551.501.777: 551.508.85

NEW ZEALAND METEOROLOGICAL SERVICE

TECHNICAL NOTE 211

USE OF THE COSSOR CR353 RADAR FOR REMOTE ESTIMATION OF RAINFALL RATES

A.P. Ryan

Issued for limited distribution by:

The Director
New Zealand Meteorological Service
P.O. Box 722
Wellington.

12 July, 1972

NEW ZEALAND METEOROLOGICAL SERVICE

USE OF THE COSSOR CR353 RADAR FOR REMOTE ESTIMATION OF RAINFALL RATES

A.P. Ryan

Abstract

Radar estimates of rainfall in the test area (about 12 n.m. southeast of Ohakea) were made using a stepped attenuation technique to contour the echoes. These estimates were compared with rainfall determined from a network of recording raingauges in the test area. The equivalent rainfall rates were obtained both using a standard Z-R relation for Ohakea, and using a Z-R relation from concurrent drop samples. The latter gave better agreement with rainfall found from gauge measurements. Use of the first 30 minutes of rainfall at a centrally located gauge to obtain a correction factor for the radar, gave a further improvement both for point falls and areal falls. The radar reproduced isohyetal patterns well, but estimates were too high. This is due to contouring on a 'mean peak' signal. The standard error of the radar estimates using the standard Z-R relation is +60%, -37% of the rainfall rate determined from the gauge network. Factors contributing to the errors are discussed.

Introduction

Many workers (e.g. Chernikov and Kessler, 1965; Harrold, 1965) have shown that radar can give useful estimates of areal rainfall. Such estimates can be comparable with those found from a raingauge network denser than that available for normal climatological use (Huff, 1966). In applications such as flood forecasting, where real time estimates are not available by conventional means, radar has an important potential.

The present work is part of a study, the aim of which is to assess the potential of the Cossor CR353 Meteorological Radar for rainfall estimation under New Zealand conditions. Development of an operational system can be considered under the following headings:

(1) Calibration of equipment and standardization of performance.

(2) Determination of the relation of radar reflectivity to rate of rainfall.

(3) Trials to compare radar estimates with raingauge measurements.

(4) Development of operational techniques.

This paper is mainly concerned with stage (3). The tests made were performed under optimum conditions and further development would be required to implement stage (4). Stage 1 has been investigated for the CR353 (Ryan 1969) and is summarized briefly in the next section.

Calibration

The average reflected power from a precipitation target received at the radar can be expressed as

$$\bar{P}_r = CZ/r^2 \quad . \quad . \quad . \quad . \qquad (1)$$

Where $\bar{P}_r$ is the average power received at the radar from the distributed target of spherical scattering particles filling the beam.

Z is the radar reflectivity, defined by $Z = \sum D^6$, where D is particle diameter and the summation is over unit volume. It is normally expressed in mm^6/m^3

r is the target range
C is a constant

combining equipment parameters and refractive index term.

The constant C can be found by calibration of the radar using a standard target of known reflectivity. The calibration is obtained (Ryan 1969) by attenuating the signal (of known power), until the display amplitude at an A-scope is reduced to a fixed reference level (Fig. 7). A secondary calibration is then obtained as necessary by measuring the signal from a small isolated permanent echo feature. At the same time the PPI is aligned with the A-scope. During the calibrations equipment performance is monitored and standardized.

Relation Between Radar Reflectivity and Rate of Rainfall.

Both Z and the rate of rainfall R are functions of the drop size distribution. If assumptions are made regarding the form of the distribution, and a suitable expression used for the terminal fall speed of drops with size, a Z-R relation can be found analytically. However, drop size distributions vary widely in nature, and there is no one-to-one correspondence between Z and R. If a series of drop samples is taken an empirical relation can be found, which takes the form $Z = AR^b$, where A and b are constants. Using this, $\bar{P}_r = CAR^b/r^2$, and measurement of $\bar{P}_r$ allows rate of rainfall to be estimated.

Radar Rainfall Estimation

After alignment of the radar, contours of PPI echoes are taken manually, first with zero attenuation, then with 5 dB increments, corresponding to a factor of about two in rainfall rate. Location of the attenuator on the input side of the i.f. amplifier avoids limitation of dynamic range due to receiver saturation. Automatic gain control is not used.

A square grid, with 2 n.m. mesh is prepared on a transparent overlay. Each square is marked with the correction factor, in dB, required to reduce readings in that square to a standard range of 10 n.m. and to incorporate the current calibration factor of the radar, and the coefficient A in the Z-R relation.

The appropriate overlay is selected and aligned with the echo tracing, and the mean attenuation is then estimated for each grid square, applying the correction indicated for that square. A radar rainfall slide rule, on which can be set the constant b, is used to calculate the equivalent rainfall over a ten minute period. The rate found at time t is assumed to apply over the period t-5 to t+5 minutes.

Comparisons with raingauge network

The test area was in flat country, centred about 12n.m. southeast from the Ohakea radar, with ground rising steeply to about 1000m just to the east of the network. There were no permanent echo features in the test area, and the beam was free of intervening obstructions. The beam extended, between half-power points, from 600 - 1800m above the ground in the middle of the area.

