# STATISTICS OF $K_u$-BAND MICROWAVE RESPONSE OF THE UNITED STATES WITH A SATELLITE-BORNE RADIOMETER/SCATTEROMETER


## Abstract

The Skylab S-193 radiometer/scatterometer collected thousands of measurements of scattering coefficient and brightness temperature over various parts of the United States during the summer of 1973 at angles of incidence between vertical and about 45°. These measurements have been combined to produce histograms of the response at each of several angles within this range, and to establish average scattering coefficient vs angle curves with 10% and 90% exceedance levels as well.

The variation of the radiometric measurements is primarily in the region from 255°K to 285°K, with very few measurements giving higher values, but a significant, though small, number giving values down to and even below 200°K. The scattering coefficient varies, for the mean, from about 0 dB at 1° off vertical to a low in the neighborhood of −10 dB at 45°. The variability of the scattering coefficient measurements with this coarse-resolution sensor is surprisingly small.

The number of distinguishable levels is slightly more for the scatterometer than for the radiometer, but the amount of variation in brightness temperature caused by the physical temperature of the ground is enough so that the scatterometer can be used to distinguish significantly more meaningful levels than the radiometer.



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## 1.0 INTRODUCTION

Preliminary results are presented of the radiometer brightness temperature and the scatterometer differential scattering coefficient from a large number of points in the United States, obtained with the Skylab RADSCAT instrument during the summer of 1973. These data were obtained with a quite large resolution cell; consequently, each point represents a significant average of various kinds of terrain. The total statistical picture presented gives the distribution and mean or median values for a large and heterogeneous sample of the United States. Consequently, the results on both mean and variability of the data should be quite useful for future design of high-altitude, modest-resolution microwave sensors in the two-centimeter wavelength regime.

The Skylab Earth Resources Experiment Package carried two microwave instruments. One of these was the S-193 Radiometer/Scatterometer. The system operated at 13.9 GHz (2.16 cm). The antenna was a parabolic reflector that could be scanned mechanically over a range from vertical out to about 48° off vertical in many different modes. The one-way beamwidth appropriate to radiometric measurements was 2.02°; at vertical incidence this corresponds with a circle 15.4 km in diameter and at 45° an ellipse 21.6 x 30.5 km. For the scatterometer, the round-trip half-power beamwidth is required; this is 1.54° and corresponds with a circle 11.7 km in diameter at vertical or an ellipse 16.6 x 23.5 km at 45°. The radiometer had a precision of measurement that varied between about 0.7°K and 1.3°K for one standard deviation, with the particular value depending upon the mode selected. The scatterometer precision was 0.25 to 0.5 dB for one standard deviation. Again the variation is due to mode selection.

Data presented here was collected during the first and second occupancy of Skylab in June and in August/September of 1973. Data collected during the winter will be reported later.

A coarse-resolution sensor of this type has somewhat limited utility, for most remote sensing applications involving the land require resolutions of the order of 200 meters or better. However, certain applications appear likely, even for poor resolution sensors of this kind. These include monitoring regions of differing soil moisture content, possible monitoring of snow, monitoring the extent of frozen ground (important in flood forecasting), and monitoring the extent of ice over the ocean. A major purpose of a catalog of scattering coefficients and brightness temperatures at this resolution is providing information to the designers of future radar and radiometer systems for spacecraft.

Although most future spacecraft radars will probably have finer resolutions, with the synthetic aperture imaging radar being the most important system, data collected with this poor resolution is important to the design of these systems. The dynamic range and required sensitivity for the synthetic-aperture radar, prior to processing the signal to achieve fine resolution, will be approximately modeled by the data collected with the S-193 scatterometer. This is because a spacecraft synthetic-aperture radar will illuminate with its actual physical antenna aperture a patch on the ground that is several kilometers across in one dimension, although it may be only a few tens of meters in the other direction. Such a large illuminated area will have about the same degree of averaging as the S-193.

Another potential application of these data is comparison of the experimental results with theory for radar backscatter and verification of the validity of the theories for large areas. This may be particularly interesting when applied to the theories currently used for comparable or larger resolution cells on the other planets. Here, we have an opportunity to test the techniques used for analysis of the surface properties of other planets on our own planet, for which we have collateral information.

## 2.0 COVERAGE

The S-193 operated on numerous passages over the United States in each of its modes. Figure 1, 2, and 3 illustrate coverage with three of the different modes.

