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DESIGN DATA FOR RADARS BASED ON 13.9 GHZ SKYLAB ^{o} MEASUREMENTS

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$$\sigma^\circ = 1.29\, e^{-(\theta/5.8^\circ)} \qquad 0 < \theta < 12^\circ$$
$$= 0.29\, e^{-(\theta/34.6^\circ)} \qquad 12^\circ < \theta < 45^\circ$$

A reasonably good fit at larger angles is obtained using the theoretical expression based on an exponential height correlation function and also using Lambert's law. For angles under 10°, a different fit based on the exponential correlation function, and a fit based on geometric optics expressions are both reasonably valid.

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ABSTRACT

Measurements made at 13.9 GHz with the radar scatterometer on Skylab have been combined to produce median curves of the variation of scattering coefficient with angle of incidence out to 45°. Because of the large number of observations, and the large area averaged for each measured data point, these curves may be used as a new design base for radars. Comparison with models for scattering shows that the best fit to the observations is

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INTRODUCTION

The 13.9 GHz scatterometer on Skylab made thousands of measurements of scattering coefficient at angles of incidence between vertical and about 45°. The measurements made during the summer of 1973 over the United States have been combined to produce a curve of the median scattering coefficient for these angles, as well as a range from the values exceeded 10% of the time to those exceeded 90% of the time. These results provide new data that can be useful in the design of radars, particularly as they relate to design of STC circuits. Use of the decile values must be done with caution, however, for they only apply to those cases for which the resolution cell is large enough to average out the much wider fluctuations expected for smaller areas.

The observations have been compared with several of the theoretical and empirical models used in the past to describe ground backscatter: Lambert's Law, geometric optics, Kirchhoff approximation with exponential form of the autocorrelation of surface heights, and exponential angular variation. None of these fits the data over all ranges of angles, but a dual exponential seems to give the best results and geometrical optics the worst. This is particularly interesting since lunar returns have been shown to follow a law based on the use of the exponential correlation coefficient in the Kirchhoff approximation of physical optics.

THE SKYLAB RADAR SCATTEROMETER EXPERIMENT

Skylab was a manned spacecraft launched in May of 1973 and occupied by three different crews, one in May and June, one in August and September, and one from November into February of 1974. The spacecraft contained a set of earth resources experiments, including a microwave radiometer-scatterometer (Experiment S-193). Characteristics of the RADSCAT instrument have been described in various NASA publications and in some journals, so only the briefest summary will be included.[1]

The Skylab RADSCAT instrument operated at a frequency of 13.9 GHz (wave length 2.16 cm). It used a parabolic antenna with approximately a two degree beam at the half-power point. This beamwidth was effectively 1.54 degrees for the scatterometer where the two-way half-power point is used. The antenna could be mechanically scanned in four different modes:

1. In-Track Non-Contiguous (Overlapping measurements at angles of 0, 15, 29, 40 and 48 degrees between the antenna pointing direction and the vertical at the spacecraft, with 100 kilometers between centers of each set of measurements)
2. Cross-Track Non-Contiguous (Measurements at the same angles of incidence, but perpendicular to the track so they are spaced approximately 100 kilometers rather than overlapping)
3. In-Track Contiguous (Points at the same angles as for 1 and 2 for scatterometer and intermediate angles for radiometer, with the points spaced approximately 25 kilometers)
4. Cross-Track Contiguous (12 points over a 22 degree angular range about the center point; center point may be vertical or tilted ahead or to the side by 15, 30 or 40 degrees)

The radiometer had a precision (1σ) which varied with mode, but was in the neighborhood of $1^{\circ}K$. The scatterometer had a precision which varied with mode, but was usually between 5 and 7 percent (about 0.25 dB). In the non-contiguous modes, the radiometer received both horizontal and vertical polarization, and the scatterometer transmitted horizontal, receiving both horizontal and vertical. In the contiguous modes, when both radiometer and scatterometer were used, the transmission for the scatterometer was with the same polarization as the selected radiometer and scatterometer receiver polarization. It was also possible to operate in a radiometer-only or a scatterometer-only mode, in which case both vertical and horizontal polarizations were used.

In this paper we summarize scattering coefficients measured over land during the two summer occupancies of Skylab; data from the winter occupancy will be reported later, and oceanic results have already been reported.[2] The measurements reported here were made over the United States on numerous passes of the spacecraft. Most of these involved the CTC mode at 0°, 15°, or 29° pointing angles, but many data points were also obtained using the ITC mode. The area covered is shown in Figure 1. Although it is weighted somewhat toward the western part of the U.S., the long ITC pass parallel to the east coast helps to balance this.

One of the passes was over the salt flats near Great Salt Lake, and the near-vertical values were very high for this pass while the off-vertical values are lower.