A network of Dines tilting syphon recording raingauges was installed in the test area. Between 9 and 12 gauges were available. Density varied from $0.15/\text{n.m.}^2$ to $0.3/\text{n.m.}^2$. Most of them were maintained by inexperienced volunteers, and there were difficulties in timing some of the records. Occasionally a record had to be timed by interpolation between surrounding sites for the times of occurrence of well-marked features in the records common to those sites. Unless several such features could be found to give agreement in timing, the record was rejected. The gauges were tested for comparability of recorded catch for some weeks on a small area, and no significant differences were noted. Exposures were moderate to good.

Isohyets were hand-drawn from the gauge records, and from the radar grid amounts. Radar falls were interpolated for gauge positions. Two sets of radar estimates were prepared. The first was based on a standard Z-R relation for Ohakea. This was obtained from a series of 220 drop samples, taken over about a year, using a stained filter paper technique (Magarvie, 1957). Linear regression of log R on log Z gave $Z = 223R^{1.46}$, with R in mm/hr. The standard error of estimate of R from Z is +.27R, -.21R.

During each comparison, drop samples were taken at Ohakea, and occasionally also at the Plant Physiology Division, D.S.I.R., Palmerston North, near the eastern edge of the network. The number of samples varied between 5 and 12. In these trials, the samples showed only small scatter about a linear log Z - log R relation. The second set of radar estimates was based on the Z-R relations found from these concurrent samples.

Figure 1 shows the point fall comparisons. All radar estimates in this figure are reduced by a factor of 5 dB, equivalent to about 0.5 in R. This was obtained by adjusting the grand mean of all radar estimates using drop samples, to agree with the mean of all raingauge estimates. This over-estimation by the radar is discussed in the next section.

A trial was included in the comparisons if beam filling in the vertical occurred throughout; if not more than two gauges were inoperative; at least one gauge recorded more than 1 mm, and at least three gauges recorded measurable falls. Twelve trials fulfilled the requirements between August 1966 and May 1967. Mean areal falls (MAR) varied between 0.3mm and 5.5mm. They were obtained from the isohyets by planimetry. The total duration of comparisons was 21 hours. Results are summarised in Table I.

TABLE I

MAR(G) - Mean areal rainfall in mm, determined from recording gauge network

$E(R_{st})$ - % deviation from MAR(G) of radar estimate using standard Z-R relation

$E(R_{sa})$ - % deviation from MAR(G) of radar estimate using Z-R relation from concurrent drop samples

$E(R_{cg})$ - % deviation from MAR(G) of radar estimate using standard Z-R relation corrected for central gauge record after 30 minutes of rain at that gauge

E(G) - % error MAR(G) using formula (McGuinness 1963). See text.

Date	Period (M)	MAR(G)	$E(R_{st})$	$E(R_{sa})$	$E(R_{cg})$	E(G)
24. 8.66	1435-1600	9.6	29	-10	- 6	±13
18. 9.66	1820-2000	2.3	23	40	-36	24
19. 9.66	1855-2145	5.0	170	122	1	17
23. 9.66	0830-0955	6.7	60	-25	21	15
6.10.66	0920-1010	1.3	35	8	35	32
23.10.66	1325-1525	4.4	-37	10	-27	19
8.11.66	0915-1045	8.5	-41	-33	-31	14
17.11.66	0750-1030	12.1	0	7	2	12
17.11.66	1305-1455	11.5	81	25	-34	12
24.11.66	1345-1535	3.2	- 5	-22	5	22
23. 3.67	1500-1700	1.7	52	2	- 9	29
24. 4.67	1520-1620	21.4	-42	-30	-14	8

Four of the comparisons are shown in Figs 2-5. In all except two trials, the radar reproduced the isohyetal patterns well. One of these is shown in Fig. 5.

Discussion of errors

Errors in the primary calibration are about ±1dB. The only factors which can affect the secondary calibration are changes in A-scope gain, changes in reflectivity of secondary calibration target, and changes in the receiver noise factor (Ryan, 1969). The latter did not change during the period of the trials. A-scope gain was not known, but the model in use is normally stable. Observed fluctuations in receiver output power from the secondary target amount to about ±2dB. It is not known whether these are due to changes in radar performance or to changes in target reflectivity. Target reflectivity might be expected to vary with weather conditions. No systematic changes in power were noted as between wet and dry days, or between calm and windy days, and it was assumed that the observed changes were due to variations in radar performance. Radar estimates were corrected for indicated changes in output power from the secondary target, and if the above assumption is correct, the estimates should be free of error from this source.

Radar estimates are obtained from a sampling volume of about $5 \times 10^8 m^3$, with its axis lying about 1000m above ground level. The gauges accumulate the fall at an aperture of $.06m^2$. However, the large radar sampling volume probably acts to smooth out small-scale fluctuations in Z-R relations, and whilst this will adversely affect point comparisons, it should result in some improvement in areal estimates.