In Figure 1, the In-Track Contiguous Mode coverage is shown. With this mode, a measurement was made for each of five incident angles every four seconds (about 30 kms of travel). Thus, in regions where all angular measurements overlapped, a curve of scattering coefficient versus angle is possible. On the illustration, the open part of each coverage bar shows the region where vertical-incidence measurements were made. The stippled extensions show the regions where the antenna made measurements while tilted ahead, but for which the instrument was turned off as the spacecraft passed overhead. Thus, the data sets for different angles come from similar areas, but the areas are not identical. Measurements made with this mode involve a single antenna polarization; that is, the scattering coefficient was measured with the same polarization for transmitting and receiving, and the same receiving polarization was used for radiometer and scatterometer.

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Figure 2 shows the coverage for the In-Track Non-Contiguous Mode. With this mode, a measurement was made every 100 km at each of the five angles, but this measurement usually consisted of vertically and horizontally polarized radiometric measurements and vertical, horizontal, and cross-polarized scatterometer measurements. This mode was primarily intended for use over the ocean so that its use over the land was quite restricted as obvious from the figure.

Figure 3 illustrates the large coverage obtained with the Cross-Track Contiguous Mode. In this mode, 12 measurements are made in a scan across the track with a scan interval of 2.1 seconds. The center of the scan may be in various position as indicated on the figure. The angular range is approximately 22°; thus, when the center is at pitch-angle 0, roll-angle 0, the scan goes through nadir with a maximum angle of incidence of about 11° on each side of the spacecraft ground track. The scan center, pitched ahead 15°, 29°, or 40°, results in a smaller range of incident angles for the 11° motion either side of the track. When the antenna is pitched at angle 0, but rolled to the right or left, the full 22° scan results in different incident angles. The ground track is shown at center for each case where the roll angle is 0, and at the left or right for the rare cases where the roll angle is 15°. Since most of the data collected with the Cross-Track Contiguous Mode are in the western part of the United States, some bias exists in the data sets. However, the large ITC pass (indicated in Figure 1) over the eastern part of the United States should partially balance the western bias of the large quantity of Cross-Track Contiguous Mode data shown in Figure 3.

## 3.0 OBSERVATIONS NEAR VERTICAL INCIDENCE

Histograms have been prepared of the brightness temperature and differential scattering coefficient both for the entire data set and for various subsets. In this section are shown histograms for the angle of incidence near vertical. The complete data set includes all of the angles out to 11°, but examples are shown only for the 1 - 2° and the 10 - 11° cases.

Dense clouds may significantly attenuate the radar signal resulting in a reduced measured value for scattering coefficient, but they are even more important with with regard to the radiometric brightness, for they not only attenuate but also radiate into the radiometer receiver. No attempt has been made here to correct the results for the presence of clouds. Such an attempt will be made later and reported separately.

Figure 4 shows the radiometric brightness temperature at the 1 - 2° angle of incidence for the complete data set. Efforts are underway to estimate the emissivity related to these brightness temperatures, but the results are not yet available. Thus, the temperatures shown here have a wider dispersion than the emissivities, for some of the measurements were made in the northern tier of states and others in the southwestern deserts. The histogram shown extends down to 200°; few measurements were made with brightness temperatures lower than this value. In every case, these could be ascribed to water surfaces so they are not reported here since this discussion deals only with land surfaces. The preponderance of measurements is in the range from 265°K to 285°K. Since the anticipated differences in ground temperatures are about 10°, the corresponding emissivities probably have an even narrower range of variation.

Figure 5 shows differential scattering coefficients for the same 1 - 2° range of angles of incidence. As expected, the scattering coefficient peaks up in the neighborhood of 0 dB or slightly below, with almost no values less than -5 dB and only a few greater than +8 dB. The +15 dB value may in fact be even larger, for this is the saturation level of the instrument. Values in this region were found for the salt flats adjacent to Great Salt Lake in Utah and for smooth water surfaces. Probably the cluster of points around +10 dB also should be associated with either water or the salt flats.

Figure 6 shows a histogram similar to that of Figure 4, for the brightness temperature in 10 - 11° range of incident angles. The dispersion at this angle of incidence is significantly greater than that closer to vertical. The comments regarding the effects of cloud and of surface temperature apply in this case as well.

Figure 7 for 10 - 11° should be compared with Figure 5 for 1 - 2° for the scattering coefficient. The dispersion at 10 - 11° is much less for the scatterometer than that at vertical incidence and peaks around a value of about -7 dB; that is, the scattering is considerably weaker at 10 or 11° than closer to vertical. This is in accord with both theory and experiments made with aircraft and ground-based instruments. The relatively small dispersion at this angle of incidence is perhaps in part caused by the cross-over of scattering-coefficient-versus-angle curves in the neighborhood of 10 - 15°. That is, most theories and previous experiments indicate that relatively flat surfaces have steeper scattering-coefficient-versus-angle curves than relatively rough surfaces, and the curves tend to cross in this range of angles of incidence.