The same can be said for those passes partly over water. Accordingly, the resulting bimodal distributions were split, and the mode associated with salt flat or water was discarded for the results reported here. Thus, these results are representative of land that does not contain large areas of mirror-flat (at centimeter vertical scale) terrain.

EXPERIMENTAL DATA

Histograms were prepared of the responses at the various angles. These have already been reported orally.[3] An example of the kind of variation that occurs in an angular range having large numbers of samples is shown in Figure 2, where the histogram for the 32-33° incident angle range is shown. The relatively small spread in the measured values is probably largely due to the size of the resolution cells (ellipses about 12 x 14km); each value is thus an average over a quite large area. If smaller resolution cells had been used, one would expect that the range of variation would be much larger. Thus, the spread in the data reported here can only be considered representative for radar systems illuminating large areas in each resolvable element. On the other hand, the average or median values reported here should be representative of similar values regardless of cell size.

Observed scattering coefficient values seem to split naturally into two regions: below 10 or 12°, and above that angle. Consequently, the range of small angles is presented here in more detail. This is also possible because more measurements were made at each angle in this region than were possible at angles far away from the central angles of the scan.

Figure 3 illustrates the variation of mean scattering coefficient with angle in this near-vertical region, along with the upper and lower decile boundaries. The larger variation in return at 1.5° is interesting, for this occurs even after excluding the mode in the distribution associated with specular returns from water and salt flat.

Figure 4 shows the variation over the entire range of angles. Experimental points selected for preparing this figure include only those where there were at least several hundred hundred data points. In the 16-18° range 879 observations are included; in the 18-22° range there are 790. For 31-35° there are 2175 points, and for 43-47° 291. Thus, the median values (and means) for these angles are well established. Decile values, however, contain small enough numbers of points that they may be strongly influenced (except at 31-35°) by site selection.

COMPARISON WITH SCATTERING MODELS

The data presented above can be used for the design of radars as indicative of average returns to be expected over these angles. Models of various kinds have been used in the past for this purpose, so one of the objects of this paper is to compare the values with these models to determine which model or models are most representative of the mean values actually observed.

Past observations have established that radar return can be divided into three general regions: near-vertical, mid-range, and near-grazing.[4] No data are available here for the near-grazing range, but both of the other regions can be readily observed in Figure 4. One of the earliest models used for the mid and near-grazing ranges was the Lambert-Law model proposed during World War II by Clapp.[5] We find here that this model does not do too badly in the mid range, although the average variation is in fact somewhat greater than Lambert's Law would forecast even for this region.

Four models have been selected for comparison here:

A	Lambert's Law
B	Geometric optics (also obtained using Gaussian correlation function in the Kirchhoff-approximation physical-optics theory)
C	Physical optics using an exponential form of the correlation function
D	Exponential variation with angle, an empirical relation.

The variation with angle for Model A is given by:

$$\sigma^{\circ} = \sigma_{M}^{\circ} \cos^{2}\theta \qquad (1)$$

Model B has been considered by some as the only proper use of physical optics,[6] although this has been shown not to be true.[7] In it, a correlation function of surface heights is given by

$$\rho(x) = e^{-x^{2}/x_{0}^{2}} \qquad (2)$$

and the resulting form for the scattering coefficient is

$$\sigma^{\circ} = \sigma_{M}^{\circ} e^{-(\theta/\theta_{0})^{2}} \qquad (3)$$

although some formulations show this as

$$\sigma^{\circ} = \sigma^{\circ}_{M}\, e^{-(\tan\theta/\tan\theta_{o})^{2}} \qquad (3a)$$

This model was first proposed by Davies.[8]

Model C has been widely used by radar astronomers because it seems to fit lunar and planetary data reasonably well.[9] Hayre[10] showed that this also corresponds with the correlation function observed at a scale derivable from contour maps. The correlation function is

$$\rho(x) = e^{-|x|/x_{1}} \qquad (4)$$

and the resulting expression for the scattering coefficient is

$$\sigma^{\circ} = \sigma^{\circ}_{M}\left(\cos^{4}\theta + A\sin^{2}\theta\right)^{-3/2} \qquad (5)$$

Model D has no good theoretical basis, although it too has been used in radar astronomy with some success. Surprisingly, it seems to give the best fit to these observations. This empirical model is

$$\sigma^{\circ} = \sigma^{\circ}_{M}\, e^{-\theta/\theta_{1}} \qquad (6)$$

None of the models can be made to fit the observations over the entire range of angles represented here. Model B, geometrical optics, bears little relation to observations over a wide range of angles, so it is not even shown for the full range. The other three models have been fitted to the data for the larger incident angles in Figure 5.