Data reduction by averaging of attenuation over the area of a grid square introduces errors in mean rainfall rate over that square, since the rate is an exponential function of attenuation. Where reflectivity gradients are strong, this error may be large, and it results in radar underestimation.

The echo returned from precipitation is incoherent, Equation (1) relates to mean received power. The averaging is needed because the instantaneous value of received power depends on the phase shifts of signals reflected from individual drops, resulting from relative movements between them. From Marshall and Hitschfield (1953), the probability function, W, for received power, P, is given by

$$W(P) = (P/P_o) \exp (-P/P_o) \quad . \quad . \quad . \qquad (2)$$

where P_o is mean received power. As the receiver gain function is approximately linear, this will also apply to output power. The radar has no signal averaging devices, and the outline of an echo area presents a characteristically granular appearance on the PPI. The only feasible technique for manual contour tracing is to trace the outer edge of the entire echo area, including the granular outer fringe. Any other method would necessarily be highly subjective. The granules arise because of fluctuations in received power from pulse to pulse. The radar estimates obtained from this 'mean peak' signal can be expected to be correspondingly high. If we examine the probability that the signal power is less than a specified value, m, of P/P_o, then integration of (2) gives:

$$\int_0^m W(P)\,d\,(P/P_0) = e^m(1-m)+1$$

If m is taken as 5dB, the probability is 92%. This suggests that the average error in radar estimates was due to contouring on a 'mean peak' signal, corresponding to a level of received power which is exceeded in only 8% of pulses from that location. For the rotation rate of the CR353 aerial, the number of pulses passing through a target point on a single sweep (for field strength close to axial value) is about 20. However, these are not fully independent samples of reflectivity, and a reasonable estimate of the number of independent samples would be about 10 (Barclay, 1971). This agrees with the probability given above. Lhermitte and Kessler (1966) suggest that estimation if $\bar{P}_r$ from the virtual peak signal should give good results.

No figures are available under New Zealand conditions from which to assess the accuracy of the gauging network in estimating MAR. McGuinness (1963) gives $E = 0.03^{\cdot 54}G^{\cdot 24}$, where E is the absolute error, R is measured mean rainfall rate in inches/hr, and G miles^2/gauge. Another formula (Huff and Neill), 1966) gave similar results, and the McGuinness formula was used. The errors are given in Table I.

Since there is considerable scatter about the log R - log Z regression, the use of a standard Z-R relation introduces errors. In nature, both the coefficient and index of R can vary widely. For individual rains at Ohakea, A has been found to vary between 56 and 437, and b from 1.04 to 2.19, though there is a tendency for variations in the two factors to oppose each other. Furthermore, the Z-R relation may vary both in space and time over an individual precipitation event. However, in all of the Ohakea trials, plots of log R against log Z showed little scatter. Use of the Z-R relations obtained from the samples increased the correlation coefficient between log (gauge falls) and log (radar point falls) from o.75, for the standard relation, to 0.85, significant at the 90% level.

If a rainfall measurement is available from one or more raingauges in the test area, the radar estimate can be calibrated against the gauge falls. If only one gauge is available, the radar estimates can be multiplied by the ratio of gauge fall to radar fall. This is equivalent to correcting for differences in the factor A between the standard relation and the actual relation, and for day-to-day (but not minute-to-minute) variations in radar performance.

A central gauge in the network was selected, and a correction applied to the radar estimates found from the standard relation, on the basis of the first 30 minutes of rain at the gauge, which was used to correct the entire period of rainfall. This increased the correlation coefficient between log (gauge falls) and log (radar point falls) to 0.91. Similar increases were found in the case of MAR, though, owing to the small number of cases, the increases were not significant (see Fig. 6). Even so, it is considered worthwhile to analyse the errors. The standard error of log (radar estimates) from the standard relation is 2.0dB, for MAR. Using samples, we get 1.4dB. Hence the standard error due to use of a standard relation is about 1.4dB, a figure which compares with the standard error of estimate of 1.1dB for log R from log Z for the Ohakea drop samples.

Comparing point falls, the figure is also 1.4dB. The standard error of log (radar estimate), corrected for central gauge reading is 1.1dB. Comparing this with the figure of 1.4dB, when samples are used, we find that the error due to short period radar fluctuations, and to variations between rates in the pulse volume and at the gauges is about 1dB. However, the probable error of the gauging estimate is of this order.

The error quoted for the standard Z-R relation corresponds to an error in rainfall rate of +60% and -37%. Using samples the figures are +40% and -28%, whilst correcting for the central gauge they are +28% and -22%.

Since the beam axis lies above the ground, the estimates will also be affected by variations in the vertical in Z, and by both horizontal drift of precipitation between the beam and gauges, and sorting of drops by size in horizontal wind shears. At the range used, vertical variations are probably less than 1dB (Harper, 1957). An attempt was made to correct the radar estimates for horizontal drift, on the basis of observed upper winds at Ohakea. Fall speed was selected for the drop size range midway between the sizes contributing most to rate of rainfall, and to Z. This was possible for six of the trials, and in each case the MAR and most of the point estimates showed an improvement. However, this factor becomes of less importance for larger areas, and the mean improvement was only about 0.6dB.

