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AN ANALYSIS OF MULTI-FREQUENCY  
HIGH RESOLUTION RADAR RAIN RATE DATA

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## TABLE OF CONTENTS

|                                  | Page |
|----------------------------------|------|
| I. INTRODUCTION                  | 1    |
| II. EQUIPMENT AND FACILITIES     | 2    |
| III. EXPERIMENTAL CONDITIONS     | 2    |
| IV. THE DATA                     | 2    |
| V. SYSTEM REPRESENTATION         | 4    |
| VI. CALIBRATION                  | 7    |
| A. Matching the Radars           | 7    |
| B. The Regression Technique      | 7    |
| C. Preliminary Calculations      | 11   |
| D. Obtaining the Radar Constants | 11   |
| VII. ANALYSIS AND RESULTS        | 14   |
| VIII. CONCLUSIONS                | 21   |
| PUBLICATIONS                     | 22   |
| REFERENCES                       | 23   |

## I. INTRODUCTION

Weather radar installations have generally been confined to frequencies at which the attenuation of the signal by liquid water and the atmosphere is not very significant. The difficulties of making proper attenuation corrections and the instability in current methods, which can result from errors in calibration, have discouraged their use at attenuating frequencies [1,2]. Precise calibration of radars has long been recognized as a major problem. Traditional calibration methods have been based upon the use of a known target, such as a sphere [3], or comparison with ground rain rate measurements [4].

The experiment described herein uses three radars, two of which operate at attenuating frequencies. The three-frequency High Resolution Radar/Radiometer System at the Ohio State University includes radars in the S, X and Ku bands, (3.05, 9.35 and 15.56 GHz), looking simultaneously at the same spatial region. Such a configuration possesses some unique advantages.

This system was developed to explore the potential improvement in radar rain rate measurement accuracy which would result from calibration of radar backscatter at a second frequency or in terms of an independent measurement of radiometric temperature. The use of simultaneous measurements relaxes the need for high absolute accuracy in each individual instrument as well as making possible compensation for variations in drop-size distribution. The use of higher frequencies also improves the spatial resolution capability of the radar.

The Ohio State University Multi-Frequency High Resolution Radar/Radiometer System was implemented and operated for a brief period of time during the calibration and debugging phase of the program in 1973. Subsequently, a shift in program emphasis and funding curtailed this unique effort. Nevertheless, during this "shake-down" period, approximately 100,000 records of high resolution radar/radiometer data were recorded. Editing and analysis of these data have been performed and are described herein.

In order to accomplish this objective, several calibration techniques were examined and tested. The calibration procedure finally chosen is also described in the following. Attenuation corrections were applied and the resulting multi-frequency data were checked for self consistency. The techniques and theory used follow some new theoretical work on weather radar calibration [6].

Cell width, equivalent reflectivity and peak equivalent reflectivity distributions are computed using the edited and calibrated data. The average cell width at several relative reflectivity levels below the peak are obtained for the cells observed. The feasibility of using attenuating frequency radars is demonstrated.

## II. EQUIPMENT AND FACILITIES

The High Resolution Radar/Radiometer System at The Ohio State University consists of three radars operating at 3.05 GHz (S-Band), 9.35 GHz (X-Band) and 15.56 GHz (Ku-Band), together with radiometers at 3.30, 8.50 and 15.10 GHz respectively. The radars are fired in sequence under computer control, the pulse-repetition frequency of each radar being 100 Hz. The initial range is adjustable from 15 to 45 km and the range window is 30 km with a resolution of 300 meters. The returns of 32 pulses of each radar are summed on a range bin-by-range bin basis and recorded on digital magnetic tape, together with time, look angle and other relevant information. A summary of the system parameters is given in Table 1. For a complete description see reference [5].

## III. EXPERIMENTAL CONDITIONS

The available data consist of about 100,000 records. These were taken during the final stages of construction and commissioning of the equipment while debugging and calibration were being performed. Consequently, hardware problems are evident in some of the data. Furthermore, the termination of the effort curtailed the calibration and documentation process. Some uncertainty remains in parameters such as antenna gain, transmitted power and receiver gain slopes.

The problem of data analysis is further aggravated by the four year lag between the taking of the data and its analysis. Some personnel working on the system, who might have been able to provide valuable information on the problems encountered, are no longer available. Nevertheless, it was felt that the information contained in the available data warranted its analysis and that adequate calibration information was available to make a complete calibration possible.

## IV. THE DATA

Approximately 100,000 records on magnetic tape were edited to remove unsuitable data. Records showing hardware problems such as loss of transmitter power, integrator overflow, etc. were discarded. Many records showing only portions of cells of significant size were also rejected. The remaining usable 10,000 records show four rainfall events. The X- and Ku-band radars were operational during all four data periods, while the S-band radar was operated during only one of these. All three radars were oriented to the same pointing angle, which was fixed in elevation at 6°, during each event. The radars were allowed to dwell on a rain cell for some time and then rotated in azimuth to another cell of interest. Seven rain cells are seen as they move through the fixed beams.

TABLE 1  
RADAR PARAMETERS

|        | Frequency<br>(GHz) | Wavelength<br>(cm) | Peak<br>Power<br>(Kw) | Pulse<br>Length<br>( $\mu$ s) | Repetition<br>Rate<br>(Hz) | Threshold<br>(dbm) | Noise<br>Figure<br>(dB) | Bandwidth<br>(MHz) | Firing<br>Interval<br>(ms) | Number of<br>Samples<br>Integrated |
|--------|--------------------|--------------------|-----------------------|-------------------------------|----------------------------|--------------------|-------------------------|--------------------|----------------------------|------------------------------------|
| HI-RES | S                  | 9.84               | 20.0                  | 1.0                           | 100                        | -99                | 6.1                     | 10                 | 10                         | 32                                 |
|        | X                  | 3.21               | 25.0                  | 1.0                           | 100                        | -98                | 7.1                     | 10                 | 10                         | 32                                 |
|        | Ku                 | 1.93               | 7.9                   | 1.6                           | 100                        | -100               | 11.5                    | 2                  | 10                         | 32                                 |

ANTENNA PARAMETERS

|        | Antenna<br>Diameter<br>(m) | Beam<br>Width<br>(deg.) | Minimum<br>Elevation<br>(deg.) | Unblocked<br>Azimuth<br>(deg.) | Polarization | Polarization<br>Control | Azimuth<br>Slew Rate<br>(deg/sec) | Antenna<br>Gain<br>(dB) | Surface<br>Tolerance<br>(mm) | F/D   |
|--------|----------------------------|-------------------------|--------------------------------|--------------------------------|--------------|-------------------------|-----------------------------------|-------------------------|------------------------------|-------|
| HI-RES | S                          | 0.75                    | 3.0                            | 50 - 300                       | V            | manual                  | 0.3-1.0                           | 46                      | 1.90                         | 0.416 |
|        | X                          | 0.26                    | 3.0                            | 150 - 40                       | V            | manual                  | 0.3-1.0                           | 56                      | 1.98                         | 0.416 |
|        | Ku                         | 0.29                    | 5.5                            | 30 - 300                       | V            | servo                   | 0.3-1.0                           | 54                      | 0.64                         | 0.48  |