Model A, Lambert's Law, fits the observations to within 1 dB over the 17-45° range. Since the only parameter available for fitting with this model is the scale factor on amplitude, it was arbitrarily fit at 45°. The result is

$$\sigma^{\circ} = 0.16\cos^{2}\theta \qquad (7)$$

Model C was fit by selecting a value for A forcing a match at 9.5° and at 45°. The resulting equation is

$$\sigma^{\circ} = 0.27\left(\cos^{4}\theta + 4.065\sin^{2}\theta\right)^{-3/2} \qquad (8)$$

This fit is within 1 dB over the range from 7.5° to 45°, but seems to be trending downward at 45° more rapidly than the data.

Model D, the exponential, is quite arbitrary, yet fitting it at 17° and 45° results in a perfect match at 33°! The resulting equation with scale factor included is

$$\sigma^{\circ} = 0.29\, e^{-\theta/34.6^{\circ}} \qquad (9)$$

This fit is within 1 dB to 9°. If it had been fit at 9° as was Model C, it would have been within 1 dB in to about 5°, but the perfect fit at 33° and 17° would have been lost, and the variation beyond 45° would have been greater than the trend of the data seems to indicate. Thus, the exponential fits best with the data, but Model C does quite well over almost the same range of angles; if it had been fit at 17° instead of 9°, it would have been better at 33°, but would have deviated further at 9° than Model D.

In the near-vertical range, Model A, Lambert's Law, is not applicable, but all of the other models fit reasonably well, as shown in Figure 6. Here again, however, the empirical Model D gives the best fit. Equations describing the constants for the various models in this region are

$$\sigma^{\circ} = 1.05\, e^{-(\theta/7.5^{\circ})^2} \qquad (10)$$

$$\sigma^{\circ} = 1.07\left(\cos^4\theta + 60\sin^2\theta\right)^{-3/2} \qquad (11)$$

$$\sigma^{\circ} = 1.29\, e^{-\theta/5.8^{\circ}} \qquad (12)$$

Comparing the fits in the two retions, we see that the best fit to the observed median (mean in the smaller angles) scattering coefficient is given by

$$\sigma^{\circ} = 1.29\, e^{-\theta/5.8^{\circ}} \qquad 0 < \theta < 12^{\circ}$$
$$= 0.29\, e^{-\theta/34.6^{\circ}} \qquad 12^{\circ} < \theta < 45^{\circ}$$

Thus, we believe that this model can be used effectively in the design of radars operating over the range from 1.5° to 45° incidence-angle.

Since minimum scattering coefficients are important in design of radars, it is tempting to include the 1% level data in this paper. They have been excluded, however, because the number of samples is not high enough to place much confidence in these values.

CONCLUSIONS

The Skylab 13.9 GHz backscatter measurements reported here provide useful design values for the mean value of scattering coefficient to be expected in radar design. Thus, they may be useful in establishing required antenna patterns and STC functions for radars operating out to 45° incidence, and results can probably be safely extrapolated at least another 10°. The surprisingly small range between upper and lower deciles is likely to be representative of systems having large illuminated areas within each resolution cell (e.g., a spacecraft synthetic-aperture imager before compression), but cannot be used to determine the ranges to be expected for smaller resolution cells.