In the first four trials, contouring was done at 5 minute intervals. Rainfalls were accumulated for 5, 10, 15 and 20 minute intervals. The estimates for 10 minutes were not significantly worse than those for 5 minutes, but accuracy fell off markedly at 15 and 20 minutes. Accordingly 10 minutes was selected for all trials.

Operational considerations

Most error sources cannot be corrected in the operational application. Use of a standard Z-R relation is obligatory. These results indicate that a useful improvement in accuracy could be achieved if appropriate Z-R relation can be used for each rainfall. A further series of drop samples is being obtained from several New Zealand locations, and these will be analysed in the hope of reducing the error of estimate of R from Z by stratification of the samples according to readily observable meteorological or precipitation factors.

Whilst a primary calibration should not often be needed, a good secondary calibration is required. Use of a suitable microwave signal generator to calibrate the system would be the best approach to this problem, but if this is not adopted, a calibration of the A-scope using a square wave generator would be useful. Monitoring of video gain would be desirable.

One factor which was excluded in the trials was that of beam-filling, and the allied problem of inclusion of the region above the melting level in the beam. This restricts the useful hydrologic range of the radar, because of the rather large beam width of 2.8° between half-power points. The author prepared a radar climatology for Ohakea over a three-year period. Echo frequency per unit area decreased with range. At a range of only 40 n.m., frequency averaged over all azimuths, is less than half of that close to the radar. This indicates that beam filling would constitute a serious problem. Beam filling would normally occur in most very heavy falls to greater ranges, but this cannot be guaranteed.

Manual contouring and data reduction can just be done by two operators in real time, using the overlays and slide rule, but owing to the small time margin, the results are error-prone. Electronic data reduction from manually digitised data is probably the best compromise between the manual system and a fully automated pulse integration, digitising and computer system. If manual digitisation were done, a digital computer with very modest memory storage would suffice.

Conclusions

Providing a correction is made for over-estimation of reflectivity due to contouring on a 'mean peak' signal, a useful estimate of mean areal falls can be obtained with the CR353, out to ranges where beam filling limits performance. These estimates can be improved significantly if an appropriate Z-R relation can be used. If a telemetering raingauge is available in the precipitation area, the radar estimates become very good (Huff, 1966). Pulse integration would be desirable, since it would greatly facilitate contour tracing. It would be better not to use manual data reduction, but a digital computer would give greater flexibility (e.g. in respect of appropriate Z-R relations) than would an analogue computer.

References

Barclay, P.A., 1971: Weather radar signal processing. Aust. Bureau of Meteor., Working Paper No. 136, Melbourne.

Chernikov, A.A., and E. Kessler, 1965: The radar measurement of areal rainfall, W.M.O.

Harper, W.G., 1957: Variation with height of rainfall below the melting level. Quart. J. R. Meteor. Soc. 83: 368-371.

Harrold, T.W., 1965: Estimation of rainfall using radar - a critical review. U.K. Meteor. Office Sci. Paper No. 21, H.M.S.O., London.

Huff, F.A., and J.C. Neill, 1957: Rainfall relations on small areas in Illinois. Bull. 44, Illinois State Water Survey, Urbana.

Huff, F.A., 1966: The adjustment of radar estimates of storm mean rainfall with raingauge data. Proc. 12th. Conf. Radar Meteor: 198-203.

Lhermitte, R.M., and E. Kessler, 1966: Estimation of the average intensity of precipitation targets. Proc. 12th Conf. Radar Meteor: 23-27.

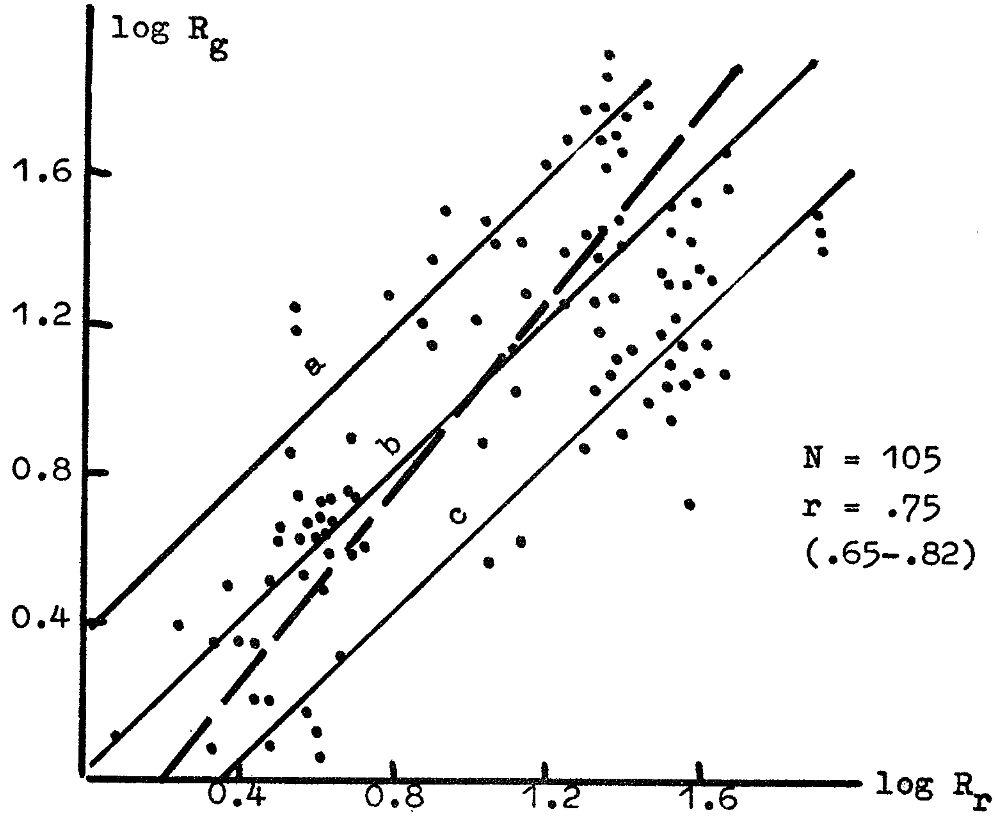
Magarvie, R.H., 1957: Stain method of drop-size determination. J. Meteor. 14: 182-186.