3

RADIONETER PARAMETERS

|        | Frequency<br>(GHz) | Bandwidth<br>(MHz) | Integration<br>Time<br>(sec.) | Bits/Sample | Dicke<br>Switching<br>Rate<br>(KHz) |
|--------|--------------------|--------------------|-------------------------------|-------------|-------------------------------------|
| HI-RES | S                  | 3.30               | 0.1-1.0                       | 8           | 1.6                                 |
|        | X                  | 8.50               | 0.1-1.0                       | 8           | 1.6                                 |
|        | Ku                 | 15.10              | 0.1-1.0                       | 8           | 1.6                                 |

## V. SYSTEM REPRESENTATION

A block diagram of one of the receivers is shown in Figure 1. Based on available preliminary calibrations each radar receiver was represented by a straight line characteristic on a log-power in vs. output voltage plot with gradient GR dB/volt and noise level  $FN_{ref}$  dBm. After the A/D converter and 32 pulse digital summer, the overall gradient was A dB/digital level recorded on tape. If

$P_r$  = received power per pulse from any range bin,

$D$  = digital level for that range bin,

$D_o$  = digital level at the tail edge of record, representing receiver noise,

then it can be shown that

$$P_{r(mw)} = FN_{ref(mw)} \left\{ 10^{\frac{(D-D_o)A}{10}} - 1 \right\} \quad (1)$$

Also, the monostatic beam-filled radar equation can be written as

$$P_r = \frac{Q}{r^2} e^{-2A_r} Z_{eq} \quad (2)$$

where

$$Q = \frac{P_t G^2 \theta^2 c \tau \pi^3}{\lambda^2 1024 \ln 2} \cdot \left| \frac{n_c^2 - 1}{n_c^2 + 2} \right|^2 \quad (3)$$

$P_t$  = transmitted power

$G$  = antenna gain

$\theta$  = antenna beam width

$\tau$  = pulse width

$\lambda$  = wavelength

$c$  = velocity of light

$n_c$  = complex refractive index of water

$Z_{eq}$  = equivalent reflectivity factor  $\text{mm}^6/\text{m}^3$

$r$  = range to point of reflection

$A_r$  = total one way attenuation to point of reflection.

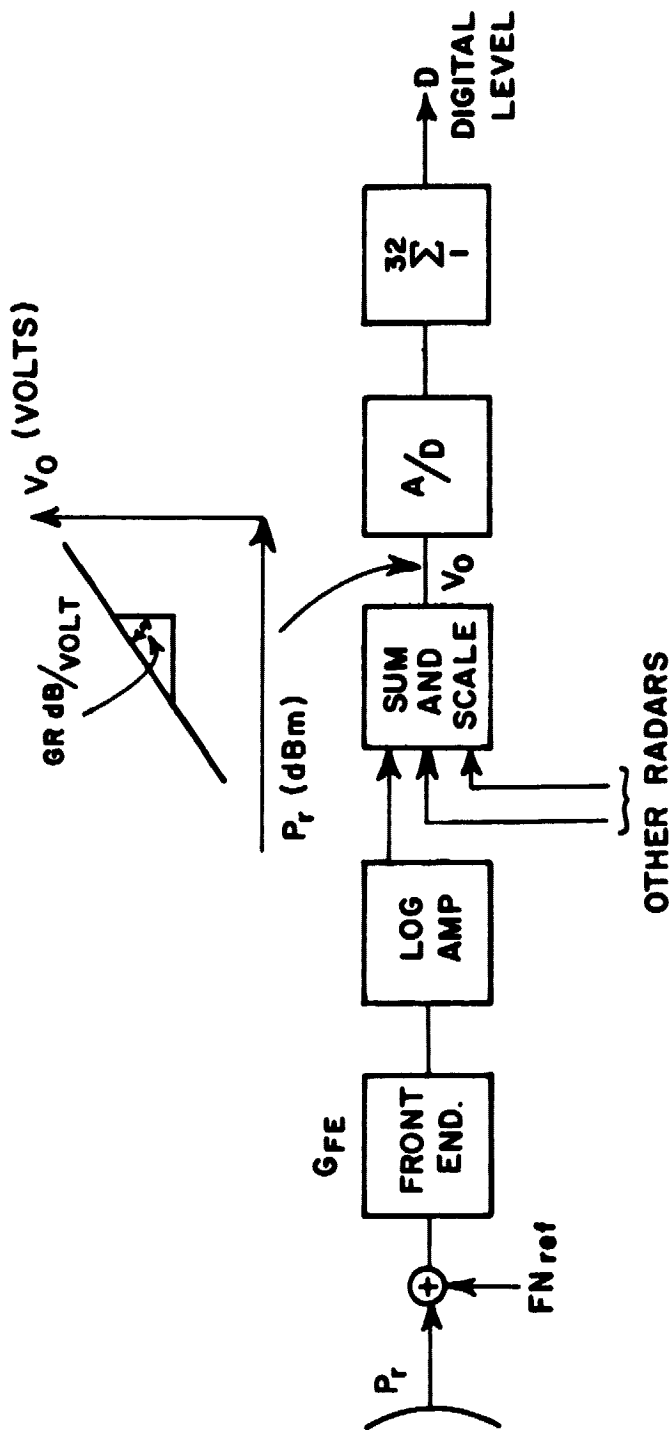


Figure 1. Block diagram of a radar receiver.

It has been shown by Hodge [6] that if  $Z_{eq}$  and the specific attenuation,  $\alpha$  (dB/km), could be represented in terms of rain rate,  $R$  (mm/hr), as

$$Z_{eq} = a_Z R^{b_Z} \quad , \quad (4)$$

$$\alpha = a_{RD} R^{b_{RD}} \quad , \quad (5)$$

then

$$e^{-2A_r} = (1 - I_r)^{b_Z/b_{RD}} \quad (6)$$

where

$$I_r = \frac{2 a_{RD} (b_{RD}/b_Z)}{4.343(a_Z Q)} \int_0^r (r^2 P_r)^{b_{RD}/b_Z} dr \quad . \quad (7)$$

Hence

$$P_r = \frac{Q}{r^2} (1 - I_r)^{b_Z/b_{RD}} Z_{eq} \quad . \quad (8)$$

Substituting from Equation (1) for  $P_r$ , dividing both sides by  $FN_{ref}$  and writing

$$\frac{Q}{FN_{ref}} = Q' = \frac{P_t G^2 \theta^2 c \tau \pi^3}{\lambda^2 FN_{ref} 1024 \ln 2} \left| \frac{n_c^2 - 1}{n_c^2 + 2} \right|^2 \quad (9)$$

$$10^{(D-D_0)\frac{A}{10}} - 1 = \frac{Q'}{r^2} (1 - I_r)^{b_Z/b_{RD}} Z_{eq} \quad (10)$$

$$I_r = \frac{2 a_{RD} (b_{RD}/b_Z)}{4.343(a_Z Q')} \int_0^r \left\{ r^2 \left[ 10^{(D-D_0)\frac{A}{10}} - 1 \right] \right\}^{b_{RD}/b_Z} dr. \quad (11)$$

where  $Q'$  is a new calibration constant including receiver characteristics.