ACKNOWLEDGEMENT

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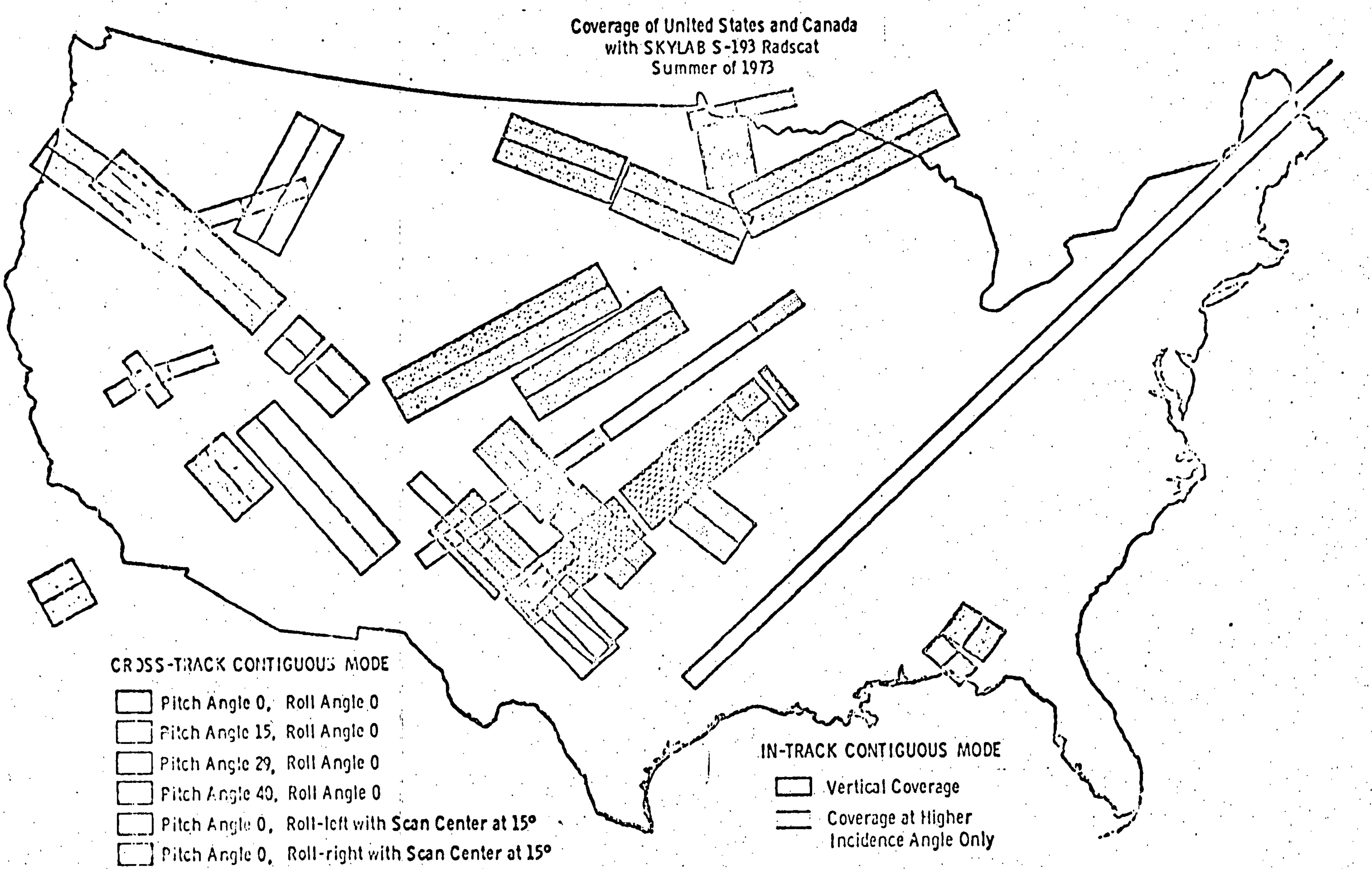
Coverage of United States and Canada
with SKYLAB S-193 Radscat
Summer of 1973
CROSS-TRACK CONTIGUOUS MODE
Pitch Angle 0, Roll Angle 0
Pitch Angle 15, Roll Angle 0
Pitch Angle 29, Roll Angle 0
Pitch Angle 40, Roll Angle 0
Pitch Angle 0, Roll-left with Scan Center at 15°
Pitch Angle 0, Roll-right with Scan Center at 15°
IN-TRACK CONTIGUOUS MODE
Vertical Coverage
Coverage at Higher Incidence Angle Only