Marshall, J.S., and W. Hitschfeld, 1951: Interpretation of the fluctuating echoes from randomly distributed scatterers, Part 1. Canadian J. Phys. 31: 962-944.

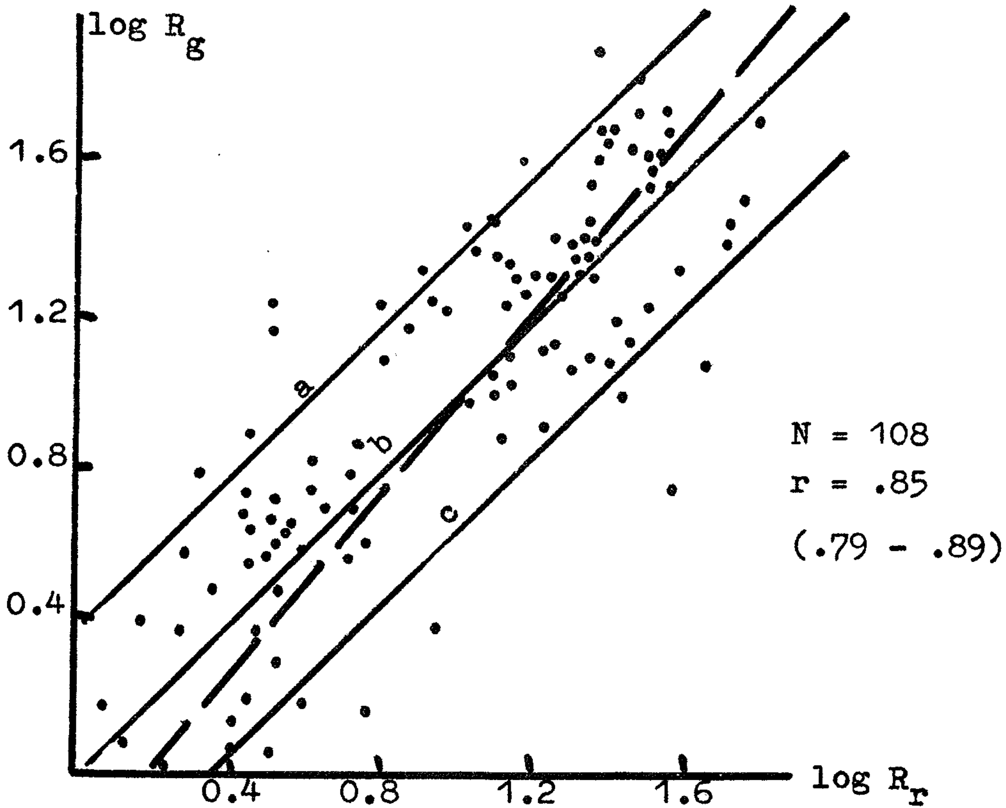
McGuinness, J.L., 1963: Accuracy of estimating watershed mean rainfall. J. Geophys. Res. 68: 16.

Probert-Jones, J.R., 1962: The radar equation in meteorology. Quart.J.R.Meteor.Soc. 88: 485-495.

Ryan, A.P., 1969: Calibration of the Cossor CR353 weather surveillance radar. N.Z. Meteor.S.Tech. Note No. 184.

