Radar Scattering Statistics for Digital Terrain Models

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Abstract

The statistical results for a digital terrain model are presented that closely match measurements for 77% of the 189 possible combinations of 7 radar bands, 3 polarizations, and 9 terrain types. The model produces realistic backscatter coefficient values for the scenarios over all incidence angles from normal to grazing. The generator was created using measured data sets reported in the Handbook of Radar Scattering Statistics for Terrain [5] covering L, C, S, X, Ka, Ku, and W frequency bands; HH, HV, and VV polarizations; and soil and rock, shrub, tree, short vegetation, grass, dry snow, wet snow, road surface, and urban area terrain types. The first two statistical moments match published values precisely, and a Chi-Square histogram test failed to reject the generator at a 95% confidence level for the 146 terrain models implemented. A Sea State model provides the grazing angle extension for predictions beyond the available measurements. This work contains a comprehensive set of plots of mean and standard deviation versus incidence angle.

1. Background

Radar Scattering Statistics for Digital Terrain Models which are comprised of backscatter coefficients where (σ^o) coefficient commonly to used measure radar reflectivity per unit area was formulated by Goldstein as $\sigma^o = \sigma/A$; where σ is the RCS of the illuminated area, and A is the illuminated surface area patch normalized [1]. The concept of backscatter in radar has common analogies in the visible light spectrum of everyday surfaces. The roughness of a road surface before and after rain settles, or a flat mirror which has little backscatter if the incident angle is great enough are frequent examples. As published by Ulaby and Dobson, the measured backscatter data set used for this research effort does not represent actual backscatter numbers, rather, the statistical properties of the backscatter numbers and their frequency of occurrence in histogram form [5]. This data reflects the reality in which backscattered energy from any patch of terrain is determined by the actual properties of the terrain. The process is so complicated it may be viewed as probabilistic [2]. This being considered, a probabilistic method was chosen over a deterministic approach when an input dataset was available. The generator utilized for this implementation was first proposed by Kelce Wilson for the X-Band and VV (Vertical-Vertical) polarization for the nine terrain types mentioned above [2]. Subsequently, Ricardo Mediavilla was able to expand this research to include the HH (Horizontal-Horizontal) and HV (Horizontal-Vertical) polarizations, and the remaining six radar bands listed [3]. In an adjacent effort, William O'Conner was able to use the characteristics of a modified deterministic Sea State model to extend the near horizon incident angle past 75° approaching 90°, which was done due to the scarcity of measured data in this range [4]. The attributes of the probabilistic coefficients needed to behave in two important ways: (1) the mean and standard deviation of the generated σ^o distributions approach those of the measured data, and (2) the frequency of occurrence histograms (or discrete distributions) must also be similar to the measured data[6]. This generating function was designed such that, by the nature of its construction, it returns coefficient values similar to those observed from measured terrain scattering data [2].

Targets and Backgrounds XI: Characterization and Representation, edited by Wendell R. Watkins,
Dieter Clement, William R. Reynolds, Proceedings of SPIE Vol. 5811
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.607734

2. Overview of the proposed method

These statistics are generated through the measurement conditions of the following inputs; terrain type, band, polarization, angle, sequence, and length of sequence. The input dataset consists of terrain measurements from the University of Michigan RADLAB [5] and the Army Research Laboratory [7]. This data set is comprised of the following nine terrain types; soil and rocks, trees, grasses, shrubs, short vegetation, roads, urban areas, dry snow, and wet snow. The frequency input consists of the following radar bands; L, C, S, X, Ka, Ku, and W. The wave polarizations include HH, HV, and VV for all nine terrain categories. The incident angle is measured in degrees relative to nadir. The sequence is a uniformly distributed random variable between 0 and 1, notated by U(0,1). The length of the sequence N is used for the construction series shown below, where N converges for $N \approx 100{,}000$.

$$Construction\_Series = \left\{ \frac{1}{N}, \frac{2}{N}, \ldots, \frac{N-1}{N} \right\} \qquad (1)$$

The backscatter generating function is essentially a Weibull distribution with the three input parameters α, β, and γ as shown below in equation (2).

