On the Use of Ground Return Targets for Radar Reflectivity Factor Calibration Checks[1]

R. E. Rinehart

National Center for Atmospheric Research, Boulder, CO 80307

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ABSTRACT

In order to use radar quantitatively, each component of a radar system must be measured or calibrated correctly. This paper reports the results of investigations into the use of ground return signals for checks on the calibration of the National Hail Research Experiment's 10 cm radar. Individual ground targets provided returns which were found stable to within about 1 dB; they are thus potentially quite good for calibration checks with many radar systems. Unfortunately, changes in the mode of operation of NHRE's radar made use of this potential unrealizable. A statistical approach was developed using numerous ground targets (294 pairs) which showed at the same locations in both 1972, a year for which reflectivity errors were suspected, and 1974, a year when our radar reflectivity factor measurements were correct. This procedure showed that the 1972 radar reflectivity factors were low by 7.7 dB with a standard deviation of 8.7 dB and a standard error of estimate of the mean of 0.5 dB; this difference was statistically significant at better than the 0.01% level.

1. Introduction

The quantitative use of weather radar data requires careful measurement and calibration of the various components of the system. While direct measurement of each parameter is desirable, some, such as antenna gain, can only be determined indirectly (Atlas and Mossop, 1960; Rinehart and Eccles, 1976). Occasionally problems arise in doing a calibration which make the outcome quantitatively uncertain. When this uncertainty occurs, the calibration must be repeated or, if that is impossible, some independent means of checking the calibration must be invoked. The technique presented herein utilizing ground return was developed in an attempt to eliminate the uncertainty which occurred during the 1972 operations of the National Hail Research Experiment (NHRE).

2. Theory

The Probert-Jones (1962) form of the radar equation for meteorological targets used for the National Hail Research Experiment's Grover radar is given in Eq. (1). Any consistent set of units can be used providing a factor is included to account for unit conversion. Those commonly used are given in parentheses after each term.

$$Z_e=\frac{\bar{P}_r\lambda^2r^2 1024\ln 2}{P_tG^2\theta\phi h|K|^2S\pi^3}. \tag{1}$$

Here Z_e is the equivalent radar reflectivity factor (mm^6 m^{-3}), $\bar{P}_r$ the average received power for the target (mW), λ wavelength (cm), r range (km), P_t the peak transmitted power (mW), G antenna gain (gain is dependent on the position of target in the antenna beam), θ and ϕ the horizontal and vertical beamwidths of the radar antenna (degrees), $|K|^2$ is related to the complex index of refraction of the target ($|K|^2=0.93$ for water), S is the term which accounts for the fact that we average the logarithm of the powers rather than the powers themselves ($S=0.564$ for the Grover radar) and h is the pulse length of the radar (m). The values of some of these are constant and are listed in Table 1. The units given in parentheses after each term are those generally used; any convenient but consistent set of units could be used. Probert-Jones assumed that the antenna gain pattern can be approximated by a Gaussian distribution with a center value of G. Eq. (1) can be simplified into a more useful form which shows that the equivalent radar reflectivity factor (henceforth to be referred to simply as "reflectivity factor") is related to a constant (C), the received power and the range, i.e.,

$$Z_e=\bar{P}_rr^2C. \tag{2}$$

The value of C is given in Table 1. As an additional simplification, it is customary to work on a decibel scale such

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that the reflectivity is defined as

$$Z_e(\mathrm{dBZ}) = 10 \log Z_e(\mathrm{mm}^6\ \mathrm{m}^{-3}). \tag{3}$$

The radar equation for the backscattering cross-sectional area σ of a point target is given as

$$\sigma = \frac{P_r r^4 (4\pi)^3}{P_t G(\alpha,\beta)^2 \lambda^2}. \tag{4}$$

Typically, σ is given in square centimeters with all other terms as previously defined. Again, any consistent set of units can be used. Note that Z_e in Eqs. (1) and (2) is proportional to the average received power while σ in Eq. (4) is proportional to the instantaneous received power. A true, stationary-point target, however, would have a steady return so that the power received at any instant would equal that averaged over some time period (provided the antenna beam remained fixed on the target during this measurement time). Here the antenna gain is specifically shown as being a function of the horizontal and vertical angles (α and β) from the radar antenna bore sight to the point target. This will be discussed further shortly. It is also convenient to work with backscattering cross-sectional areas on a logarithmic scale, i.e.,

$$\sigma(\mathrm{dB}\sigma) = 10 \log \sigma(\mathrm{cm}^2). \tag{5}$$

The choice of square centimeters as the units for σ results in having almost all dBσ values being positive.

Since most meteorological radars normally display values of Z_e directly, and usually in dBZ, it is convenient to determine the backscattering cross-sectional area directly from a displayed value of Z_e. Both σ and Z_e are directly proportional to the received power so that, when a backscattering cross-sectional area of a point target is desired, we may simply equate (3) and the logarithmic version of (4) for equal powers and solve for σ in terms of Z_e, i.e.,

$$\sigma(\mathrm{dB}\sigma) = Z_e(\mathrm{dBZ}) + 20 \log r(\mathrm{km}) - 36.4\ \mathrm{dB}. \tag{6}$$

TABLE 1. Grover S-band radar specifications.