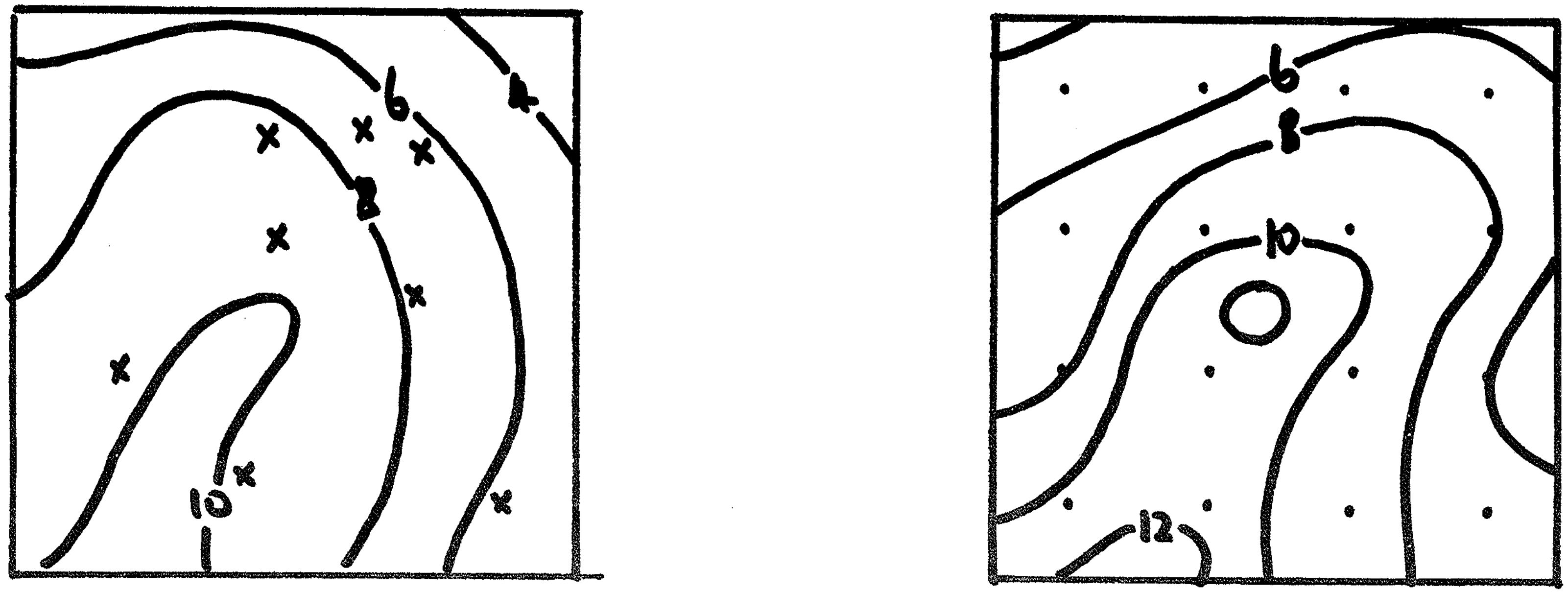


(a) using standard Z-R relation.



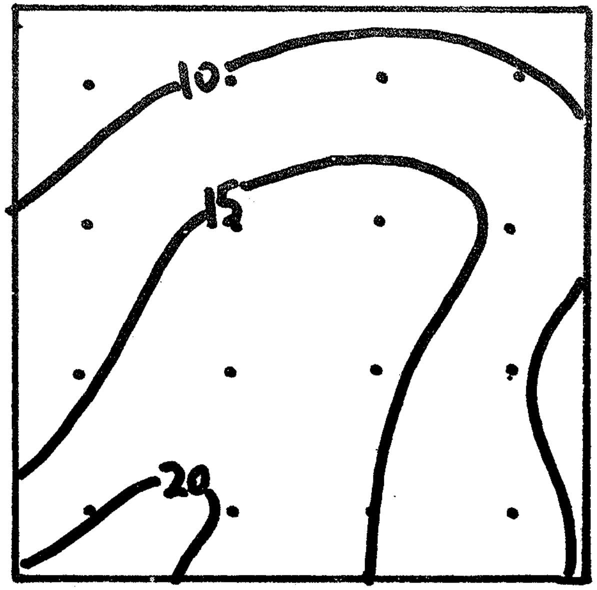
(b) using Z-R relation from concurrent drop samples.

Fig. 1. Comparison of radar rainfall (R_r) with gauge measured falls (R_g) at gauge locations. Lines a,b,c show, respectively, $R_r=0.5R_g$; $R_r=R_g$ and $R_r= 2R_g$. The dashed lines show the regression of R_r on R_g. N is the number of comparisons, and r the correlation coefficient, with 95% confidence limits shown.



(a) raingauge network ; gauge locations shown with cross.

(b) radar using drop samples , and 2 n.m. grid.

