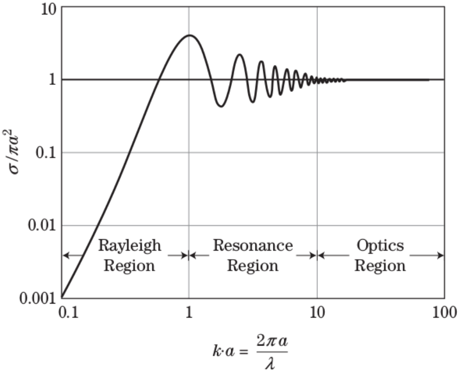
Theory predicts Gaussian-shaped spectra, but actual measurements often result in a slower roll-off with frequency. This may be due to imperfections in the systems, since a very well-controlled experiment (Billingsley, ref [11]) was well modeled by a Gaussian distribution.

Outline

Atmospheric clutter

Most volumetric (atmospheric) clutter is due to rain or other precipitation. It depends on rain rate, and the drop-size (typically 0.5–4 mm) in relation to the wavelength λ.

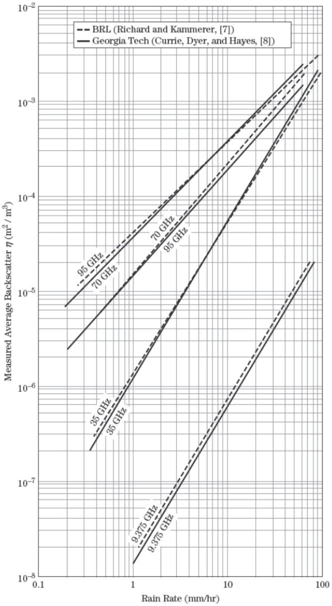
FIGURE 5-5 ■ Dependence of the RCS of a sphere on wavelength.



Strongest response around $ka \approx 1$, radius $a \approx \lambda/(2\pi)$, or a diameter around $\lambda/10$.

Rain data

FIGURE 5-33 ■ Least squares fit to rain data at four frequency bands. (From Currie [32]. With permission.)



Snow data

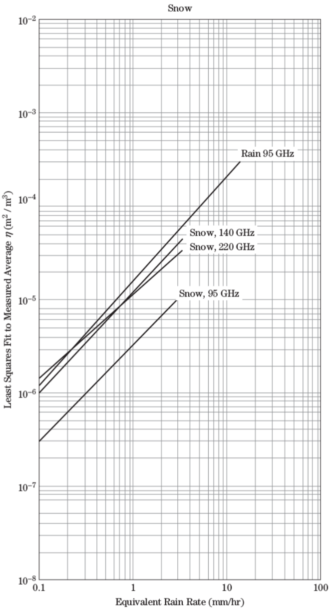
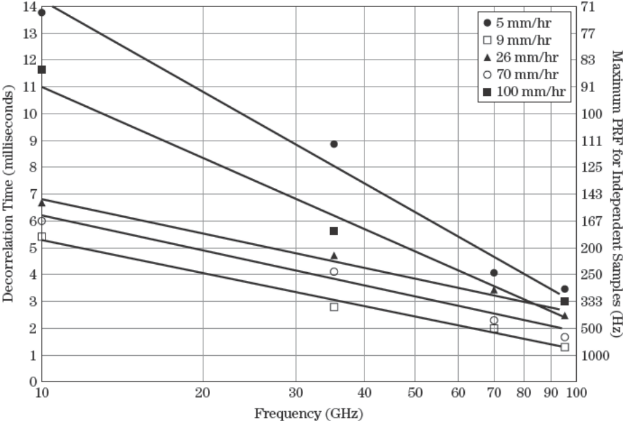


FIGURE 5-34 ■ Least squares fit to snow data at two frequency bands compared with rain data. (From Currie et al. [34]. With permission.)

Rain decorrelation time

FIGURE 5-35 ■ Decorrelation time for rain backscatter as a function of frequency. (From Currie et al. [8]. With permission.)



Decorrelation time in the order of milliseconds. This corresponds to a limit for maximum PRF in order to have uncorrelated clutter responses in each pulse ($\mathrm{PRF}_{\max} = 1/\tau_0$).

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General remarks

Clutter is notoriously difficult to model, due to the complexity of the real world phenomena it represents. But still, explicit models may provide useful approximations when evaluating the radar scenario.