Antenna	
Horizontal beamwidth (deg)	0.99
Vertical beamwidth (deg)	0.94
Gain (dB)	44.2
Transmitter	
Frequency (MHz)	2801
Wavelength (cm)	10.7
Peak power (dBm)	88.1
PRF (s^{-1})	937.5
Pulse duration (μs)	0.92
Receiver (logarithmic)	
Minimum detectable signal (dBm)	−108 (1974)
Constant for use in radar equation [Eq. (2)]	
$C[\mathrm{m}^6\ \mathrm{m}^{-3}(\mathrm{mW\ km}^2)^{-1}]$	1.418×10^7

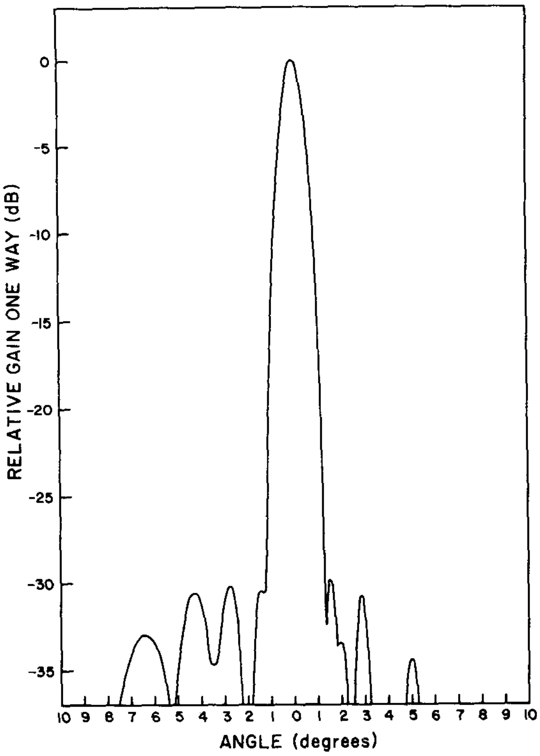

FIG. 1. Antenna gain pattern (horizontal) for the Grover radar.

The constant of −36.4 dB is for the Grover radar and accounts for the various constants in Eqs. (3) and (4) as well as unit conversion to those specified in Eq. (6). Thus, through (6) we can readily convert a displayed Z_e value into a backscattering cross-sectional measurement which is appropriate to a point target.

The power received by the radar from a meteorological beam-filling target is dependent on the pulse length, the antenna gain, and the horizontal and vertical beamwidths of the antenna. Point targets, on the other hand, do not fill the beam, so the beamwidth dependence is not implicitly shown in (4) for point targets. There is, however, a direct relationship between a target's position within the beam and the power received from a point target as can be seen by an examination of Fig. 1 which shows the horizontal antenna beamwidth pattern of the Grover radar. A target located exactly on the center of the axis of the antenna beam pattern will give back the maximum reflected power to the radar. If the target is located off the main axis by a slight amount, the power incident at the target will be reduced and the power reflected from the target and received by the radar will also be reduced; hence, the dependence upon $G(\alpha,\beta)^2$ in (4) where the gain achieved is a function of the target's position (α and β) in the antenna beam. The beamwidth pattern of Fig. 1 is typical of most meteorological radars in that there is a strong main lobe which typically contains about 99% of the transmitted power and several lobes of much reduced sensitivity on either side of the

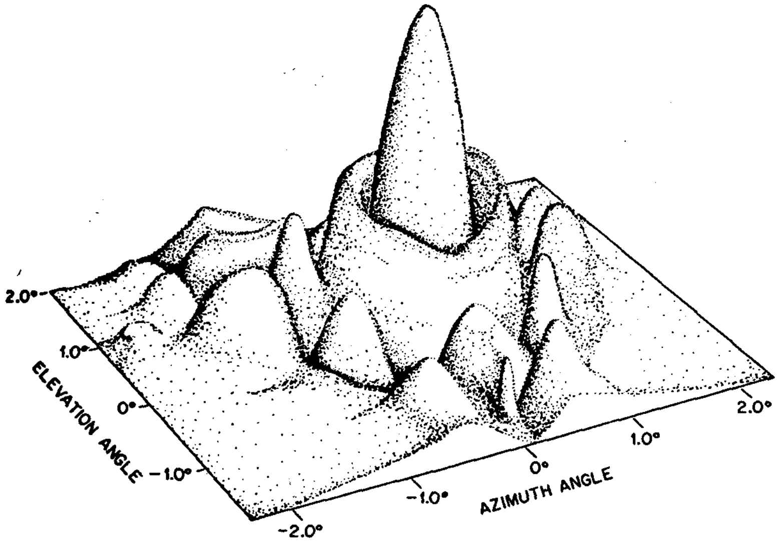

FIG. 2. Three-dimensional pencil-beam pattern of the AN/FPQ-6 radar antenna. (Courtesy of D. D. Howard, Naval Research Laboratory.)