$$\sigma = \beta \cdot (-\ln(U)^{\alpha}) + \gamma \qquad (2)$$

Here β is an amplitude term, α is a skew-ness parameter, and γ is a distribution adjustment parameter. These values form a set of combinations that yield the required mean σ^o and standard deviation values $s(\theta)$. This process forms an array or a surface of values for these combinations. In most cases γ is constant and the form of a typical set of values is shown below as an example [4].

$$\alpha = 0.06, 0.61, 0.62, \ldots, 2.0 \qquad (3)$$

$$\beta = 0.01, 0.011, 0.012, 0.013, \ldots, 14.0 \qquad (4)$$

$$\gamma = 0.01 \qquad (5)$$

Once this surface is formed, a search space in which the minimum weighted error is found between the desired and calculated data sets for both the mean and standard deviation. Once these values of α, β, and γ are found, they are then stored in memory. These parameters are then used with the random variable U(0,1) to yield the output coefficients. The construction series is used such that the random variable algorithm will produce a truly uniform distribution, and that the random variable will contain enough elements to ensure a reliable and stable set of α, β, and γ. The output is a transformed random variable now containing the simulated coefficients, assuming phase is uniformly distributed.

In conditions of high angles of incidence ($75^o \leq \theta \leq 90^o$) for which there are limited available measurements, the GIT (Georgia Tech Research Institute) sea clutter model was integrated into the generator created by Kelce Wilson, and Ricardo Mediavilla above. The sea state model can vary in terms of roughness depending on the descriptors used from smooth to very high. This adaptation of the sea state approach is based on the theory that for σ^o, similar surface roughness of two different terrain types results in similar σ^o shapes [4]. This can be tested by calculating the σ^o of a generated surface which is constant between the sea state model and another terrain type, and varying the electrical constants of the surface facets. The GIT model variables and equations utilized are shown below [8].

λ = radar wavelength
θ = grazing angles
ϕ = angle between antenna boresight and wind direction
h_{av} = average wave height

A_i = interference factor
A_u = upwind-downwind factor
A_w = wind speed factor
V_w = Velocity of the wind
qw = Power factor
σ_ϕ^o = calculated backscatter

$$\sigma_{HH}^o = 10\log[3.9\times10^{-6}\lambda\theta^{0.4}A_iA_uA_w] \tag{6}$$

For 1 to 3 GHz

$$\sigma_{VV}^o = \sigma_{HH}^o - 1.73\ln(h_{av} + 0.015) + 3.76\ln(\lambda) + 2.46\ln(\theta + 0.0001) + 222 \tag{7}$$

For 3 to 10 GHz

$$\sigma_{VV}^o = \sigma_{HH}^o - 1.05\ln(h_{av} + 0.015) + 1.09\ln(\lambda) + 1.27\ln(\theta + 0.0001) + 9.70 \tag{8}$$

$$\sigma_\phi = (14.4\lambda + 5.5)\theta h_{av} / \lambda \tag{9}$$

$$A_i = \sigma_\phi^4 / (1 + \sigma_\phi^4) \tag{10}$$

$$A_u = \exp\{0.2\cos\phi(1 - 2.8\theta)(\lambda + 0.015)^{-0.4} \tag{11}$$

$$qw = 1.1(\lambda + 0.015)^{0.4} \tag{12}$$

$$V_w = 8.67h_{av}^{0.4} \tag{13}$$

$$A_w = [1.94V_w / (1 + V_w / 15.4]^{qw} \tag{14}$$

The sea state model height is determined by matching the sea-state descriptors as in Skolnik [9, p.136], and can be seen in the table 1 below. For this application of the sea state model the values of the sea state may need to be non-integer values.

Table 1. Sea State for wind speed and wave height

Sea State	Wind Speed (m/s)	Wave Height (m)
1. smooth	<3.5	<0.3
2. slight	3.5-6.2	0.3-0.9
3. moderate	6.2-8.2	0.9-1.5
4. rough	8.2-9.8	1.5-2.4
5. very rough	9.8-11.8	2.4-3.7
6. high	11.8-15.4	3.7-6
7 very high	15.4-23.2	6-12.2

The basis for making the decision as to which sea state to assign is fairly straight forward. It consisted of comparing the number of facets available, and the average slope of the facets (Fresnel Coefficients). In the limited cases where data is available in the W-band, VV polarization (grasses, coniferous trees, deciduous trees, and short vegetation) the sea state is experimentally determined. It consists of matching the roughness of the terrain type with the roughness of the equivalent sea state model. Surfaces for which data isn't available such as snow are given smaller sea states, and surfaces such as trees are given larger sea states.