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GTRI empirical model

The following model was developed in the late 1970's

$$\boxed{\sigma^0 = A(\delta + C)^B \exp\left[\frac{-D}{1 + \frac{0.1\sigma_\mathrm{h}}{\lambda}}\right]}$$

- δ is the grazing angle in radians
- σ_h is the rms surface roughness
- λ is the wavelength
- A, B, C, and D are empirically derived constants

GTRI coefficients

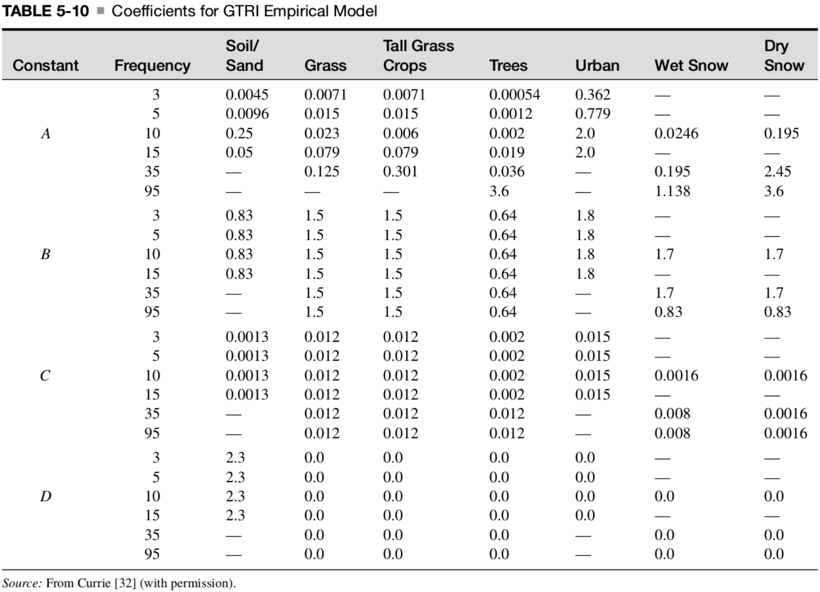


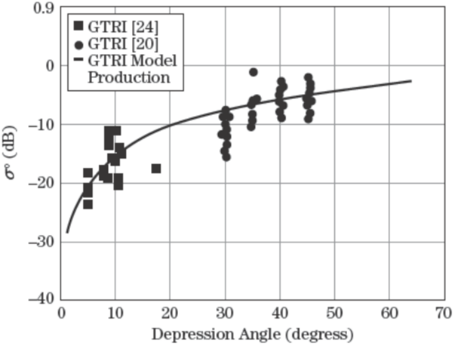
TABLE 5-10 ■ Coefficients for GTRI Empirical Model

Constant	Frequency	Soil/ Sand	Grass	Tall Grass Crops	Trees	Urban	Wet Snow	Dry Snow
A	3	0.0045	0.0071	0.0071	0.00054	0.362	—	—
	5	0.0096	0.015	0.015	0.0012	0.779	—	—
	10	0.25	0.023	0.006	0.002	2.0	0.0246	0.195
	15	0.05	0.079	0.079	0.019	2.0	—	—
	35	—	0.125	0.301	0.036	—	0.195	2.45
	95	—	—	—	3.6	—	1.138	3.6
B	3	0.83	1.5	1.5	0.64	1.8	—	—
	5	0.83	1.5	1.5	0.64	1.8	—	—
	10	0.83	1.5	1.5	0.64	1.8	1.7	1.7
	15	0.83	1.5	1.5	0.64	1.8	—	—
	35	—	1.5	1.5	0.64	—	1.7	1.7
	95	—	1.5	1.5	0.64	—	0.83	0.83
C	3	0.0013	0.012	0.012	0.002	0.015	—	—
	5	0.0013	0.012	0.012	0.002	0.015	—	—
	10	0.0013	0.012	0.012	0.002	0.015	0.0016	0.0016
	15	0.0013	0.012	0.012	0.002	0.015	—	—
	35	—	0.012	0.012	0.012	—	0.008	0.0016
	95	—	0.012	0.012	0.012	—	0.008	0.0016
D	3	2.3	0.0	0.0	0.0	0.0	—	—
	5	2.3	0.0	0.0	0.0	0.0	—	—
	10	2.3	0.0	0.0	0.0	0.0	0.0	0.0
	15	2.3	0.0	0.0	0.0	0.0	—	—
	35	—	0.0	0.0	0.0	—	0.0	0.0
	95	—	0.0	0.0	0.0	—	0.0	0.0

Source: From Currie [32] (with permission).

Comparison of GTRI model with measured data

FIGURE 5-38 ■ Comparison of GTRI model output with data for deciduous trees at X-band. (From Currie [32]. With permission.)