main lobe. It is important to note, however, that the beam pattern is three-dimensional in shape so that Fig. 1 represents only one slice through it in the horizontal (azimuthal) direction. Fig. 2, for an AN/FPQ-6 radar antenna, illustrates the fact that an antenna beam pattern is not circularly symmetric but contains irregularities which complicate interpreting the return from targets located off the axis of the beam. For meterological use, the power received by the side lobes is generally much less than that received by the main lobe such that the side-lobe return is of little consequence. There are occasions, however, in both storm detection and point target detection, when the side lobes contribute a significant portion of the returned power and hence provide misleading information if not used carefully. For beam-filling targets, the side lobes usually do not prevent a significant problem for intensity measurements because the vast majority of the received power is coming from the main lobe of the antenna. For point targets, on the other hand, the only return received is that from the point target so its location in the antenna beam (both relative to the beam axis and in range) is critical and exclusively determines the received power that a given radar will detect. As an antenna scans across a point target, the power received by the radar depends upon the antenna beam pattern. For a given target of known backsacttering cross section, the angular departure from the main axis can often be determined by simply plotting the received power from the target against angle. When both meteorological and ground return exist near the same location, the power received by the radar is the sum of the powers from each. This makes it difficult to make reliable quantitative measurements from either one. Fortunately, most meteorological observations are made at ranges where ground return is not a problem or with higher elevation angles so that an evern greater reduction of echo detected by side lobes is possible.

3. Specific point target study

Point targets have been used in antenna gain measurements, as already mentioned, through use of the sphere and nodding dihedral. Since the nodding dihedral target was installed late in the 1974 field season, it could not be used to check 1972 calibrations. However, other targets, such as radio towers, were present throughout 1972 and later so that use of these was investigated.

An examination of the power received from the KYCU tower, located at 115.6° azimuth and 15.79 km range, was thus undertaken. Since data are normally collected by scanning at constant elevation, the relative return from the KYCU tower at different azimuths could be measured fairly easily without introducing any variation because of changes in elevation.

When the maximum power returned from the KYCU tower was initially determined, the results were quite variable. Fig. 3 shows the frequency distribution of maximum dBσ returns from the KYCU tower for many scans on one day in 1976. The spread of values of nearly 30 dB suggests that perhaps the KYCU tower is, in fact, not very useful as a secondary standard. However, with Fig. 1 in mind, the exact azimuths recorded for each σ maximum value were plotted against σ maximum, resulting in Fig. 4. Here we see a pattern similar to the antenna beamwidth pattern and find that the spread in σ's near the peak of the curve has been reduced to only about 4 dB. This scatter can be further reduced by taking two other factors into account.

The Grover radar has had three different data processors. Typically, 64 separate transmitted pulses were averaged together at 200 separate range gates for the Data Acquisition and Display System (DADS) processor, used since 1974, at 100 range gates for the Multiplexed Input NHRE Averager, version I (MINA I), used from 1972 to 1974 and at 1020 range gates for MINA II, used since 1975 (Eccles, 1975). This averaging was done while the antenna rotated and took a certain amount of time to complete the averaging process. Since the averaging times were in no way synchronized with the antenna position, the start time of an individual averaging sequence was essentially random relative to the azimuth of the antenna. As the antenna scanned past a point target, for example, the averaging could begin at different points relative to the point target, and this contributed to the distribution of points shown in Fig. 4.

Additionally, if we take into account the fact that the antenna at some times scanned faster than at other times, the effective dwell time that the antenna spent looking at a given point target is different. Thus, we should expect that the faster an antenna scanned across a point target, given that it always recorded 64 samples of information spaced equally in time, then the lower the average received power we should get from that target. Conversely, slowing the antenna should increase the average return that we get. Fig. 5, then, is a plot of the maximum backscattering cross section detected for the KYCU tower as a function of the rate at which the antenna scanned across the target, all for an azimuth of 115.6°. While this figure does show some scatter in its return, there is a clear trend for higher returns from slower scan rates. Notice now that we have reduced the scatter about the line to a maximum of 1.1 dB with an average of 0.4 dB.

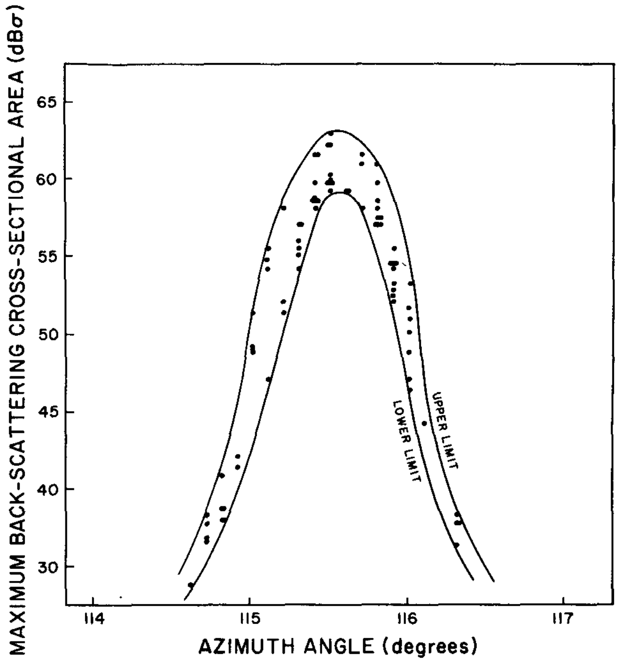

FIG. 4. Maximum backscattering cross-sectional areas of the KYCU radio tower on 2 July 1976 as a function of antenna azimuth angle.