Specific examples are presented here for two cases: one run across the Utah salt flats and adjacent high desert and mountain areas, and the other across agricultural plains of North Dakota and eastern Montana.

Figure 8 shows the radiometric brightness temperature for the Utah measurements. Note that in addition to the concentration in the neighborhood of 270 to 280° there is much dispersion to lower brightness temperatures. In fact, this pass also contains many measurements below 200°K. Most of these quite low temperatures are associated with the specular reflection in the salt flats where apparently moisture is close enough to the surface to significantly reduce the measured brightness temperature.

Figure 9 shows the scattering coefficient for the same area. Here, the scattering coefficient range splits into two parts, the one between 0 and -5 dB compares well with the scattering coefficient observed in other parts of the country. The scattering coefficients above +5 dB appear to be mostly from the nearly specular salt flats. The higher concentration in the 14.5 and 15 dB values is because of saturation of the instrument at this point. No doubt the actual effective scattering coefficient histogram would extend to higher values if saturation had not taken place. The figure shows only the angles of incidence between 0 and 2°, whereas the corresponding figure for the radiometer showed all values between 0 and 15°. This is possible with the radiometer because there is little variation with angle near vertical incidence, whereas the variation for the scattering coefficient near vertical incidence is quite large so the scattering coefficient figure must be for a confined range of angles.

Figure 10 shows the brightness temperatures measured in the first 15° from vertical over the North Dakota farmland; although these concentrate in the neighborhood of 270°, they also extend down to 260°. Since there is little likelihood of a very flat wet surface in North Dakota, the explanation of the values between 220 and 250° has not yet been established. The lower mode of the distribution presumably has to do with the lower surface physical temperatures in North Dakota relative to the surface temperatures in Utah.

Figure 11 shows the 1 - 3° scattering coefficient measurements in North Dakota (the number of measurements between 0 and 1° was insignificant). The general range for the North Dakota near-vertical measurements is comparable with that for the entire U.S. data set. Presumably the three values near 15 dB may be reflections from lakes.

## 4.0 OFF-VERTICAL MEASUREMENTS

Although measurements were made at various angles as summarized later, the examples shown here are for the region of 32 - 33° incidence and for vertical polarization. These were selected since measurements at this angle and polarization were more plentiful than at any other angle because of the preponderance of Cross-Track-Contiguous data with a 29° pitch angle for the center of the scan. The incidence angle with the curved earth is somewhat larger than the pitch angle at the spacecraft even for measurements made along the ground track, and incidence angle is somewhat larger than that for the measurements off the ground track. This explains the presence of the largest number of measurements in the range about 3° beyond the pitch angle.

Figure 12 shows the overall distribution of brightness temperature in this angular range. Note that the horizontal scale has been expanded compared with the scale used in previous figures, so the width of the distribution appears only half as great as the previous scale. Nevertheless, the distribution does have many values over the 30° range from 265 to 295°. If we assume a variation of 10 or 15° in the ground temperature, the remaining distribution would still be in the neighborhood of 20 to 15° after correction for differences in ground temperature.

Figure 13 shows the comparable range of scattering coefficients. Once again, the scale has been expanded, compared with the previous examples, so that it is now a total of 20 dB rather than 50 dB. The range of scattering coefficients observed is surprisingly small in view of the great variability evidenced by data measured in previous ground-based or aircraft programs. Presumably, this is partly due to the averaging of the large resolution cell and partly to the consistency of the measurements here made over a relatively short period of time and with the same carefully calibrated instrument, when compared with measurements made over long periods of time with instruments that in some cases are less carefully calibrated. No observations were made at these angles of incidence of scattering coefficient exceeding -6.3 dB. A very small number of measurements is less than -15 dB and these may be from occasional water surfaces.

## 5.0 SUMMARY OF MEASUREMENTS

No consistent trend of angular variation was observed for the brightness temperature measurements, but the measurements of scattering coefficient show extremely consistent trends. Consequently, curves are presented of variation of scattering coefficient with angle, but no such curves are presented for the brightness temperature.

Figure 14 shows an expanded-scale summary of the near-vertical measurements of vertical polarization scattering coefficient. No point is indicated for 0° because most of the measurements were at least at a 1° angle of incidence, so that the number of points between 0 and 1° is insufficient to obtain good statistics.