The only two unknowns are A (and hence GR) and Q'. Since  $I_r \leq 1$ , then

$$Q' \geq \frac{1}{a_z} \left[ \frac{2^{a_{RD} (b_{RD}/b_z)}}{4.343} \int_0^\infty \left\{ r^2 \left[ 10^{(D-D_0) \frac{A}{10}} - 1 \right] \right\}^{b_{RD}/b_z} dr \right]^{b_z/b_{RD}} \quad (12)$$

Hence, if a record could be found in which the radar "saturated", i.e., the rain rate was intense enough to completely attenuate the radar returns beyond some point, and if A were known, Q' could be calculated.

## VI. CALIBRATION

### A. Matching the Radars

It was shown in Section V that the calibration problem reduces to finding two parameters, A and Q', for each of the three radars. However, since all the radars are looking at the same rain cell, only one pair of values, A and Q', not necessarily of the same radar, need be known a priori. Using a regression or scatter plot technique, the three radars can then be iteratively bootstrapped into line and all the other calibration constants found. The regression technique used was described by Hodge [7] and is given below in greater detail.

### B. The Regression Technique

This technique relies on the principle that when two radars are looking at the same event the distributions of the returns of the two radars should be the same. As a refinement, returns up to only the point of peak reflectivity of the cell are considered. The returns from beyond the peak tend to be more seriously corrupted by attenuation (Figure 2).

Using a large number of records, the reflectivity,  $Z_{eq}$ , or rain rate, R, distributions for the two radars are calculated. These do not, in general, coincide (Figure 3).

Next, the values  $Z_1$  and  $Z_2$  in Figure 3 for the two radars are computed for several values of % time. Finally, a plot of  $Z_1$  vs.  $Z_2$  is made. If the two radars are consistent, the resulting curve should be a 45° line. If not, the calibration constants may be adjusted and the process repeated till the best possible agreement is obtained. For some results of this procedure see Figures 4, 5 and Reference [7].

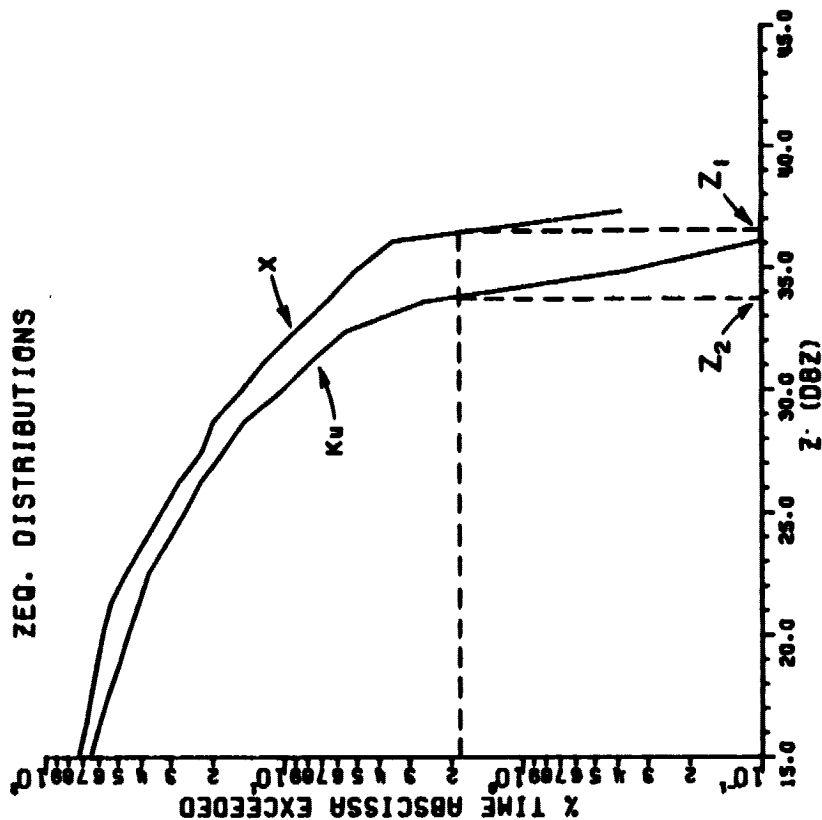


Figure 3. Equivalent reflectivity factor,  $Z_{eq}$ , distributions for unmatched radars.

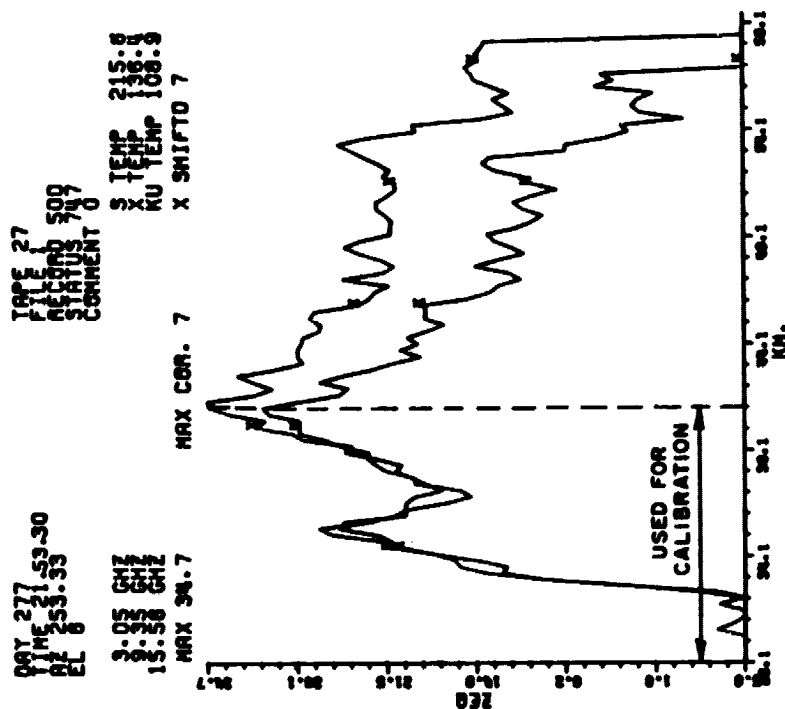
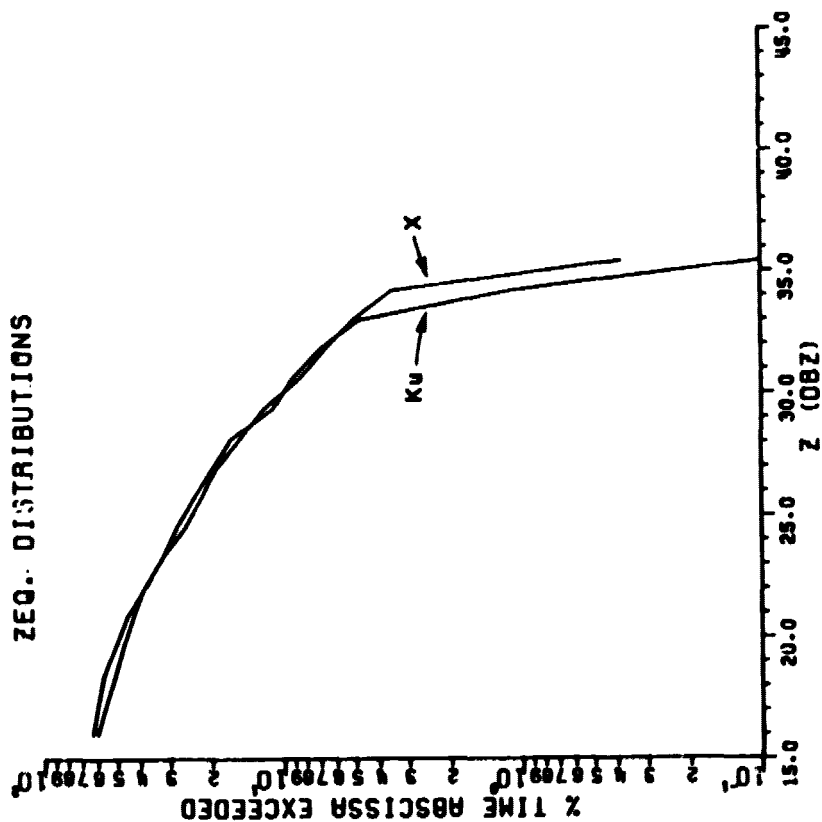
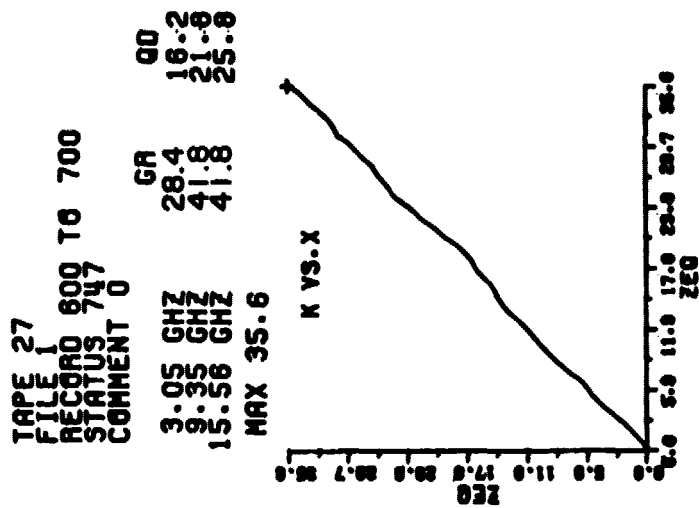