To be useful as a secondary standard, the return from a point target must be stable with time. During the 1976 field season, we made daily receiver sensitivity calibrations for converting returned power into radar reflectiv-

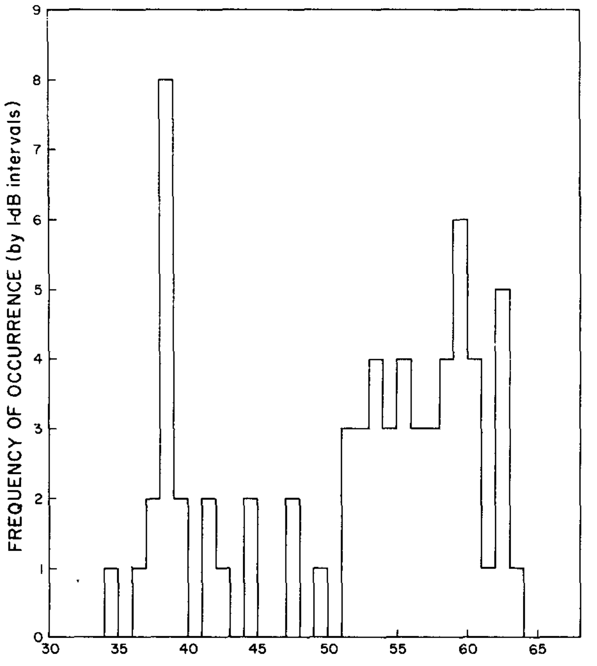

FIG. 3. Frequency distribution of maximum backscattering cross-sectional areas of the KYCU radio tower on 2 July 1976.

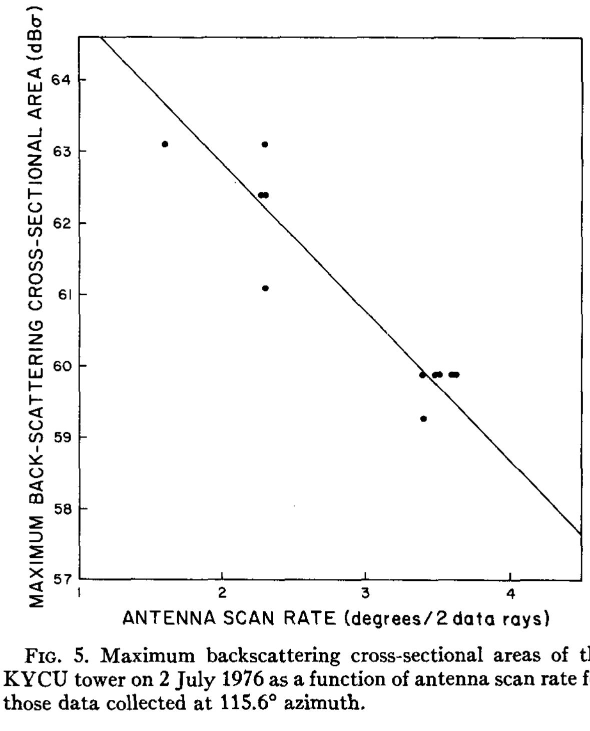

FIG. 5. Maximum backscattering cross-sectional areas of the KYCU tower on 2 July 1976 as a function of antenna scan rate for those data collected at 115.6° azimuth.

TABLE 2. Maximum backscattering cross-sectional area of the KYCU radio tower on three days in 1976 and the difference from the average.

Date	σ (dBσ)	Difference (dB)
7 June	62.7	+0.5
2 July	63.1	±0.1
30 July	64.0	−0.8
Average	63.2	

ity factor. We were able to determine that the receiver and the radar system generally varied by no more than a few tenths of a decibel from day to day. Additionally, on those days when there was perhaps a somewhat larger change, the calibration for that day effectively eliminated any quantitative problems this might have introduced. Thus, we are able to compare Z_e's or returned powers measured on different days and be reasonably confident that any differences which might exist are due to differences in the target and not in the radar system itself.