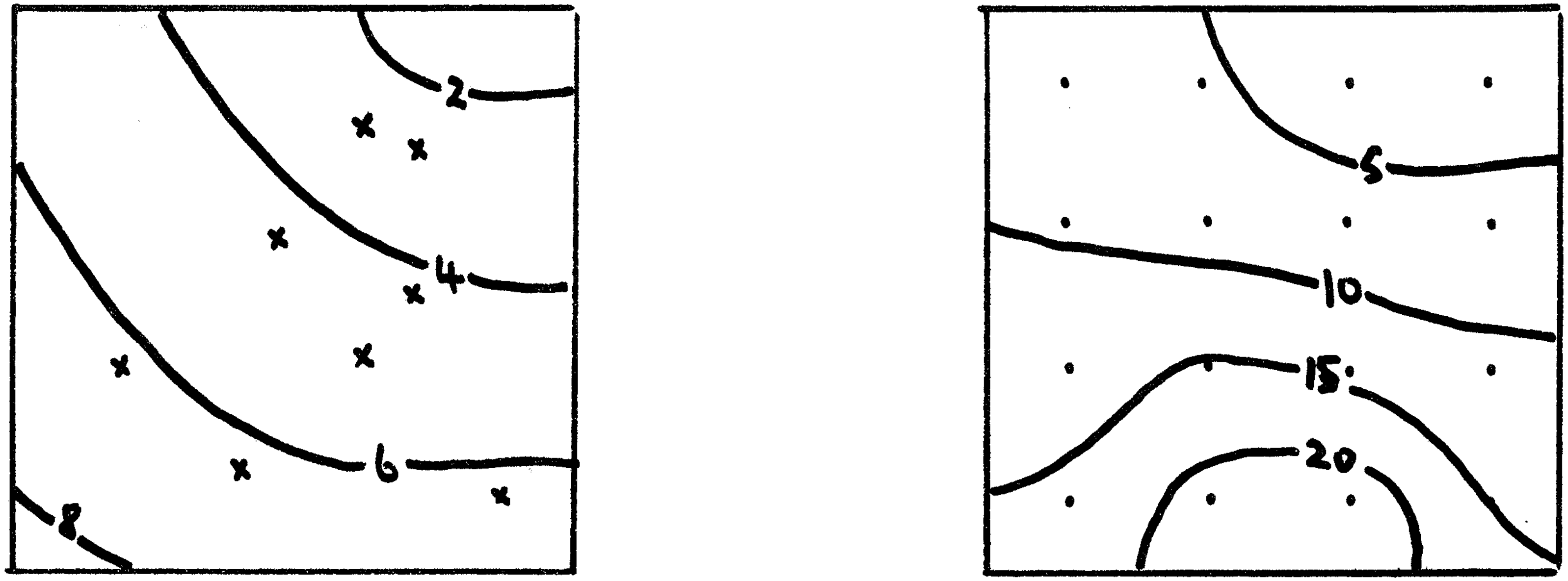


(c) radar using standard Z-R relation.

Fig.2. Isohyets (unit .01"), for period 1435-1500 NZST on 24/8/66, for cold front passage.

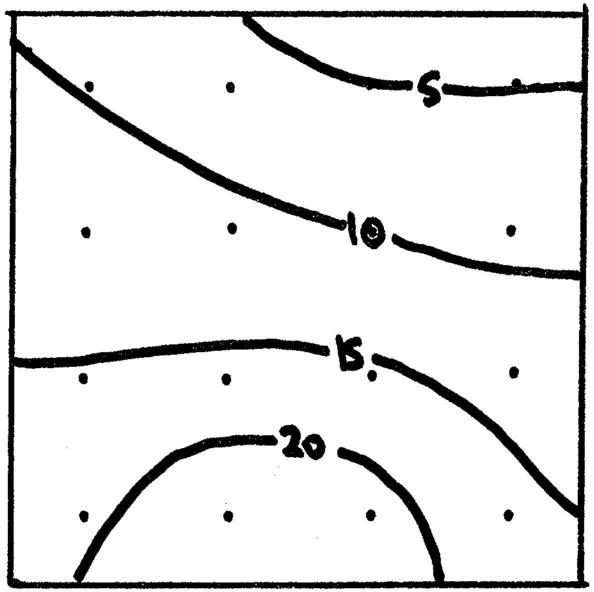
Mean areal falls:-

Raingauges	9.6 ± 1.1
Radar (using standard Z-R)	12.5
Radar (using drop samples)	9.0
Radar adjusted for central gauge (standard Z-R)	9.0



(a) Raingauge network; gauge locations shown with cross.

(b) radar using drop samples, and 2 n.m. grid.