GTRI sea clutter model

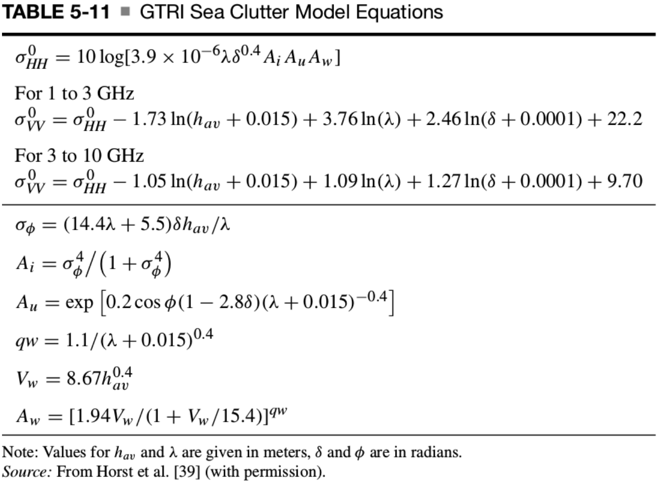


TABLE 5-11 ■ GTRI Sea Clutter Model Equations

$$\sigma^0_{HH} = 10\log[3.9 \times 10^{-6}\lambda\delta^{0.4} A_i A_u A_w]$$

For 1 to 3 GHz

$$\sigma^0_{VV} = \sigma^0_{HH} - 1.73\ln(h_{av} + 0.015) + 3.76\ln(\lambda) + 2.46\ln(\delta + 0.0001) + 22.2$$

For 3 to 10 GHz

$$\sigma^0_{VV} = \sigma^0_{HH} - 1.05\ln(h_{av} + 0.015) + 1.09\ln(\lambda) + 1.27\ln(\delta + 0.0001) + 9.70$$

$$\sigma_\phi = (14.4\lambda + 5.5)\delta h_{av}/\lambda$$

$$A_i = \sigma_\phi^4 / \left(1 + \sigma_\phi^4\right)$$

$$A_u = \exp\left[0.2\cos\phi(1 - 2.8\delta)(\lambda + 0.015)^{-0.4}\right]$$

$$qw = 1.1/(\lambda + 0.015)^{0.4}$$

$$V_w = 8.67 h_{av}^{0.4}$$

$$A_w = [1.94 V_w/(1 + V_w/15.4)]^{qw}$$

Note: Values for h_{av} and λ are given in meters, δ and ϕ are in radians.
Source: From Horst et al. [39] (with permission).

Outline

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    - Surface clutter
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Rain clutter

The model parameters A and B below can be fitted to the rain data in Figure 5-33:

$$\eta = AR^B \, [\mathrm{m}^{-1}]$$

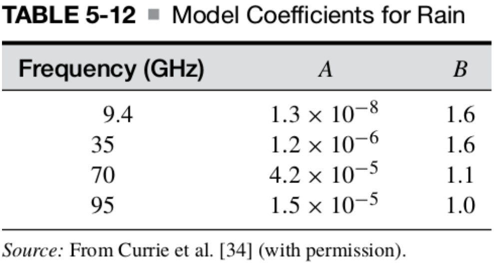

TABLE 5-12 ■ Model Coefficients for Rain

Frequency (GHz)	A	B
9.4	1.3×10^{-8}	1.6
35	1.2×10^{-6}	1.6
70	4.2×10^{-5}	1.1
95	1.5×10^{-5}	1.0

Source: From Currie et al. [34] (with permission).

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Land reflectivity

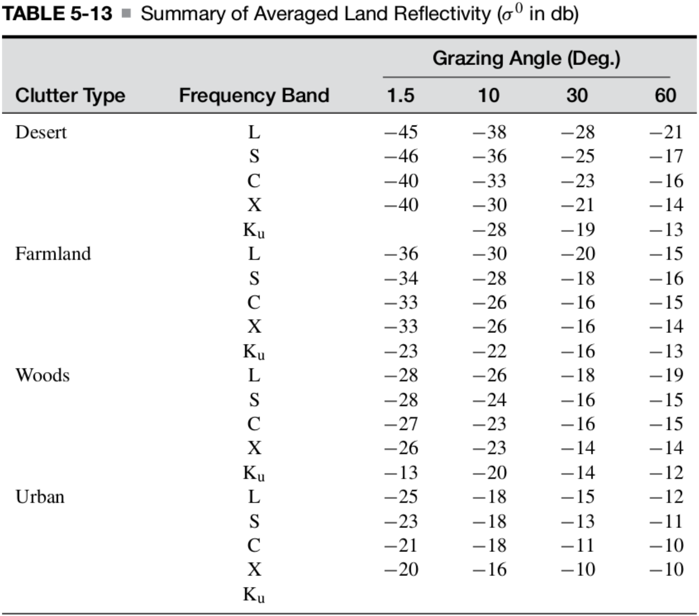
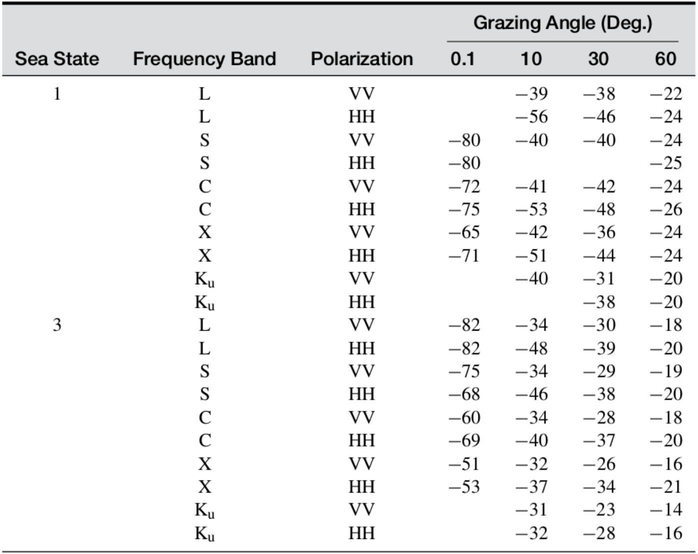