To examine the stability of the KYCU backscattering cross-sectional area, we looked at the peak value received from it on 7 June, 2 July and 30 July 1976. The decision to use only the peak value returned for a given day is dictated by the evidence in Figs. 3, 4 and 5 which suggest that the most useful return is that which occurs when the antenna beam is scanning past the target as slowly as possible, with the target being sampled as close to the beam axis as possible. Anything less than the maximum value indicates that the antenna was slightly off axis when the measurement was made or was scanning at a faster speed than at some other time. The data used were collected during routine operations, however, with the antenna scanning in a sector scan mode. The maximum values found were obtained by examining PPI's whose areas were specified such that the KYCU tower was the only target included. Hence, the maximum reflectivities found on each PPI represented that of the KYCU tower. Data from a number of scans were then examined and the maximum value of all of these selected as being the best measure of the target. While this procedure is not as good as actually stopping on the tower to make the measurements, it should give comparable results because operations generally used similar antenna scan rates. Table 2 shows the results of these three days. Here we see that the variation from one day to another was from 0.1 to 0.8 dB. While this is not as good as using a proper signal generator in running a calibration in the normal sense, the possibility of determining reflectivities to an accuracy of about 1 dB by use of a secondary standard such as a radio tower could still be quite valuable. In the case of the 1972 reflectivity question, the possibility existed that the error was on the order of 5 dB or more, so that being able to determine the error to within a couple of dB would still be very useful. Note, however, that it is mandatory at some stage to do an accurate calibration; otherwise the results can only be compared in a relative sense and not absolutely.

Having determined that the KYCU tower gave a good stable return for the 1976 field season, we compared the results of 1976 with those of 1974 when we knew that our reflectivity calibrations were done well. There was good agreement between the results of the two years when data from the DADS processor were used. Unfortunately, in 1974 the MINA I system was different than MINA II used in 1976 and the KYCU target was between its range gates. The MINA I range gates were separated at intervals of 1 km in 1974. However, point targets located within about half a pulse length of the range gate will still show up at the range gate at nearly the correct return. Differences in return by the target not being centered on the range gate are caused by the shape and length of the transmitter pulse. Fig. 6 shows the pulse returned from the nodding dihedral target used as the standard target for calibration purposes in the NHRE program. The echo within 1.5 μs is from nearby ground return. As can be seen, the pulse is not a perfect square wave; thus, a target sampled by a range gate on the leading or trailing edge of the returned pulse will be detected, but with a power lower than if the target were sampled at the peak. This discrete-sampling procedure used in the NHRE digital processors and other digital radar processors currently being used on meteorological radars effectively limits the information to a narrow band on either side of the range gates with no data between range gates unless they are spaced closer together than about half a pulse length.

When we looked for the KYCU tower return in 1974 data, we discovered that the KYCU tower was located between range gates and completely invisible to the radar porcessing system. Thus, an effort was made to find some other target or targets which would show in 1974 and in 1972. A group of radio towers near the town of Pine Bluffs, Nebraska, were examined and initially thought to show approximately equally well in both

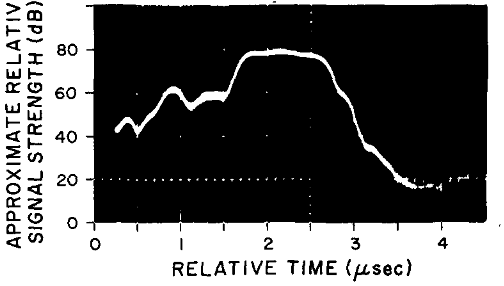

FIG. 6. The shape of Grover radar's transmitted pulse as seen from the nodding dihedral return (located at 124.34° azimuth and 14.86 km range). The dihedral's echo starts at 1.5 μs relative time; the echo within 1.5 μs is from other ground targets.

1974 and 1972. Fig. 7a shows the ground return targets as detected by the MINA I processor early in the day on 17 May 1974. Data from this day showed something which proved that the individual ground return approach would not work for the Grover radar. Fig. 7b shows the same return later in the day on 17 May 1974. Notice that some targets have changed in intensity, new ones have appeared and still other targets completely disappeared. These two patterns were stable for some time and the change from one pattern to the other was abrupt rather than gradual. The cause of this must have been a change of a fraction of a microsecond in the radar system timing. Fig. 7c shows the ground return as detected in 1976 by MINA II which has 1020 range gates. The range gates on MINA II are essentially one pulse length apart or slightly less, thereby ensuring that any point target which exists in the antenna beam must show up providing it is strong enough to be above the receiver noise level. A comparison of Figs. 7a and 7b with Fig. 7c shows that from the first period to the second period on 17 May the system timing must have introduced a slight delay such that the range gates were sampling farther from the radar than they were before. A comparison of 1972 data with 1974 data indicated a similar problem in that some targets which showed well in one year showed poorly in another and vice versa.

The conclusion based on looking at specific point targets, then, is that they can be used as secondary standards for system calibration checks providing 1) the system timing and range gate spacing in the case of using discrete range gate sampling techniques remain identically the same from one period to another, and 2) that the radar remains in the same location during this period. Mobile radars, for example, could use specific point targets to make day-to-day calibration checks but this use from one year to another would depend on the extent to which the radar was returned to identically the same position. The slight day-to-day variations and year-to-year variations which existed in the NHRE radar system, while totally trivial for meteorological purposes, were devastating in terms of comparing individual point targets for their return from one time to another. Data recording systems, such as analog tape recorders or even scope photographs which show every point target regardless of its position in range, could profit from using a study of the return from an individual target as a means of comparing power returned from one day to another or one year to another.