3. Results

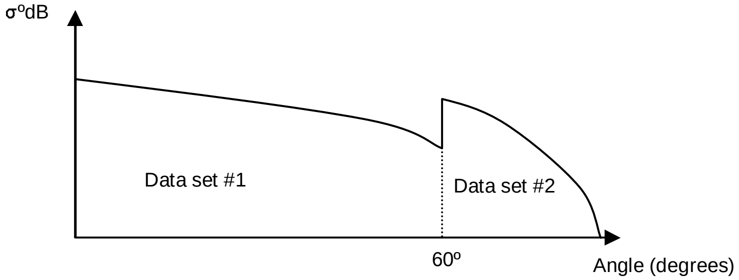
The results of the backscatter coefficient generator are shown in **Figures 1**thru **5** in the pages which follow. Using cubic-splines to fit the data points to a one degree angular resolution, this forms a comprehensive set of plots of the mean and standard deviation versus incidence angle. The horizontal axis represents the degrees off normal (90º = grazing). The vertical axis represents the unit-less σ^o in dB. The titles are labeled as terrain type (legend shown below), radar band, and polarization respectively. The solid line represents the mean values, and dotted lines above and below are ±1 standard deviations. The missing plots are the cases for which there was non-existing or insufficient data available.

Type legend:	
A	Soil and Rock
B	Trees
C	Grasses
D	Shrubs
E	Short Vegetation (combination of C and D)
F	Road Surfaces
G	Urban
H	Dry Snow
I	Wet Snow

4. Challenges

In order to create a backscatter coefficient generator, many obstacles needed to be overcome. Many of these obstacles are due to the randomness in the data measurement efforts. Terrain features in reality cover a wide variability making it difficult to classify terrain types, and once a terrain type is determined there is no guarantee that the conditions found in nature will remain constant. Calibration issues from using different instruments in unique conditions also present challenges when attempting to compile a more complete and consistent dataset. In a few instances, this difficulty manifested itself as a step change in the output for angles beyond 60º, yet following the same form (see Drawing 1. below).

Drawing 1. Illustration of step change in output due to more than one dataset.



Another obstacle that needed to be overcome was the use of N≈ 100,000. Using such a sequence of such length proved to be a difficulty in terms of the time needed for the construction of the α-β set. Reducing N to 10,000 allowed for the needed accuracy, and produced results in a timely manner.

Figure 1. σ° dB vs angle off normal in degrees (90°=grazing) for terrain types A & B