The mean value calculated here is shown with a solid line. The upper and lower 10% observation levels are also indicated. The points on the mean value curve are quite consistent. The inconsistencies in the values for the 10% and 90% levels are due to the relatively small numbers of samples outside these bounds. Even so, it is quite apparent that the spread in measured values is greatest very close to the vertical. Clearly, designers for altimeters and other devices that operate upon the signals from very close to the vertical can use values for scattering coefficients of the order of -5 dB in their designs with confidence that the instrument will indeed be sufficiently sensitive for nearly every case. Presumably, since this value is somewhat greater than those observed in ground-based experiments, the larger minimum value of differential scattering coefficient in this spacecraft experiment is in part due to averaging over relatively large illuminated areas.

Figure 15 shows the summary of measurements at all of the angles of incidence for which a large enough sample is available. Note that the horizontal scale is different from that of the previous figure by about a factor of 5. The points shown within the first 10° are the same as those plotted in the previous figure. The well-known phenomenon of flattening of the scattering coefficient curve seems to occur at around 10°, which is a somewhat smaller angle than previous ground-based measurements indicate; but is in the same order of magnitude as these previous measurements.

The numbers of measurements involved in each point are different, but the means are believed to be reasonably accurate in every case. The low value for the 10% level point at 33° is probably due to inclusion of a small amount of data from water surfaces and from the Utah salt flats. This data quantity is large enough to significantly affect the 10% level, but not large enough to significantly change the mean. Presumably, the smaller data set associated with the 45° angle of incidence does not include any such surfaces. Most of the 45° data were obtained during the long pass illustrated in Figure 1, where the In-Track Contiguous Mode was used in the eastern United States.

Perhaps the most surprising thing about this figure is the relatively small range within which 80% of the observations lie at any particular angle. In no case away from the vertical does this range exceed 5 dB (if we assume that the dash line is more representative of the 10% level at 33° for land than the observation point there). Hence, the dynamic range required for any radar system using a large illuminated area comparable with that of the Skylab scatterometer is quite small at the larger angles of incidence. Of course, if the instrument had to operate over the full range of angles as did the S-193 scatterometer, the dynamic range would be greater and if it had to operate over both land and water, the dynamic range would be significantly greater than shown here for land alone.

It is interesting to compare the relative variation of the scattering coefficient and brightness temperature measurements. To get some idea of the number of discernible levels that might be measured with each of the two instruments, Figure 15 tabulates this information. The 10 - 50% range of scattering coefficient over the entire angular range between 14 and 47° comes out to only 2.63 dB and the 50 - 90% range comes out to 1.78 dB. For the brightness temperature the values as indicated are 8.86 and 4.76°K. To get some idea of the number of discernible levels, one must divide this range by the measurement precision which is a rough indication of the width of a discernible level. This has been done in the bottom part of the figure, using the approximate precisions for the instruments of 1°K for the radiometer and 0.25 dB for the scatterometer. On this basis the scatterometer has a somewhat larger number of discernible levels than the radiometer, although the ratio is not great. In other words, the number of discernible levels is comparable in the two, but somewhat less for the radiometer. One should also consider, however, that the radiometer requires a calibration in terms of the actual surface temperature because the brightness temperature is proportional to the product of emissivity and surface temperature. Thus, the scattering measurement seems more likely to be able to discern a significant number of differences in the terrain than the radiometric temperature measurement if information is not available on the physical temperature of the ground. If information is available for the physical temperature and cloud effects are not important, the two instruments appear to have comparable amplitude resolution.

## 6.0 CONCLUSIONS

Preliminary indications from the Skylab microwave measurements made during the summer are that the brightness temperature varies over a range of about 30° for the majority of terrains relatively independent of angle of observation between vertical and 45°. The variation for the scattering coefficient with angle is quite significant and has been presented in graphical form. The range of variation of the scattering coefficient is relatively small compared with what one might have concluded on the basis of previously reported aircraft and ground measurements, but this may be due in large part to the larger area averaged by the spacecraft instrument.

The preliminary observations reported here constitute a quite useful set of information for design of future spacecraft radiometers and radars operating in the vicinity of the 2-centimeter wavelength used for this set of measurements. The observations are being further analyzed to categorize them and to determine the ability of the two instruments to measure variations in terrain of value to those charged with monitoring or determining differences on the earth's surface. Indications are that both instruments are capable of about the same degree of discrimination if the physical temperature of the ground can be determined and if clouds are not a significant factor. If clouds are a significant factor, or if the physical temperature of the ground cannot be determined readily, the scatterometer seems to offer more promise for discrimination of ground phenomenon.