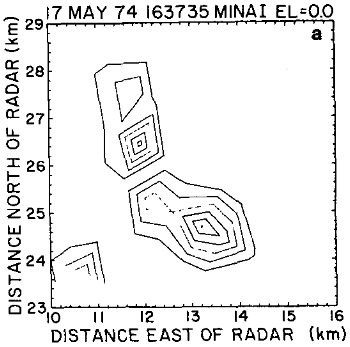

FIG. 7a. Ground return targets near Pine Bluffs, NE, at 1637:35 MDT on 17 May 1974, using MINA I data.

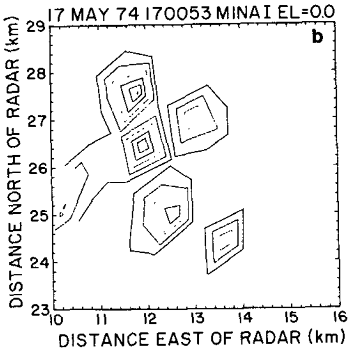

FIG. 7b. As in Fig. 7a but at 1700:53 MDT.

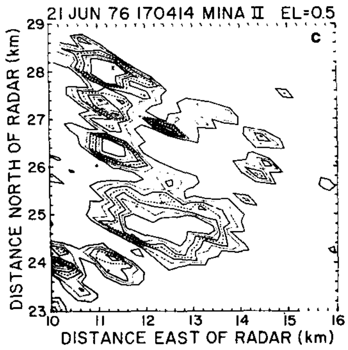

FIG. 7c. Area as in Figs. 7a and 7b but using MINA II data for 21 June 1976. MINA I has 100 range gates spaced at 1 km intervals, while MINA II has 1020 gates spaced at 0.15 km intervals.

4. Statistical point target study

The above study indicated that specific point targets are quite reliable, given the right radar operating conditions. Slight changes in radar system timing and/or range gate spacing should increase the power returned from some ground targets while reducing that returned from other ground targets. Given a sufficient number of targets in the radar field of view, the increases should approximately balance the decreases and, if they are spaced randomly in the field of view, the difference of all of these targets should approach the difference between the two years.

Year-to-year changes in the recording mode of the MINA I processor on the Grover radar introduced some problems at this point. One of these involved the angles recorded. In 1972 azimuths and elevations were recorded to the nearest whole degree, while in 1973 and throughout 1974 angles were recorded to the nearest 0.352° (i.e., 360°/1024). Thus, to make the two data sets compatible, the 1974 azimuths were rounded to the nearest whole degree. The elevation data were made

TABLE 3. Total points found and hours of data examined.

Date	Number of data points found	Time used (h:min:s)	Total number of merged points for year
22 June 1972	520	5:46:49	
23 June 1972	734	4:31:50	
27 June 1972	211	4:13:30	
1972 totals	1465	14:32:09	909
4 June 1974	1835	5:51:48	
16 June 1974	1378	5:41:22	
4 August 1974	1050	4:10:41	
1974 totals	4623	15:44:17	2786
Grand totals	5728	30:16:26	Number of pairs found 294

compatible by requiring that the target exist below 1°. The second difference between 1972 and 1974 was the range gate spacing. In 1972 the radar used a 0.75 km range gate spacing while in 1974 a 1 km range gate spacing was used. To make data compatible between years in range, all 1972 range data were rounded to the nearest whole kilometer with those exactly between whole kilometers totally ignored.

A statistical approach to the problem involving many point targets required an objective means of selecting suitable targets. Thus, selection criteria for range, azimuth, elevation, target signal characteristics and target reliability were devised. This study used targets between 5 and 55 km in range, at all azimuths, but only those which showed at elevations below 1°. A point target was required to have a range-gate-to-range-gate gradient of returned power of ~20 dB per gate upward immediately followed by a 20 dB per gate downward gradient. This two-sided gradient requirement effectively eliminates meteorological targets which, while they may have a strong gradient exceeding 20 dB per gate on one side (Mueller, 1977), have such a long extent that the double-gradient requirement would not be met. It does not, however, eliminate some topographic features such as hills which are radially smaller than the 1 km spacing between range gates. Henceforth, targets which meet the two-sided radial gradient requirement are referred to as point targets even though some of them may actually have a radial extent up to a kilometer or so.