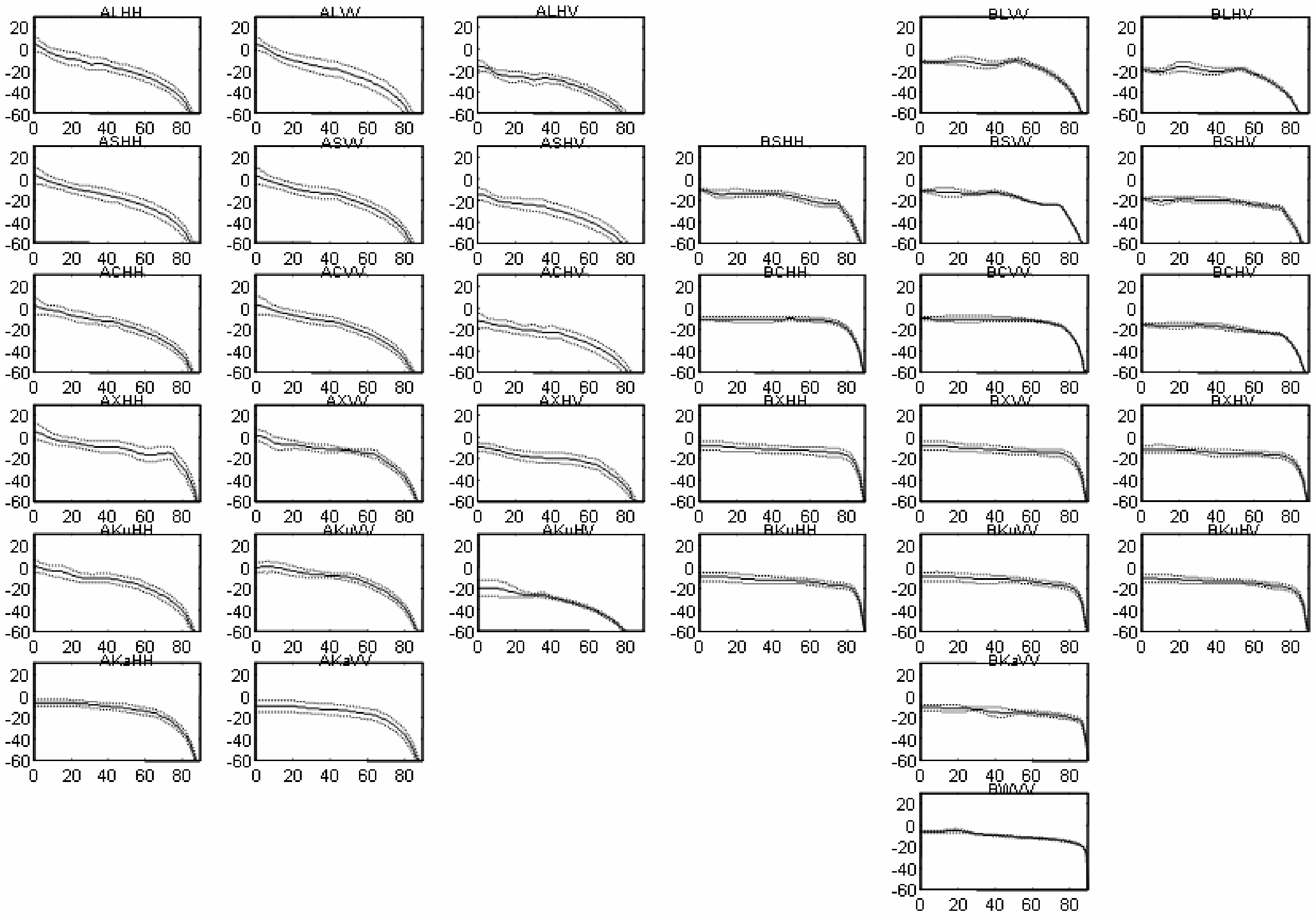


Figure 2. σ^{o} dB vs angle off normal in degrees (90°=grazing) for terrain types C & D