Figure 2. Two-frequency data on a typical record.



(a)



(b)

Figure 4. Comparison between the X and Ku radars obtained using the regression-calibration technique.

TAPE 27  
 FILE 4  
 RECORD 400 TO 750  
 STATUS 757  
 COMMENT 1

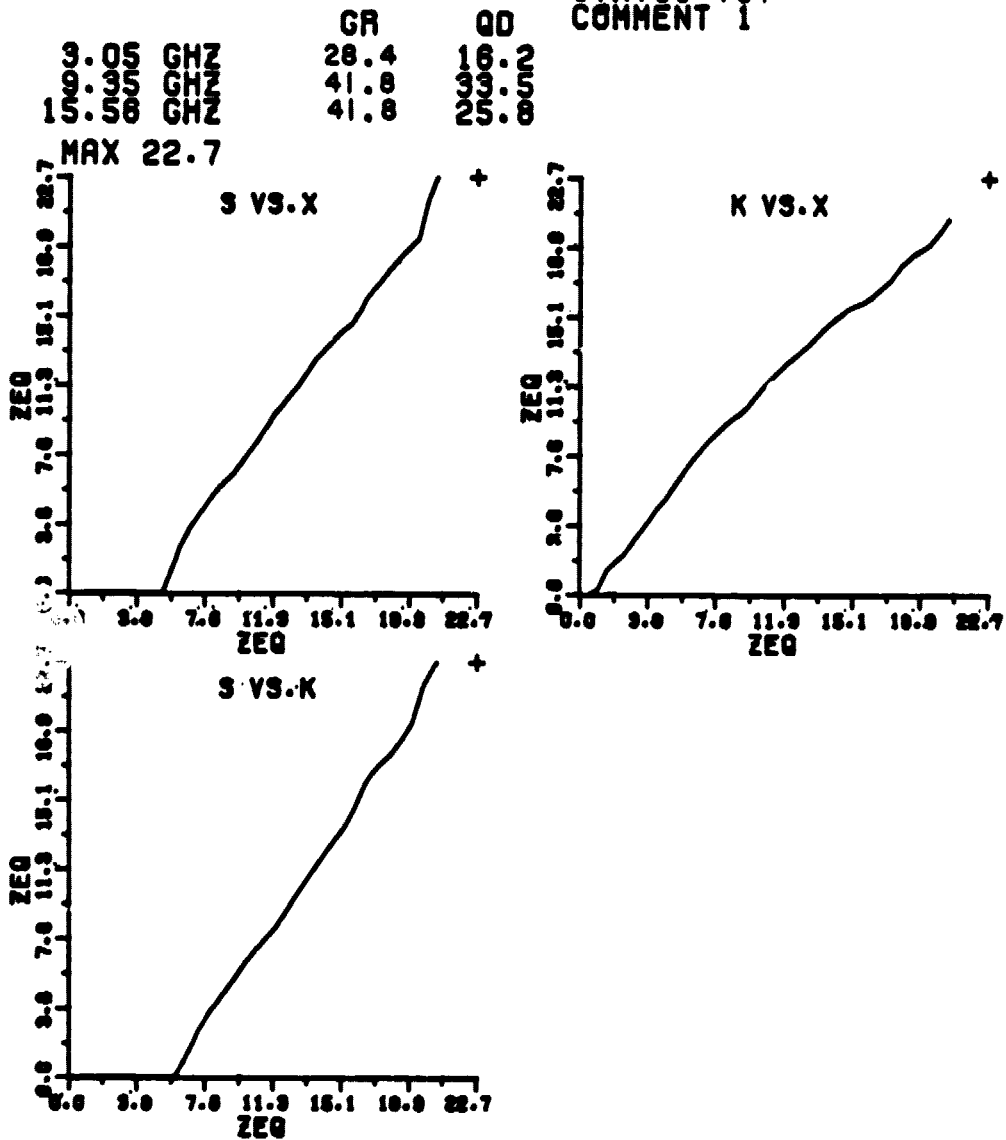


Figure 5. Comparison between the S, X and Ku radars obtained using the regression calibration technique.

### C. Preliminary Calculations

The equivalent reflectivity factor,  $Z_{eq}(\text{mm}^6/\text{m}^3)$ , and specific attenuation,  $\alpha$  (dB/km), were computed as functions of rain rate,  $R(\text{mm/hr})$ , using Mie theory at all three radar frequencies. The Marshall-Palmer drop size distribution and a temperature of  $0^\circ\text{C}$  were assumed for these calculations. A power law relationship representing these values was then developed using logarithmic regression analysis. The results are shown in Figures 6 and 7. This process gave the constants  $a_z$ ,  $b_z$ ,  $a_{RD}$ ,  $b_{RD}$  for all three frequencies. These are given in Table 2.