One problem remains in selecting targets for day-to-day and year-to-year comparisons. This is to determine criteria for matching the azimuths of targets. The definition of a point target which was used for the selection in range (i.e., the two-sided ~20 dB gradient) could be generalized to include an azimuthal two-sided gradient requirement. This azimuth requirement would need to account for both the effects of beamwidth (Figs. 1 and 4) and data ray spacing (Fig. 5). There are two reasons that this was not deemed necessary. First, Fig. 4 shows that data collected to the sides of the azimuth of peak return are quite reproducible, especially in light of the refinement obtainable using the rate of scan information in Fig. 5. In the absence of calibration errors, data collected from numerous point targets exhibiting the azimuthal characteristics shown in Fig. 4 from one day to another should show zero difference in returned power on the average. Acceptance of data long both sides (azimuthally) of a target should increase the number of available data points for comparison by a factor of 3–5. The second reason is that the use of such an azimuthal requirement would have the effect of eliminating valid targets if azimuth alignment differences existed from one year to the other. Azimuth differences were likely less than 1° and may have been near zero, however, so this possibility was cause for little concern. Thus, to avoid the complexities of formulating and implementing a satisfactory azimuth selection criteria and the potential censoring effects it might impose, we accepted any points that occurred at the same azimuths and ranges as valid data points.

The radar data were then examined for all point targets meeting the aforementioned requirements. The backscattering cross section for each such point was calculated and stored for its azimuth and range location. Each time a point target's σ was calculated, it was compared with any previously determined value of σ for the same location. In all cases only the strongest value was retained. The rationale for keeping only the peak values of σ came from the specific point target study which showed that unless the antenna was at the right azi-

TABLE 4. Statistics from day-to-day and year-to-year comparisons.

Parameter	6/23/72 with 6/22/72	6/22/72 with 6/27/72	6/23/72 with 7/27/72	6/04/74 with 6/16/74	6/16/74 with 8/04/74	6/04/74 with 8/04/74	1972 with 1974
Number of pairs found	200	34	34	403	262	399	294
$\bar{\sigma}_1$	54.0	55.0	55.7	55.1	53.9	52.8	52.6
$\bar{\sigma}_2$	55.7	55.6	58.3	53.3	56.3	54.0	60.3
$\overline{\Delta\sigma}$ $(\bar{\sigma}_2 - \bar{\sigma}_1)$	1.7	0.6	2.6	−1.8	2.4	1.2	7.7
S_{σ_1}	8.6	6.7	6.5	11.0	9.7	10.3	8.8
S_{σ_2}	9.0	7.5	8.6	11.2	10.4	10.6	9.7
r	0.86	0.63	0.67	0.53	0.56	0.76	0.56

muth and elevation and scanning relatively slowly, the power returned to the radar would not be as strong as possible. A count was maintained at each location of the total number of times a point target met all requirements; this gave a measure of the reliability of each target.

5. Results

On any given day a large number of data points were found to meet the double-gradient requirement. Table 3 lists the number of points found and the length of time for the data for the days of 1972 and 1974 used in this study. These days were selected because they generally had meteorological targets only at ranges beyond 55 km. This avoids the possible variation that would be introduced if targets were measured wet one day and dry another. On 22 June 1972, for example, a total of 520 data points were found with a fairly large number of these showing many times. However, some point targets showed only once or twice and were likely caused by insects, birds, aircraft or, on one day, the calibration pulse. These were all eliminated as "true" ground targets by requiring at least three observations of the same target on each day before a target was accepted.

Data from two days were compared using the selection criteria. The backscattering cross section for each target and the average difference among all targets on that particular pair of days were determined. Three pairs of days in 1972 and three in 1974 were used. Table 4 shows the results of these comparisons. The day-to-day variation within both 1972 and 1972 is on the order of 1–3 dB with an average of 1.7 dB (and a standard deviation of 0.7 dB).

Before making a final comparison between 1972 and 1974, we had to merge the point targets from the indi-

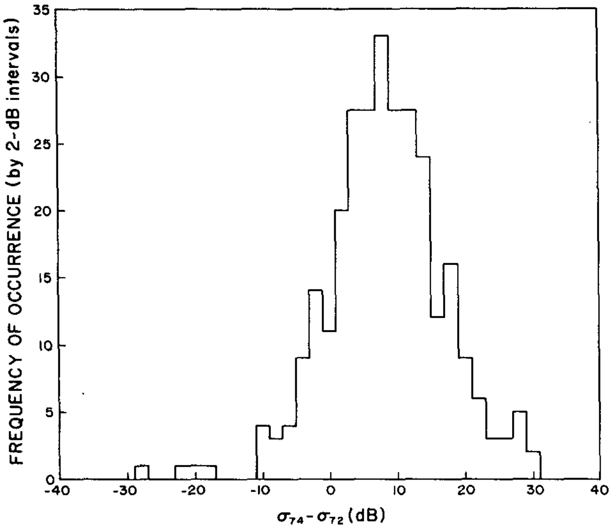

Fig. 8. Frequency distribution of the differences in 1974 and 1972 backscattering cross-sectional areas for the 294 pairs of targets found.