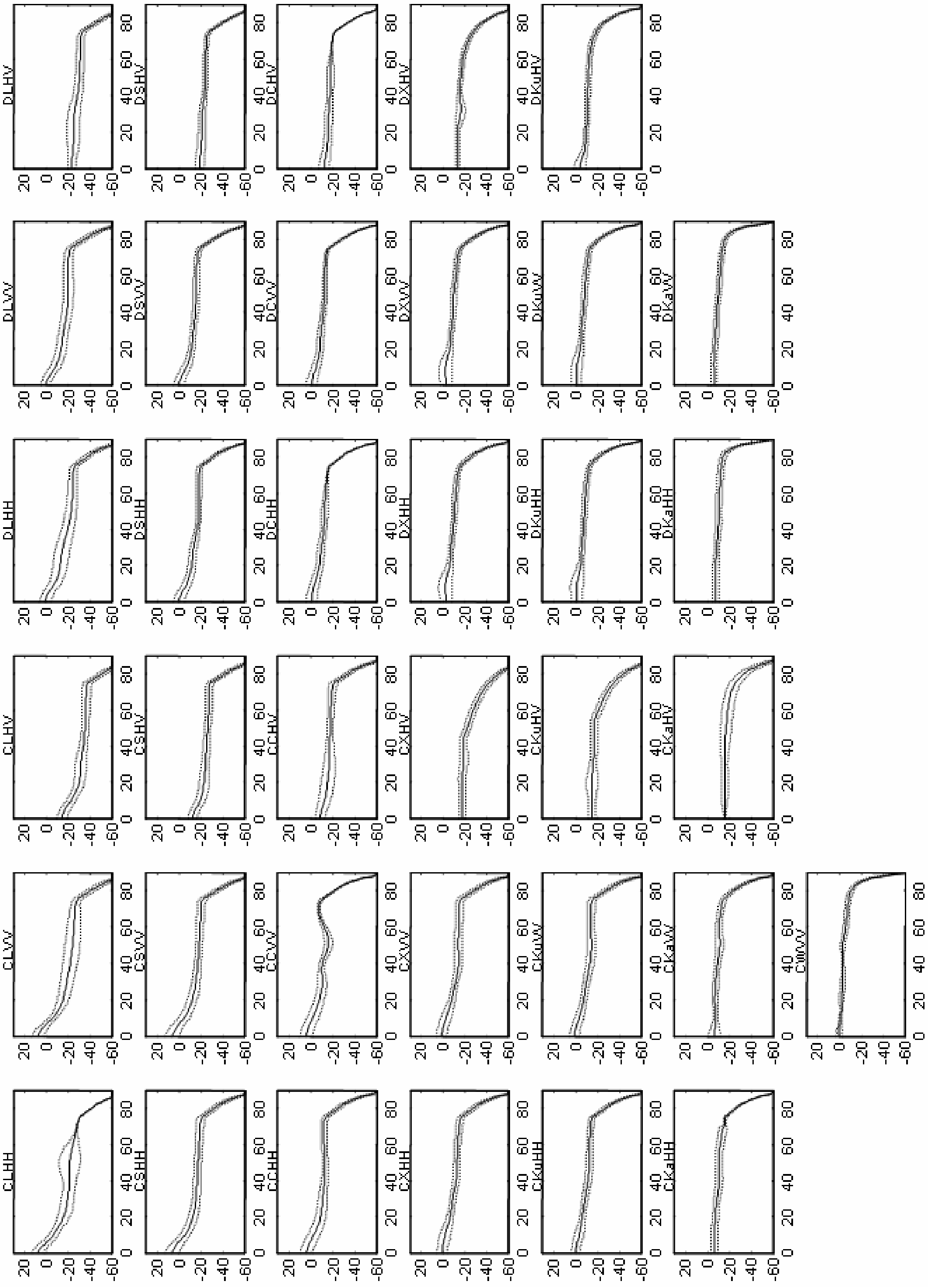