TABLE 5-13 ■ Summary of Averaged Land Reflectivity (σ^0 in db)

		Grazing Angle (Deg.)			
Clutter Type	**Frequency Band**	**1.5**	**10**	**30**	**60**
Desert	L	−45	−38	−28	−21
	S	−46	−36	−25	−17
	C	−40	−33	−23	−16
	X	−40	−30	−21	−14
	K_u		−28	−19	−13
Farmland	L	−36	−30	−20	−15
	S	−34	−28	−18	−16
	C	−33	−26	−16	−15
	X	−33	−26	−16	−14
	K_u	−23	−22	−16	−13
Woods	L	−28	−26	−18	−19
	S	−28	−24	−16	−15
	C	−27	−23	−16	−15
	X	−26	−23	−14	−14
	K_u	−13	−20	−14	−12
Urban	L	−25	−18	−15	−12
	S	−23	−18	−13	−11
	C	−21	−18	−11	−10
	X	−20	−16	−10	−10
	K_u				

Sea reflectivity

TABLE 5-14 ■ Summary of Averaged Sea Reflectivity (σ^0 in db)



			Grazing Angle (Deg.)			
Sea State	**Frequency Band**	**Polarization**	**0.1**	**10**	**30**	**60**
1	L	VV		−39	−38	−22
	L	HH		−56	−46	−24
	S	VV	−80	−40	−40	−24
	S	HH	−80			−25
	C	VV	−72	−41	−42	−24
	C	HH	−75	−53	−48	−26
	X	VV	−65	−42	−36	−24
	X	HH	−71	−51	−44	−24
	K_u	VV		−40	−31	−20
	K_u	HH			−38	−20
3	L	VV	−82	−34	−30	−18
	L	HH	−82	−48	−39	−20
	S	VV	−75	−34	−29	−19
	S	HH	−68	−46	−38	−20
	C	VV	−60	−34	−28	−18
	C	HH	−69	−40	−37	−20
	X	VV	−51	−32	−26	−16
	X	HH	−53	−37	−34	−21
	K_u	VV		−31	−23	−14
	K_u	HH		−32	−28	−16

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Conclusions

- Characterization of clutter: backscatter coefficient, surface reflectivity σ^0, volume reflectivity η.
- Illuminated area/volume determines the clutter RCS.
- Clutter decorrelation time needs to be considered for clutter suppression.
- Some empirical models exist for estimating the reflectivity for different contexts.

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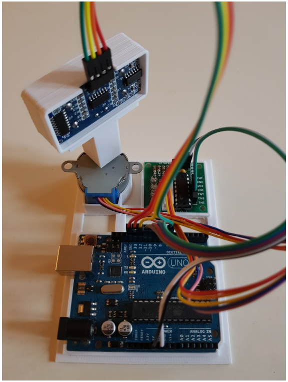
About the lab

- The lab will take place in the same room as the exercises. **Note the time: 8–12!**
- The lab is based around a simple ultrasonic sensor placed on a stepper motor, controlled by an Arduino unit.
- **Read the lab instructions carefully before the lab!** They are available on the course web site, under "Lectures".



A practical problem: interference!

Since several units will be operating at the same time, they may interfere with each other, meaning one unit may receive both its own echo (intended) and the direct signal of another unit (not intended).

- We will use (at least) two rooms: 4118 and 4115, in order to reduce problems.
- In each room, make sure to spread out, and try not to point your radar in the direction of others (remember signals will also reflect in walls, but the range is only a couple of meters).

The lab is done in pairs of two, meaning we will have 10 groups. Ask your lab leader Sebastian if you get strange results, or if there are any other questions.

Before you leave the lab, demonstrate your findings to the lab leader in order to be approved on the lab!