Table 2

| Frequency<br>(GHz) | $a_z$ | $b_z$ | $a_{RD}$               | $b_{RD}$ |
|--------------------|-------|-------|------------------------|----------|
| 3.05               | 285.4 | 1.453 | $9.6 \times 10^{-4}$   | 0.931    |
| 9.35               | 313.1 | 1.518 | $147.5 \times 10^{-4}$ | 1.070    |
| 15.56              | 326.3 | 1.496 | $457.2 \times 10^{-4}$ | 1.063    |

### D. Obtaining the Radar Constants

Calculations based on available documentation indicated that the gradient, GR, of the analog portion of the Ku band radar receiver up to the A/D converter, as it then stood, was approximately 41.8 dBm/volt. Thus the A parameter for the Ku receiver,  $A_{Ku}$ , was known.

Next, since the Ku radar would be the first to saturate in heavy rain, the value of  $Q'$  was calculated for each record of the edited raw digital data using Equation (12) and its distribution found. The records in which  $Q'$  was highest were then plotted and examined to see if they showed evidence of the Ku returns being completely attenuated by the rain beyond some point, while the S and/or X radar returns still indicated a presence of rain past that point. Unfortunately, this was not found, indicating that none of the events examined had a sufficiently high rain rate or depth to make this happen. Further, the highest value of  $Q'$  calculated in this manner was still some 15 dB below the theoretical value calculated according to Equation (12) using nominal system parameters, confirming the above. It should be noted however that this does not invalidate the idea that had a sufficiently intense storm been recorded, the radar could have been completely calibrated using only the A parameter.

Since this powerful technique for calibrating the Ku band radar was not usable with the available data, more heuristic methods were next considered.

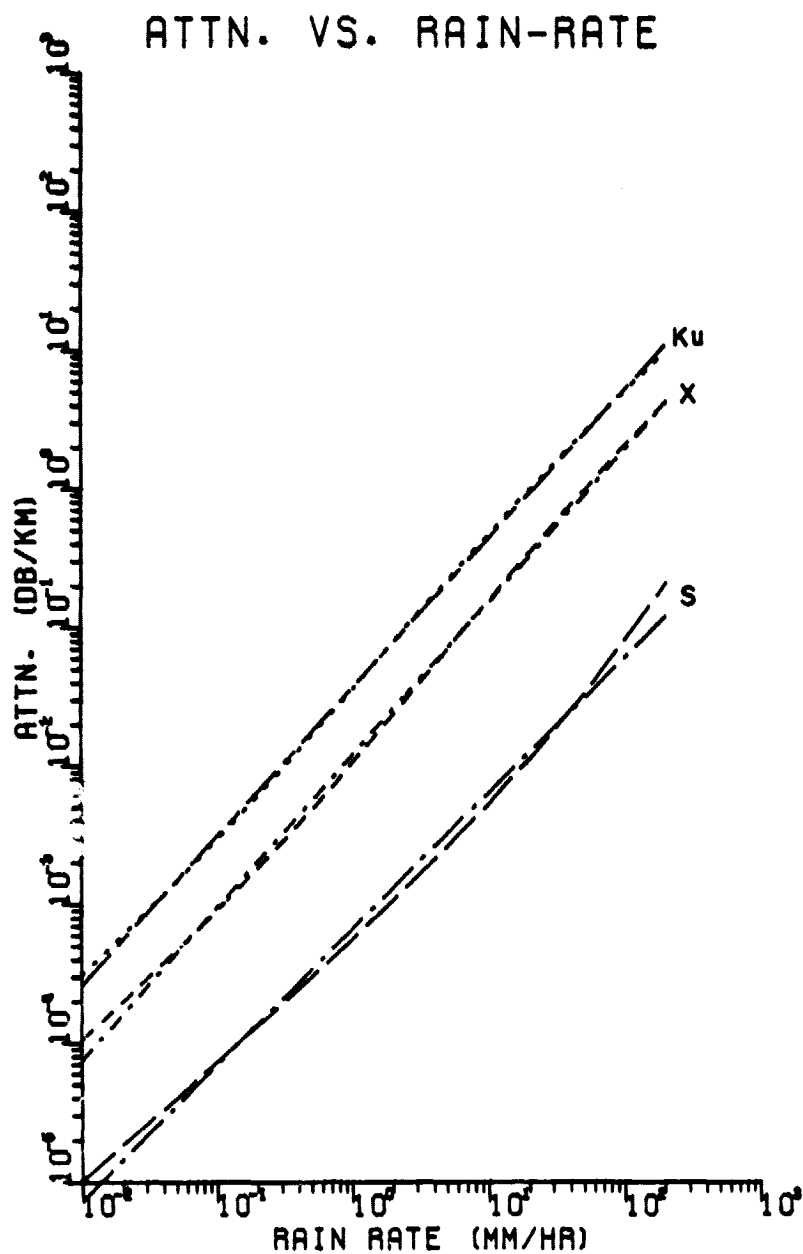


Figure 6. Theoretical attenuation vs. rain rate and the power law approximations at 3.05, 9.35 and 15.56 GHz.