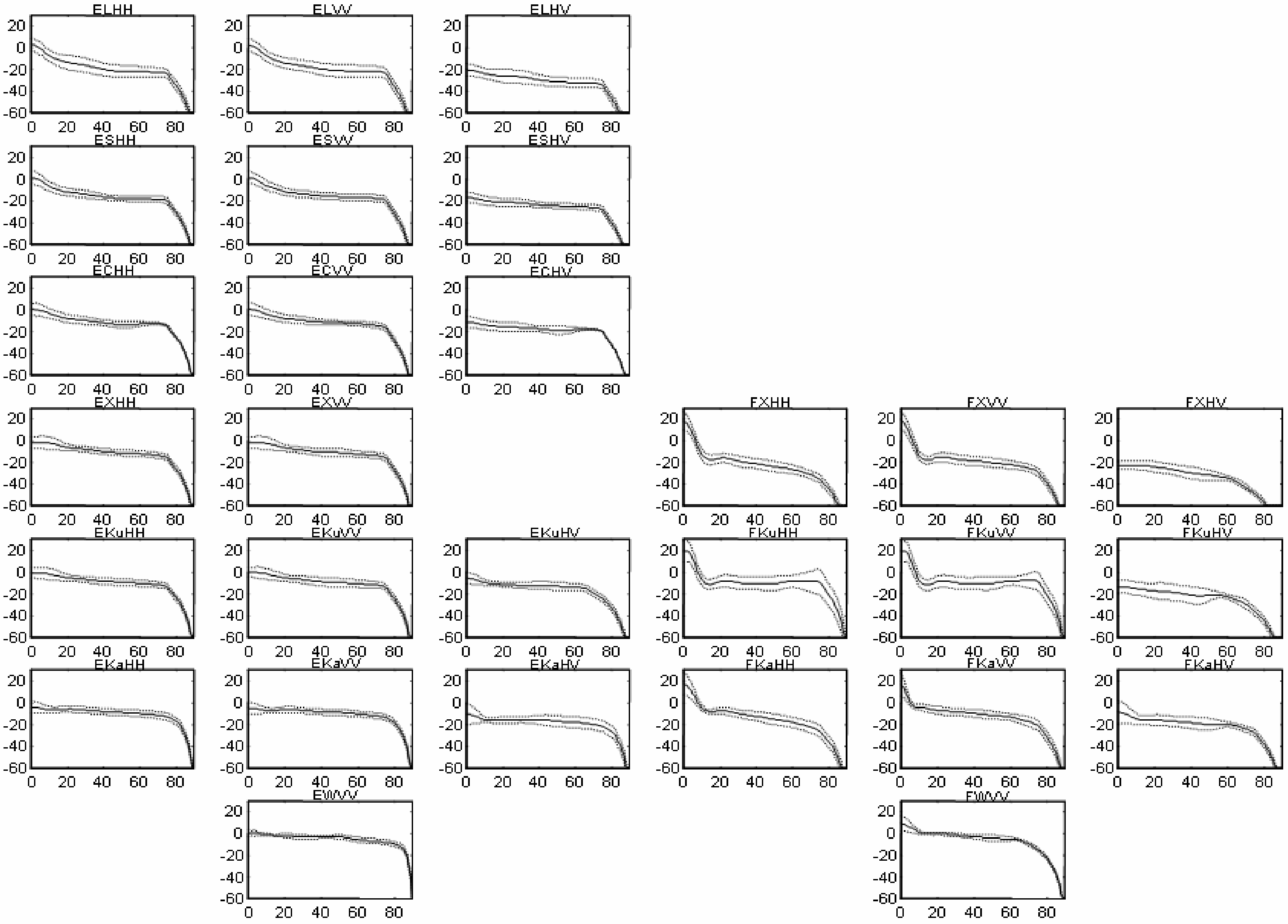