Figure 1

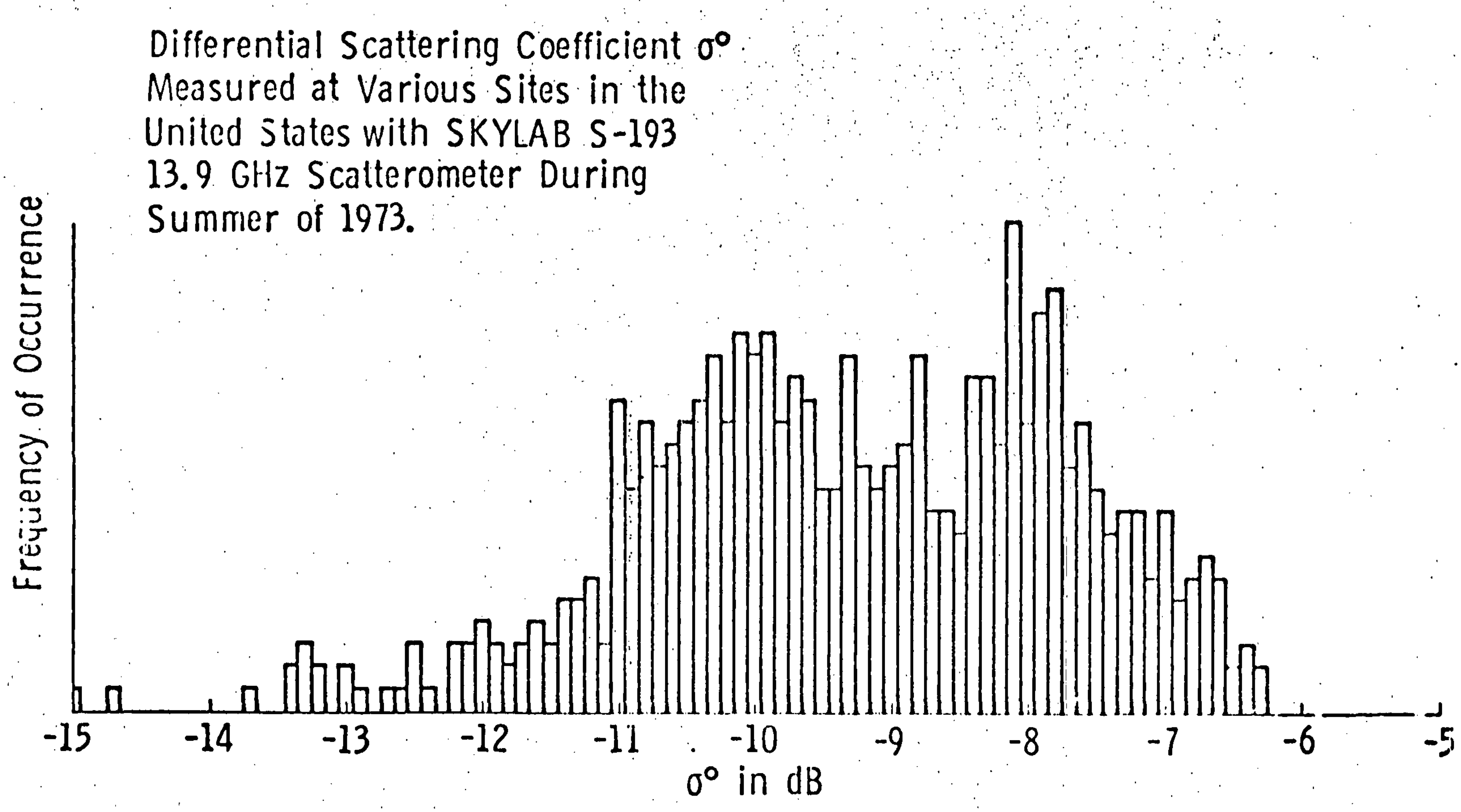

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Figure 2

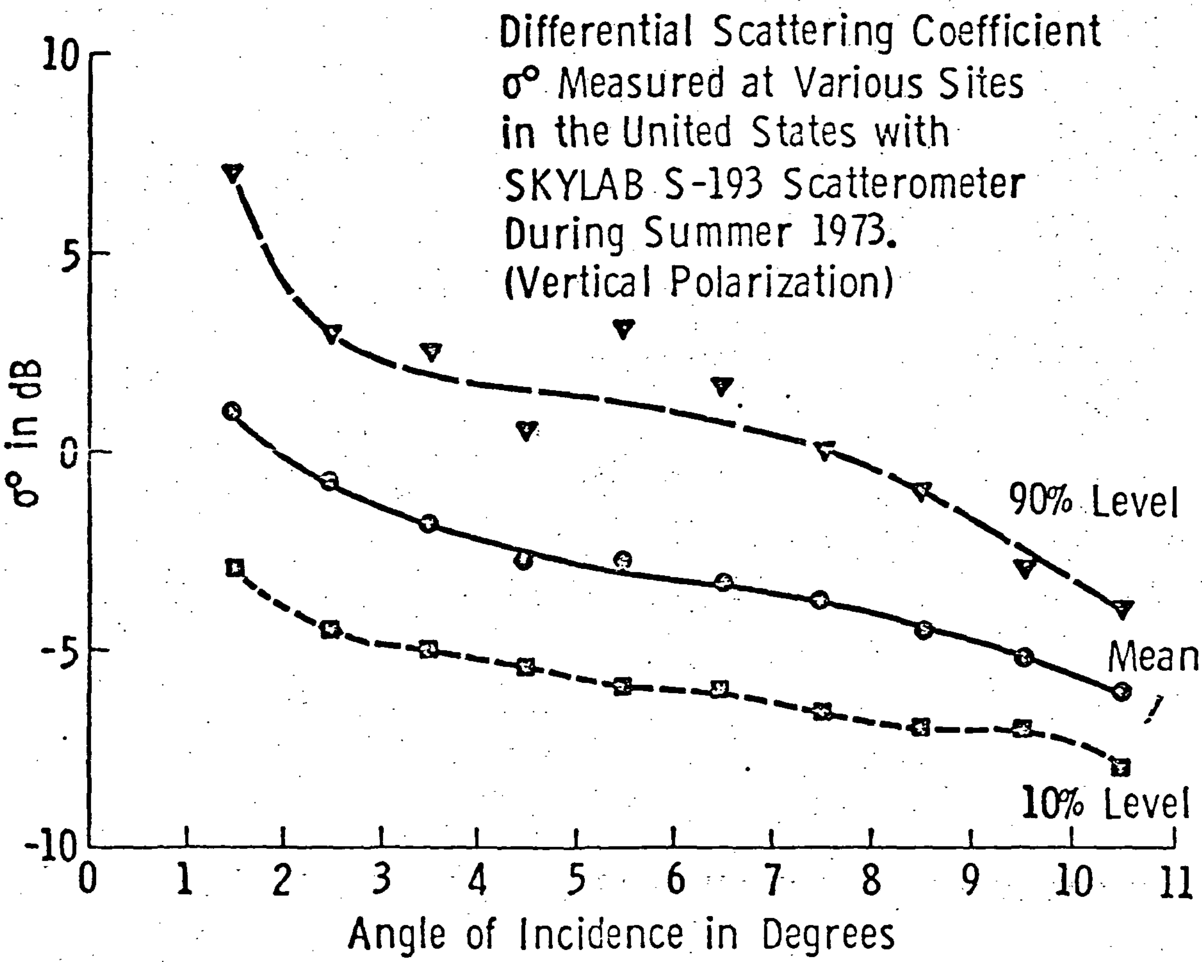

Differential Scattering Coefficient
σ° Measured at Various Sites
in the United States with
SKYLAB S-193 Scatterometer
During Summer 1973.
(Vertical Polarization)
10
5
0
-5
-10
σ° in dB
0
1
2
3
4
5
6
7
8
9
10
11
Angle of Incidence in Degrees
90% Level
Mean
10% Level