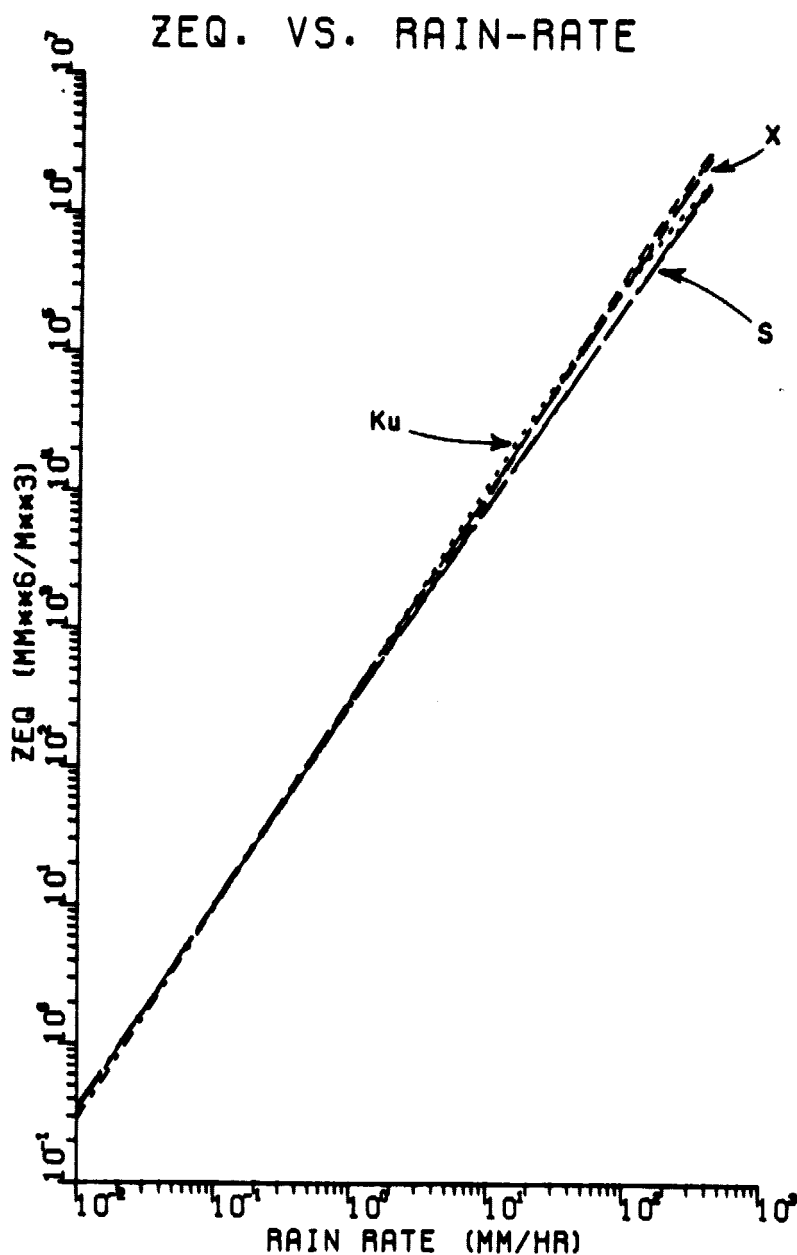


Figure 7. Theoretical  $Z_{eq}$  vs. rain rate and power law approximations at 3.05, 9.35 and 15.56 GHz.

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As a first approximation, the known value of  $A$  and the best available estimate of the  $Q'$  value for the Ku radar, based on calculations using nominal system parameters, were used and the three radars were forced to match consistently using the regression technique described above. It was then found that the  $Q'$  value for the S radar ( $Q'_S$ ) would have to be significantly increased above its theoretical value to match the radars properly. Since this implies the unlikely possibility that major parameters such as the transmitted power or antenna gain were significantly above nominal values,  $Q'_S$  was next fixed at its nominal theoretical value, together with  $A_{Ku}$  and the regression procedure repeated until the radars were again matched. This procedure gave values of  $A_S$ ,  $A_X$ ,  $Q'_X$ ,  $Q'_{Ku}$ . In other events when the S band radar was not working, the Ku radar calibrations were assumed fixed and the X radar matched to this (Figures 4 and 5). This completed the calibration procedure.

## VII. ANALYSIS AND RESULTS

The raw, usable data were converted to the equivalent reflectivity factor,  $Z_{eq}$ (dBZ), using Equations (10) and (11) and the calibration constants described above, and analyzed. Wherever possible, the analysis followed that reported earlier by Konrad [8], so that comparisons could be made. However, since the rain rates in the usable data were much lower than those in [8], the rain cells were classified according to the peak reflectivity into 8 classes in the 5-45 dBZ range in 5 dBZ intervals.

The distributions of both the peak reflectivities ( $Z_{eq}$  peak) and also the reflectivities over the whole cell for all the cells were calculated for all three radars. These are shown in Figures 8 and 9, respectively. Cell width distributions, calculated using fixed reflectivity levels, are shown for the three radars in Figure 10. The distributions differ because neither of the three radar data bases contains the entire data base of the other two radars. The X and Ku radars share the most data, however.

Contours of  $Z_{eq}$  at 3 dB intervals below the peak equivalent reflectivity were also obtained for each cell. The cell widths measured at these contour levels were averaged over each class of cells and are shown in Figures 11, 12 and 13.

The distributions of the reflectivity,  $Z_{eq}$ , and the peak reflectivity,  $Z_{eq}$  peak, both show that the cells analyzed did not exceed the 35-40 dBZ range. The X and Ku radars show very good agreement. The cell width distributions indicate that cells up to 28.5 km wide were observed, though infrequently; the three radars agreeing well even over these sizes when attenuation would be significant.

The plots of relative contours vs. cell width clearly indicate that as the peak reflectivity increases, i.e., at higher rain rates, the dimensions of the cell, at a given reflectivity level below the peak decreases. These average approximately 4 km at -6 dB and 11 km at -20 dB

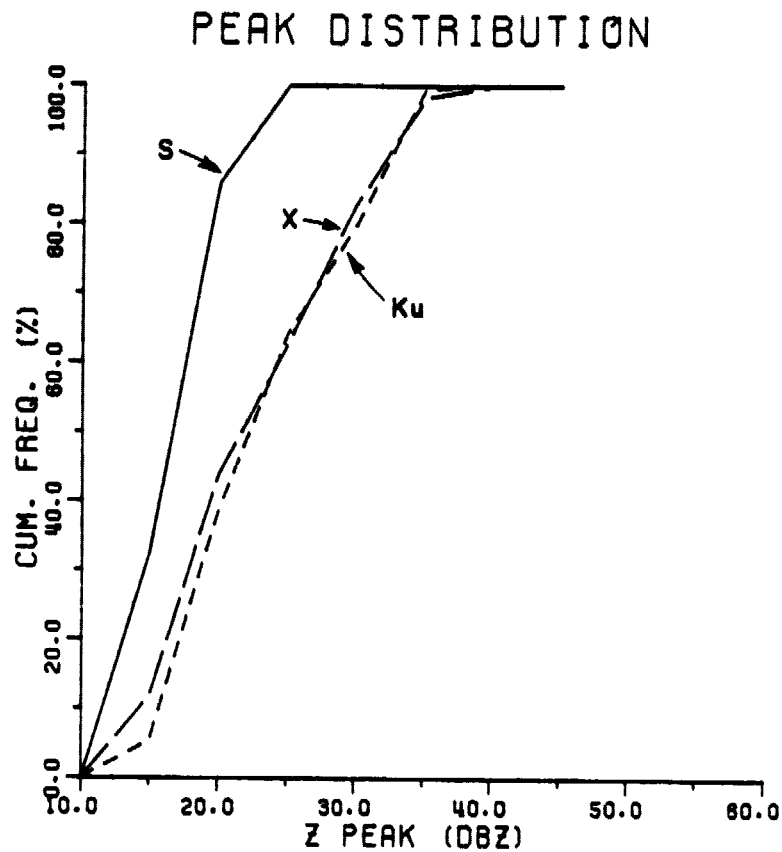


Figure 8. Cumulative frequency distributions of peak equivalent reflectivity factor.