Figure 3. σ^{o} dB vs angle off normal in degrees (90°=grazing) for terrain types E & F



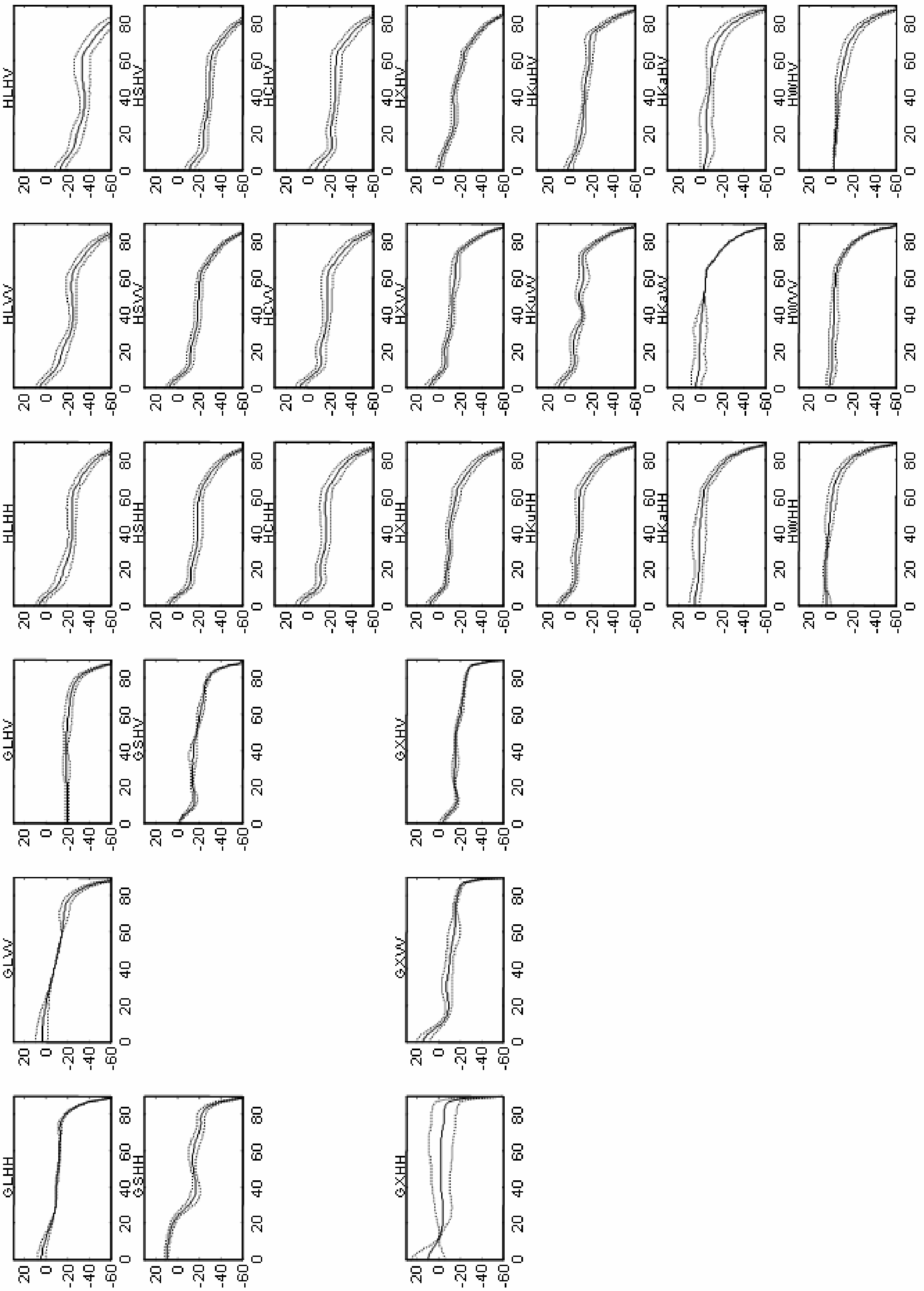
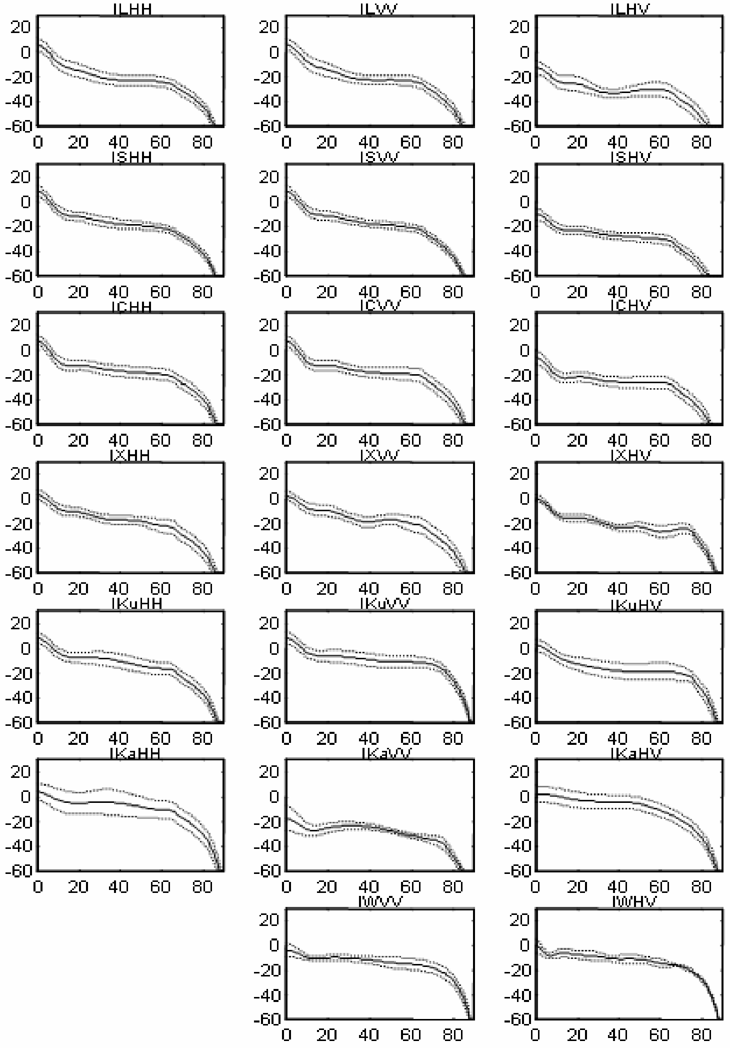


Figure 4. σ° dB vs angle off normal in degrees (90°=grazing) for terrain types G & H