Figure 3

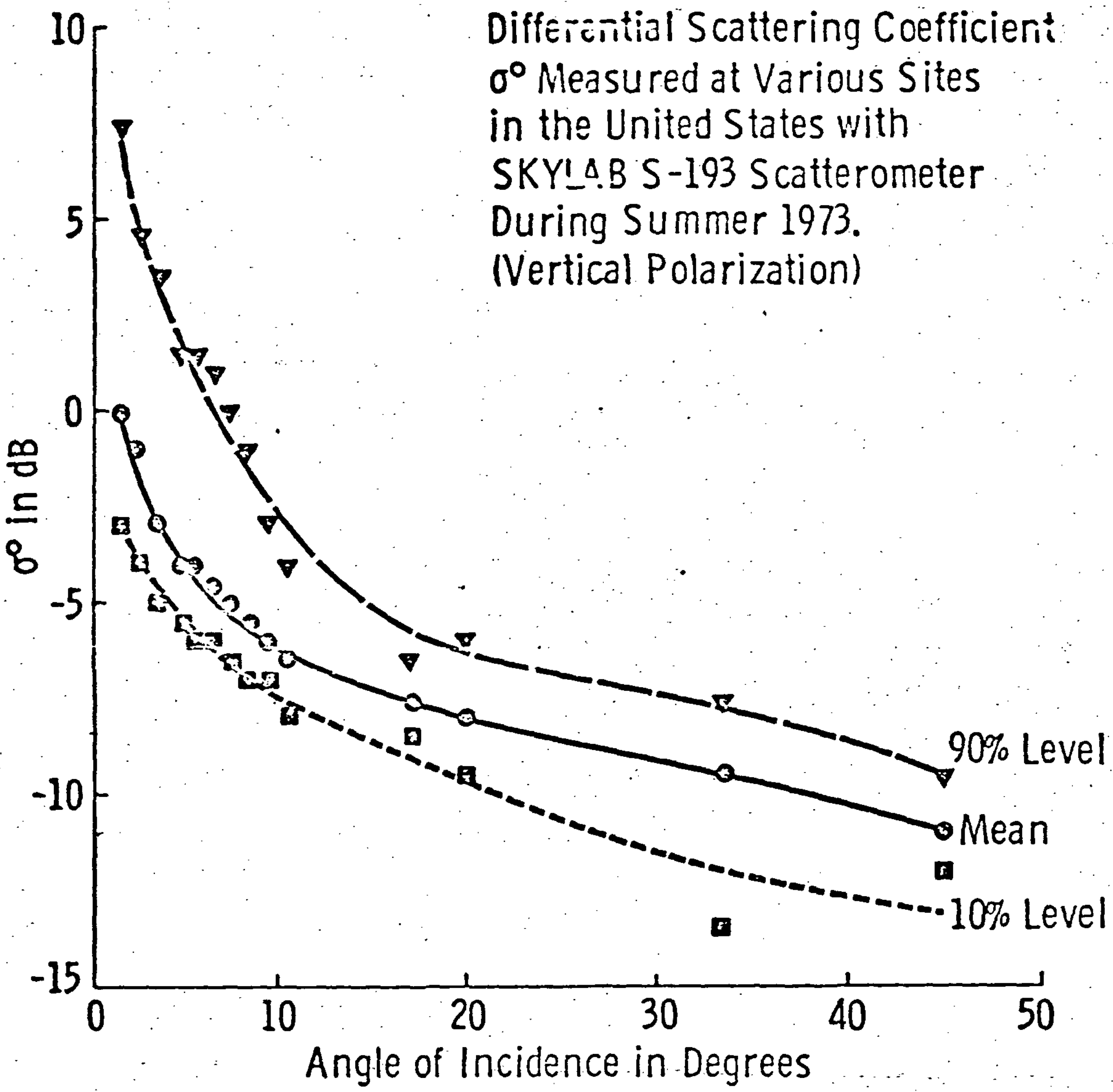
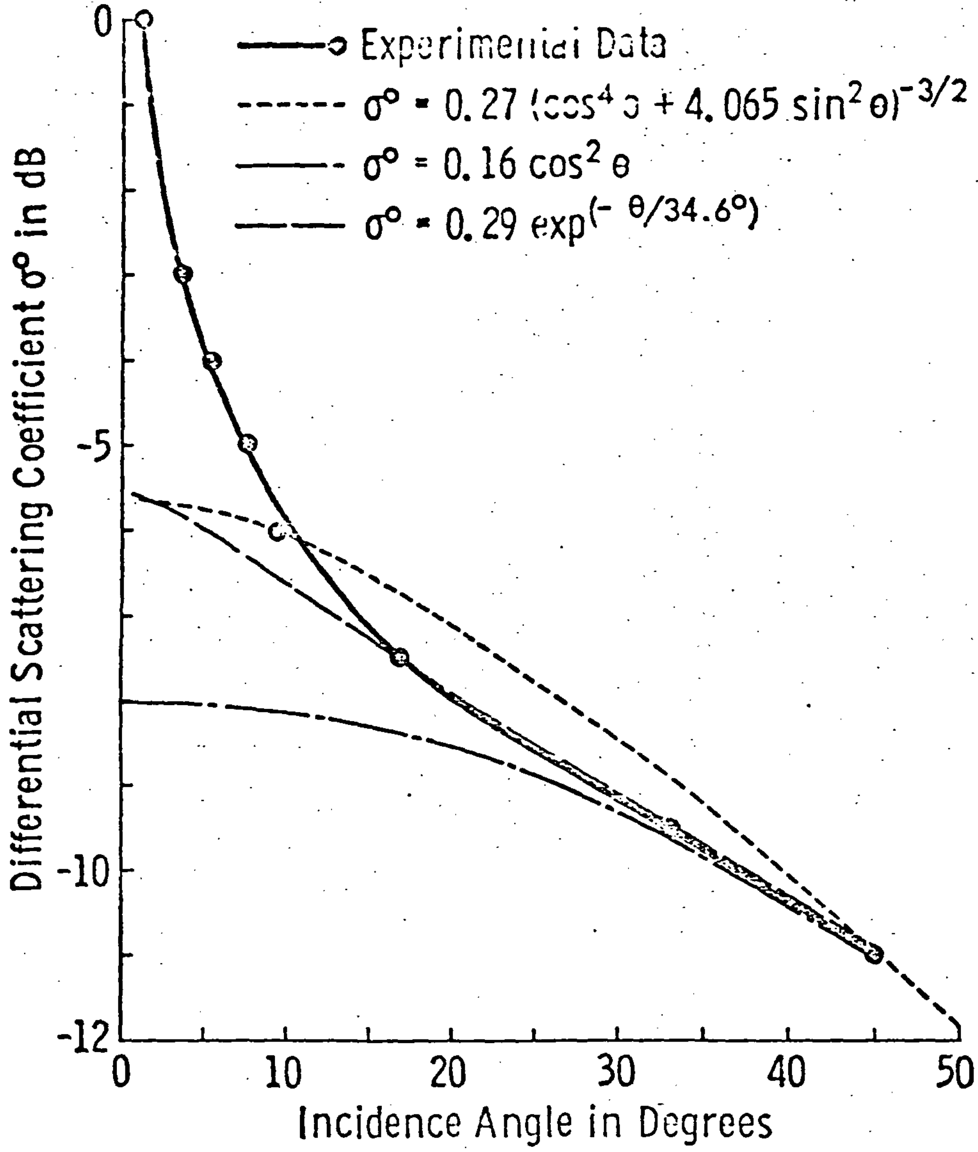
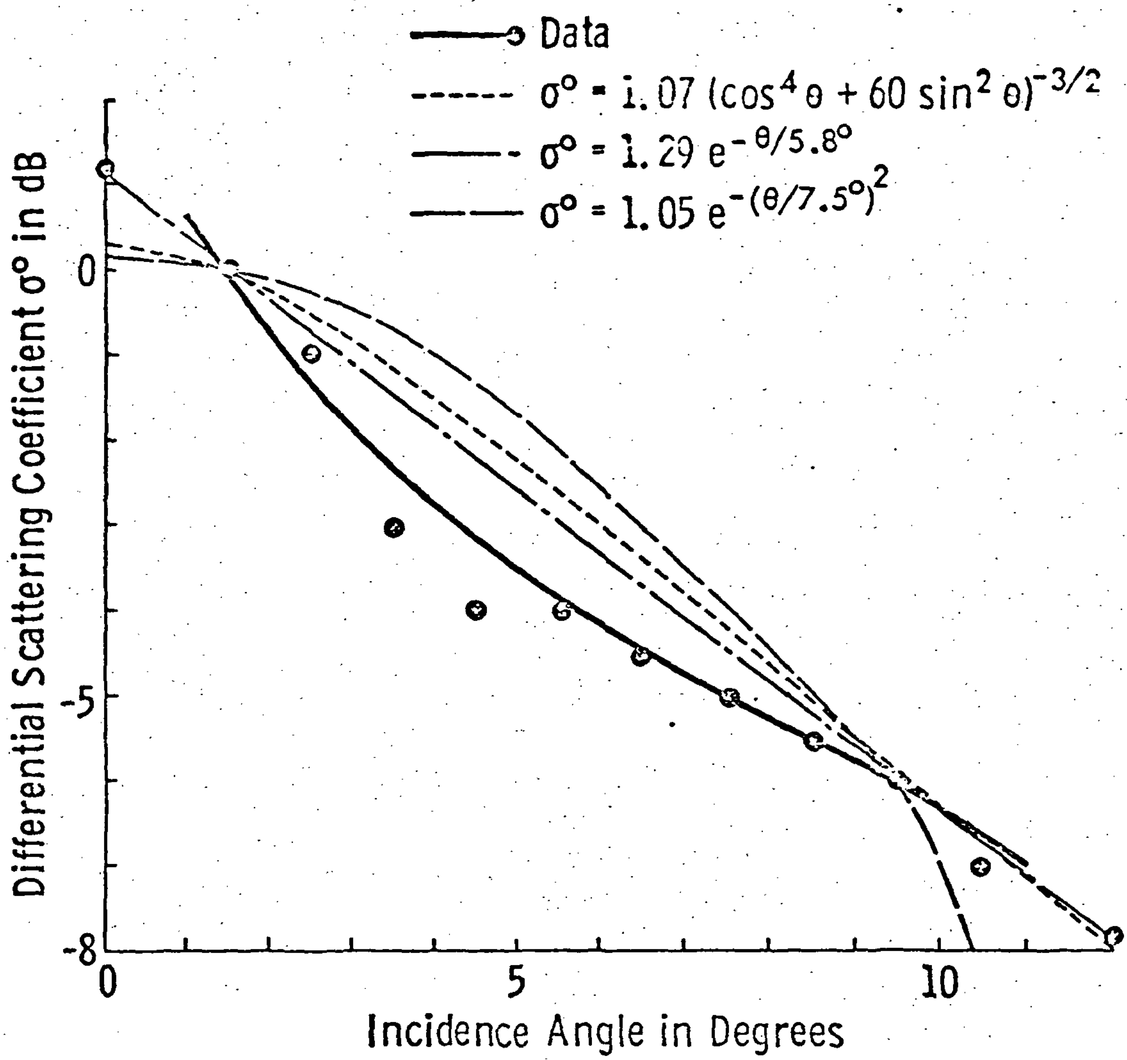

Differential Scattering Coefficient
σ° Measured at Various Sites
in the United States with
SKYLAB S-193 Scatterometer
During Summer 1973.
(Vertical Polarization)
10
5
0
-5
-10
-15
σ° in dB
0
10
20
30
40
50
Angle of Incidence in Degrees
90% Level
Mean
10% Level

Figure 4



COMPARISON OF SKYLAB MEDIAN 13.9 GHz
RADAR RESPONSE WITH VARIOUS MODELS

Figure 5



COMPARISON OF SKYLAB MEDIAN 13.9 GHz RADAR RESPONSE NEAR VERTICAL WITH VARIOUS MODELS

Figure 6