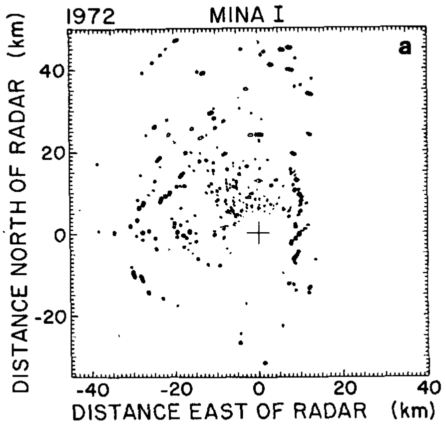

Fig. 9a. A PPI plot of the 1645 data points found for 1972 which met the $\sim$20 dB two-sided gradient and count $\geqslant 3$ requirements. Adjacent data points are contoured as single targets but with larger azimuth and/or range extent. Contours are 30, 50 and 70 dBσ.

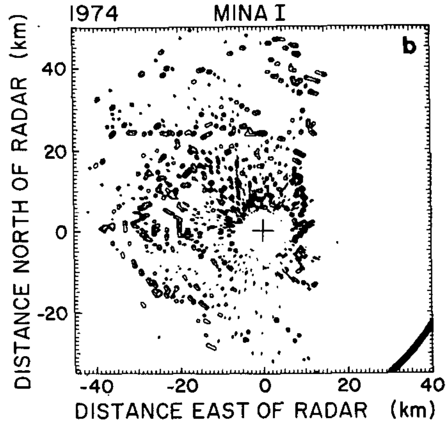

Fig. 9b. As in Fig. 9a but for the 4263 data points found in 1974. The irregular north–south line of targets about 10 km east of the radar is the Pawnee Buttes. The east–west line of targets 25 km north of the radar in the northwest quadrant is a high voltage power line which runs east from Cheyenne, WY, into Nebraska.

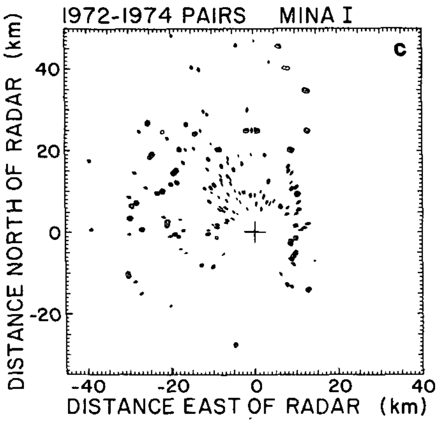

Fig. 9c. The location of the 294 pairs of data points found at the same location three or more times in both 1972 and 1974. The magnitude of the values plotted is that for 1974 with contours of 30, 50 and 70 dBσ.

vidual days within 1972 and within 1974. To do this, we determined the maximum σ value at each azimuth-range location and the total count of all times on any of the three days that a target showed up at each location. Thus, the resultant, merged data set for 1972 included only the maximum values at each point along with the total number of times that point was hit; similarly for 1974. The merged 1972 data set had 909 point targets out of a total of 1465 data points from the three individual days while 1974 had 2786 data points out of a total of 4263 from its three individual days (see the last column of Table 3).

The final comparison, then, was to determine the average difference between the backscattering cross sections in 1972 and those in 1974 for all locations which had targets in both years. The 909 points from 1972 and the 2786 points from 1974 combined to give 294 pairs of data points which existed at the same location in both years three or more times. The average difference between 1972 and 1974 was 7.7 dB with a standard deviation of 8.7 dB and a standard error of estimate of the mean of 0.5 dB. This difference was statistically significant at better than the 0.01% level. The standard error of estimate of the mean determined from the distribution of $\Delta\sigma$ values might be questioned when we recall from the previous discussion that the day-to-day fluctuations averaged 1.7 dB. Thus, we should recognize that the error bars on the 7.7 dB difference may be larger than ±0.5 dB. Fig. 8 shows the frequency distribution of $\Delta\sigma$ values for these 294 pairs of values. The distribution is a good approximation to a normal distribution.

Figs. 9a–9c show the data points in PPI format which resulted from the statistical point target study for 1972, 1974, and the common points found between 1972 and 1974, respectively. The contour interval is 20 dB starting from 30 dBσ. All targets shown in Fig. 9 are only one range gate long but approximately half of them are more than 1° wide in azimuth. The strongest target had a backscattering cross section of 82.7 dBσ with the smallest which survived the various selection criteria having a cross section of 34.0 dBσ. An examination of various targets in Fig. 9 showed that many are likely hills and other topographic features such as the Pawnee Buttes running north–south and located east of the radar about 10 km. These buttes, for example, contributed 24 or more points to the final set of 294 data points.

6. Conclusions

The calibration problems experienced by the National Hail Research Experiment with its Grover radar data are perhaps unique in cause but general in the sense that many radar installations undergo problems which produce quantitative errors of unknown magnitudes. The results of the two studies presented herein show that individual ground targets can be useful as secondary calibration standard targets when used in the mode outlined in the first part of this paper. Data recording systems which record in an analog form such as video tape recorders, analog recorders or PPI scope photographs can potentially utilize existing data to determine stability of the radar system from one year to another or from one day to another. For radar systems which sample only at discrete points, the statistical approach outlined in the section portion of this paper provides an alternate means of determining the relative calibration difference from day to day and from year to year.

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