Figure 5. σ^o dB vs angle off normal in degrees (90°=grazing) for terrain type I



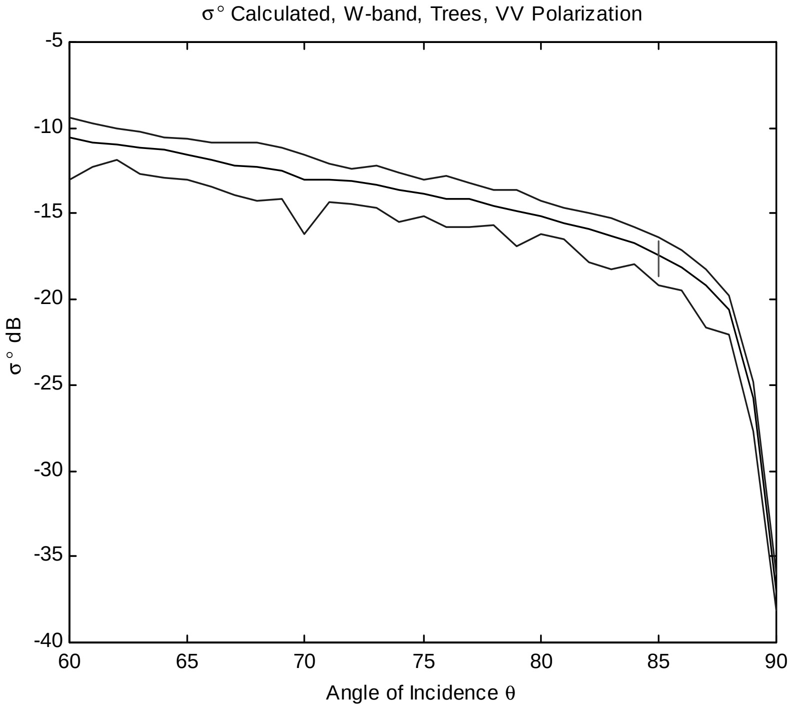
5. Conclusion

The statistical results for a digital terrain model are presented which closely match measurements for 77% of the 189 possible combinations of 7 radar bands, 3 polarizations, and 9 terrain types. Combinations for which the sample size was too limited and produced erroneous results, and obviously combinations for which there was no available data were not included in the final results. The first two statistical moments match published values precisely, and a Chi-Square histogram test failed to reject the generator at a 95% confidence level for the 146 terrain models implemented.

A sea state model provided the grazing angle extension for predictions beyond the available measurements. Since the composition at grazing has little effect on backscatter, the similarity of roughness between various sea states and terrain types was applied. In William O'Conner's master thesis [4] comparison with and without the measured ARL data available in the W-band and four terrain types have shown that the sea state model is consistent with the theory. An example of which can be seen in Figure 6 below, with the single vertical line representing the Army data out to one standard deviation [4]. In the cases for which there is no data available the sea state model is consistent with other published works.

The current result on-going of this research effort is a comprehensive set of plots of mean and standard deviation versus incidence angle.

Figure 6. Comparison of the final Model with ARL data [4,pg 45]



References

[1] Herbert Goldstein, “A Primer of Sea Echo,” Report No. 157, U.S. Naval Electronics Laboratory, San Diego, 1950

[2] K.S. Wilson, “Effects of Clutter Height Distribution on Adaptive Clutter Erasure Performance” PhD. Dissertation, Air Face Institute of Technology, WPAFB, OH, June, 1998

[3] R. Mediavilla, “Terrain Backscattering Coefficient Generator”, Masters Thesis, Air Force Institute of Technology, Dayton, OH March 1999.

[4] W.N. O’Conner, “Low Grazing Angle Terrain Backscattering Coefficients Generator”, Masters Thesis, Air Force Institute of Technology, WPAFB OH, March 1999.

[5] F.T Ulaby and M.C. Dobson, Handbook of Radar Scattering Statistics for Terrain, Artech House 1989.

[6] R. Mediavilla, W.N. O’Conner, Dr. Vittal Pyati, Dr. Kelce Wilson, “Terrain Backscattering Coefficient Generator”, Manuscript, Air Force Institute of Technology, WPAFB, OH 45433

[7] R. Wellman, G. Goldman, J. Silvious, and D. Hutchins, “Analysis of millimeter wave radar low-angle ground-clutter measurements for European-like and desert environments”, Army Research Laboratory, Adelphi, MD, Tech. Rep. ARL-TR-1102, July1996

[8] M.M. Horst, F.B. Dyer, and M. T. Tuley, “Radar Sea Clutter Model,” Proceedings of the IEEE Conference on Antennas and Propagation, November 1978.

[9] Skolnik, Merril I. Radar Handbook, McGraw Hill, 1990