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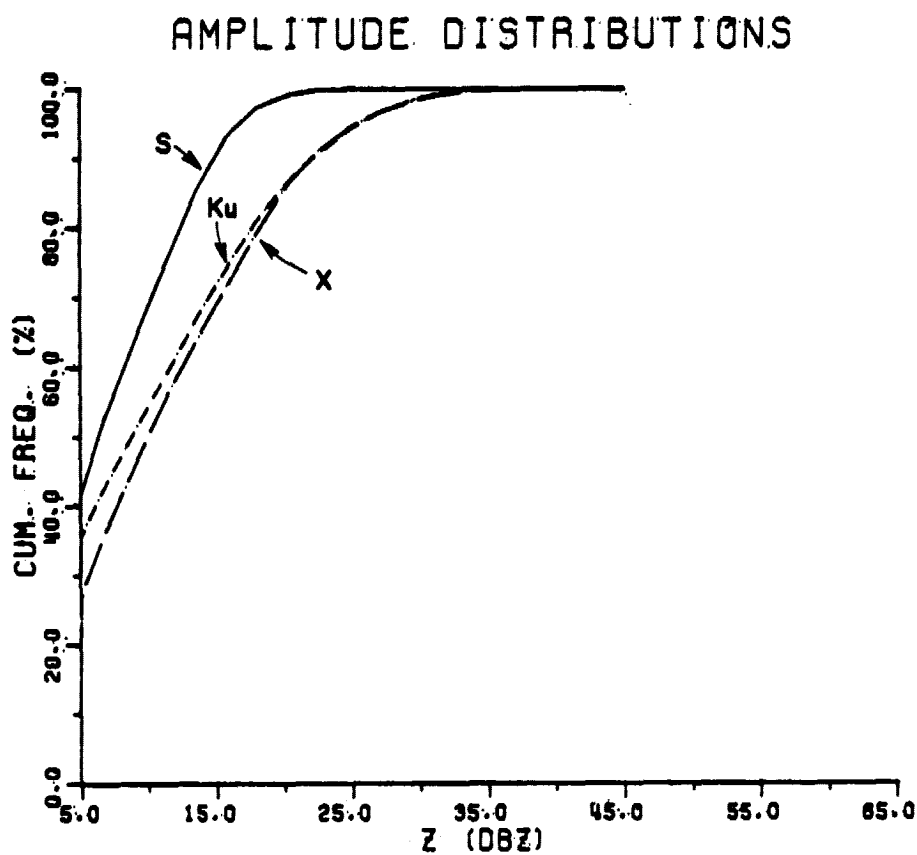


Figure 9. Cumulative frequency distributions of equivalent reflectivity factor.

## CELL WIDTH DISTRIBUTIONS

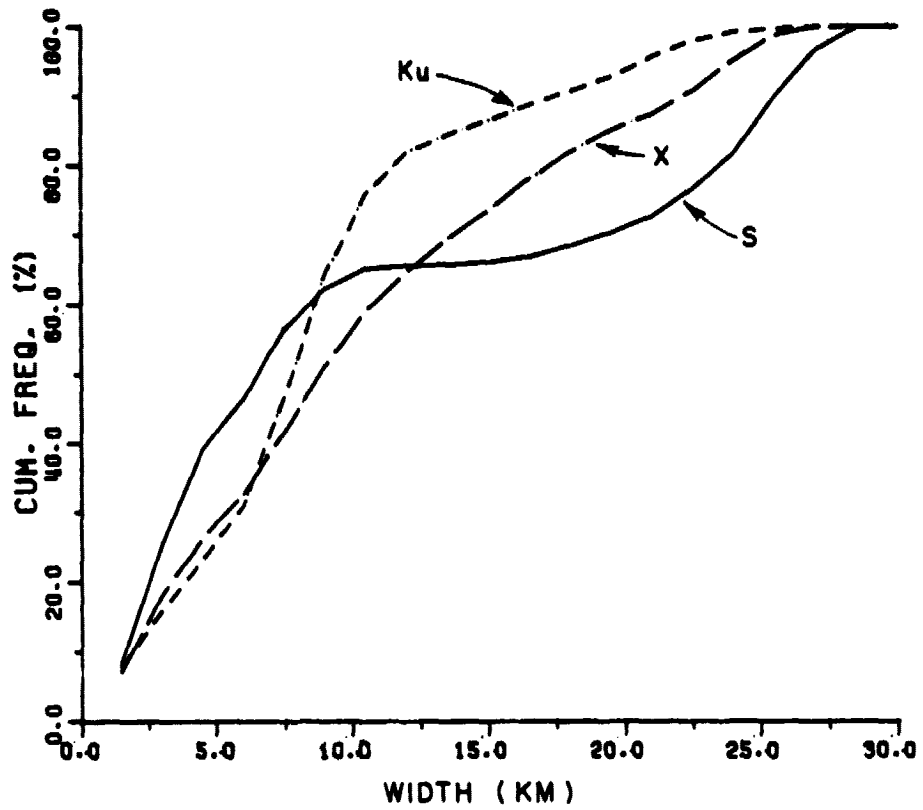


Figure 10. Cell width cumulative frequency distributions.

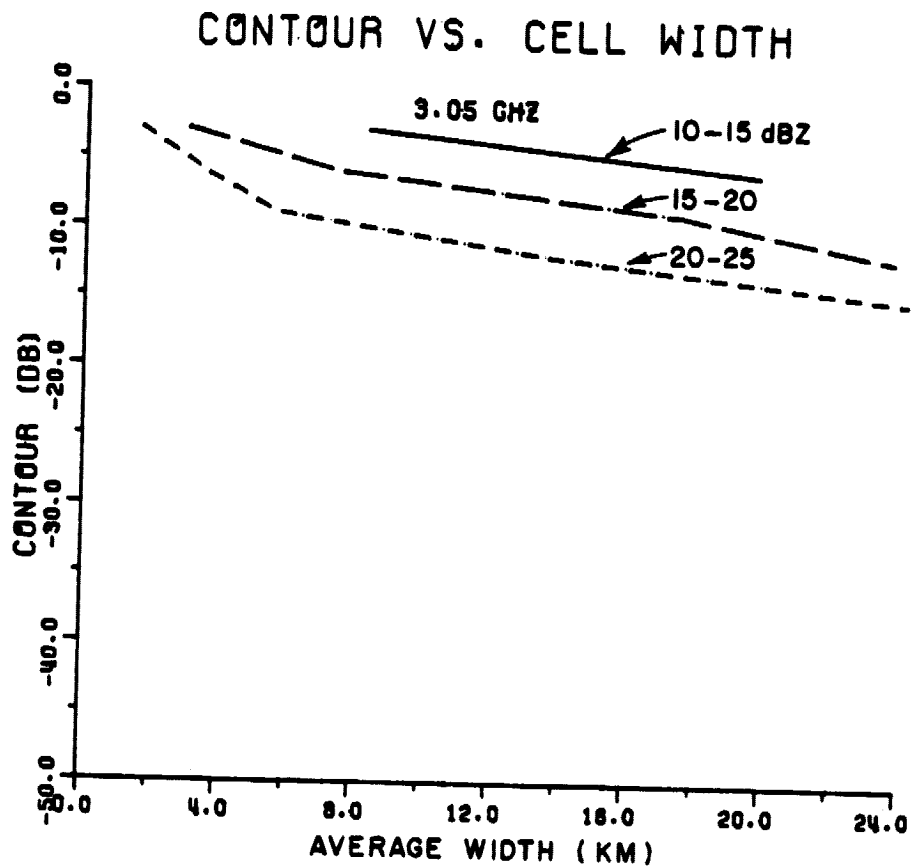


Figure 11. Relative reflectivity contour vs. average cell width at 3.05 GHz for several cell classes.

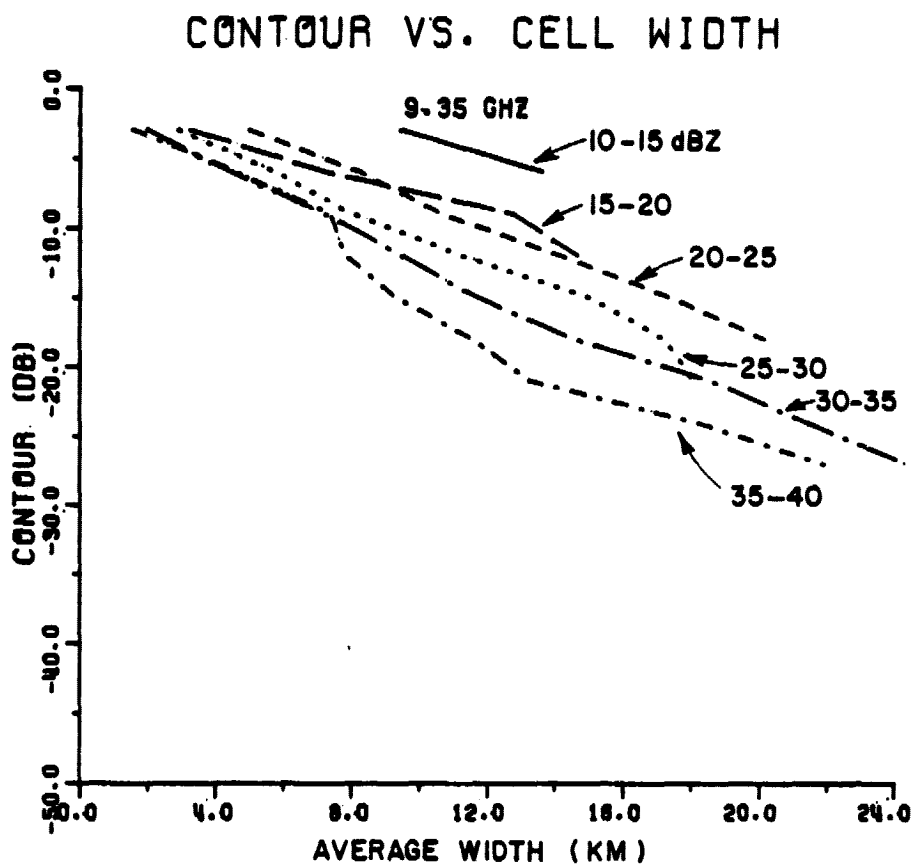


Figure 12. Relative reflectivity contour vs. average cell width at 9.35 GHz for several cell classes.

## CONTOUR VS. CELL WIDTH

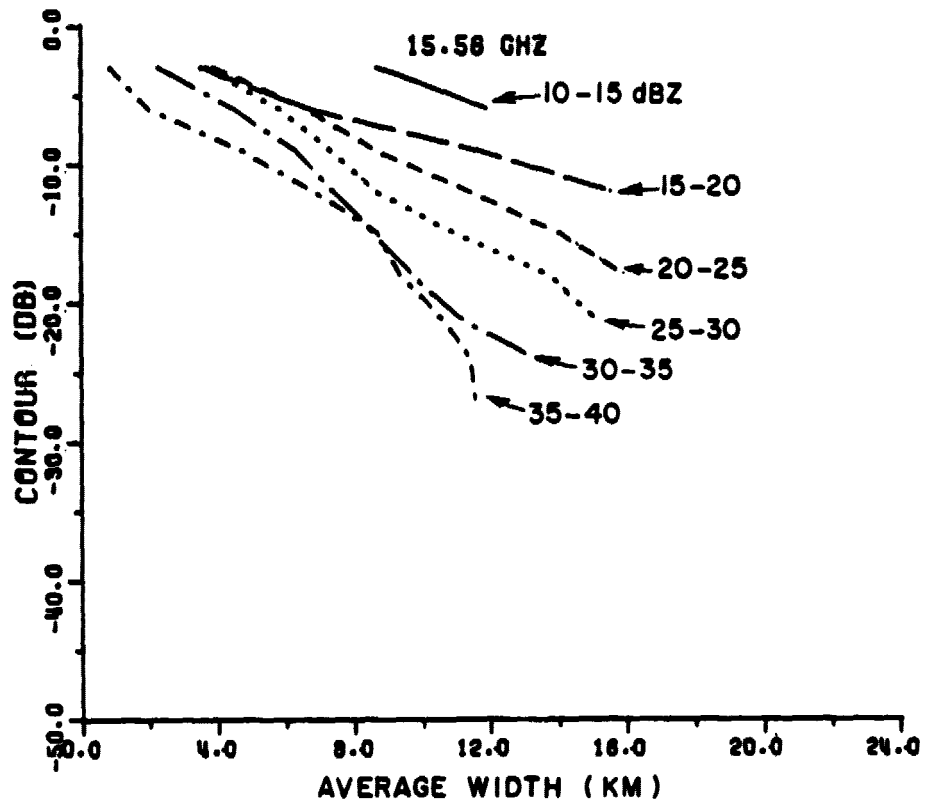


Figure 13. Relative reflectivity contour vs. average cell width at 15.56 GHz for several cell classes.

for the 35-40 dBZ cell class. The differences in the dimensions given by the three radars are again due, mainly, to the different data bases over which these were averaged.

While it is not possible to make direct comparisons with the results reported by Konrad [8] due to the much lower intensities observed and the limited data, the above results are seen to follow, in general, the trends reported by him. Hence, they are consistent with Konrad's results.

In addition to the above, attempts were made to obtain curves of  $Z_{\text{peak}}$  vs. cell width and the average slope for each peak reflectivity interval, among other parameters, as reported by Konrad in [8]. However, due to the limited data base, meaningful results could not be obtained.

### VIII. CONCLUSIONS

Three-frequency radar test data, taken in 1973, were examined. Several methods including the use of the raw radar data were utilized to arrive at reasonable and consistent calibration constants for the three radars. Using these constants, cell width, peak reflectivity and reflectivity distributions and curves of cell widths at various relative-contour levels were obtained. The results are consistent with previously reported work. Cell widths vary from 4 km at 6 dB below peak reflectivity to 11 km at 20 dB below peak reflectivity for the 35-40 dBZ cell category. Overall widths of up to 28.5 km were observed. Though the observed rain rates did not exceed a corresponding equivalent reflectivity factor of 40 dBZ, the agreement between the radars was good over even large cells.

The theory and techniques used follow some new work in this area. The results demonstrate the feasibility of using attenuating frequency radars for rain rate measurements.

## PUBLICATIONS

In addition to the results in this Final Report, other results of the effort under Contract NAS5-23850 were reported in two technical reports. The first of these [6] described techniques for radar calibration using radiometry and the utility of radar saturation as a means of direct, absolute radar calibration. The results of this radar calibration analysis were also accepted for presentation at the National Radio Science Meeting, Boulder, Colorado, January, 1978 [9]. The second technical report [10] presented the results of numerical calculations of specific attenuation,  $\alpha$ , and equivalent reflectivity,  $Z_{eq}$ , for frequencies from 1 to 500 GHz and for rain rates from 1.27 to 152.4 mm/hr. The results of a regression analysis yielding the constants  $a_{RD}$ ,  $b_{RD}$ ,  $a_Z$ , and  $b_Z$  for the power law relationships,  $\alpha = a_{RD} R^{b_{RD}}$  and  $Z_{eq} = a_Z R^{b_Z}$ , were also presented for the same frequency range.

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