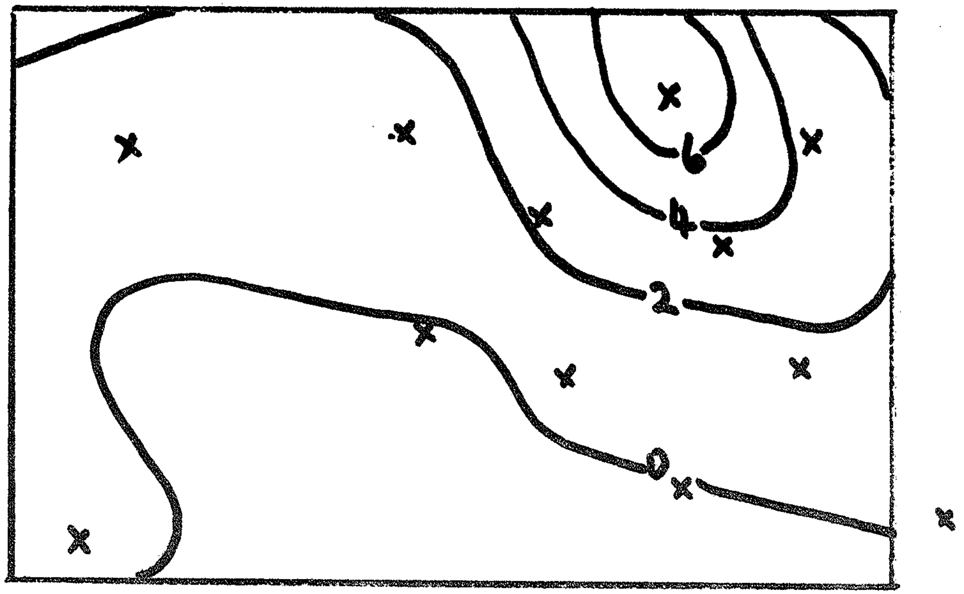


(c) radar using standard Z-R relation.

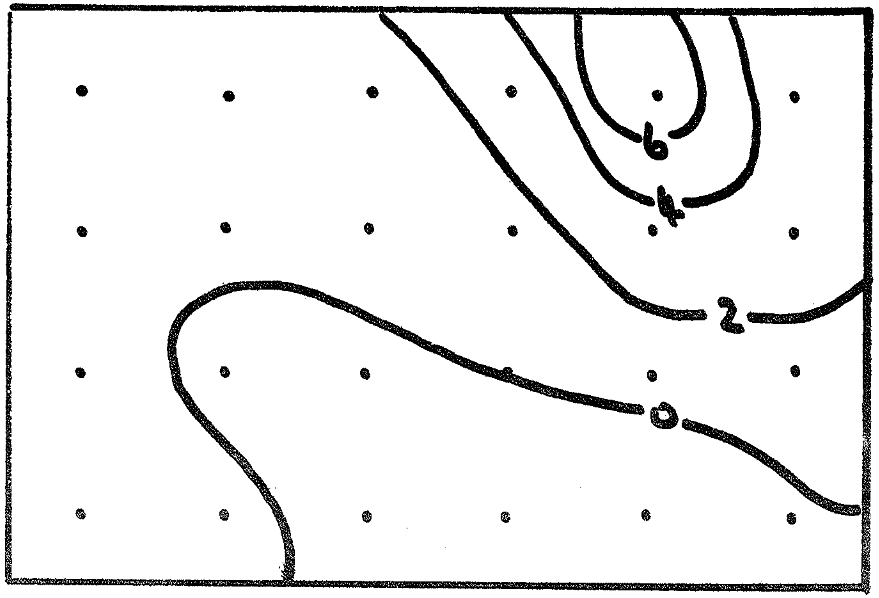
Fig. 3. Isohyets (unit .01") for period 1855-2145 NZST on 19/9/66, stationary front over area.

Mean areal falls:-

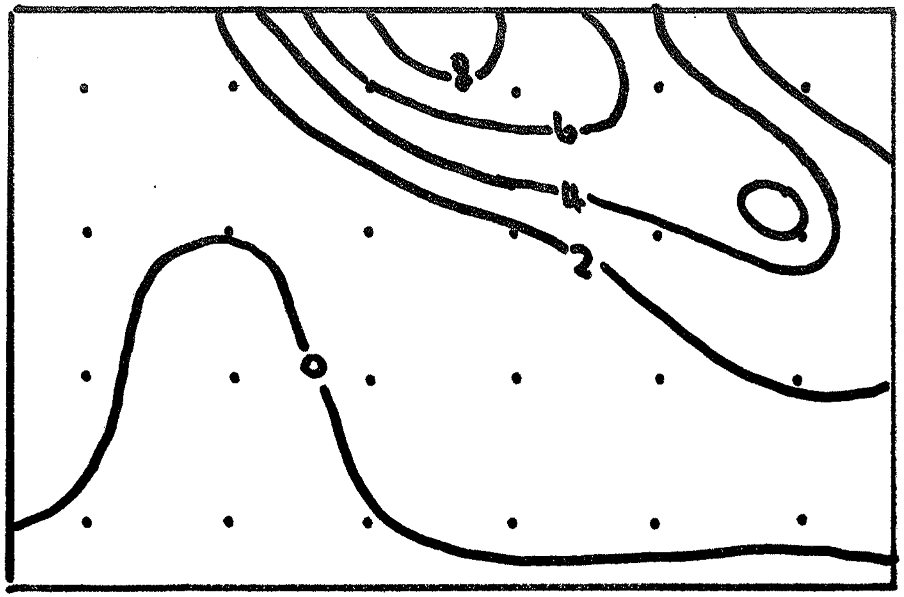
Raingauges	**5.0** ± 0.8
Radar (using standard Z-R)	13.5
Radar (using drop samples)	11.1
Radar adjusted for central gauge (standard Z-R)	5.1



(a) Raingauge network, gauge locations shown, with cross.



(b) radar using drop samples , and 2 n.m. grid.

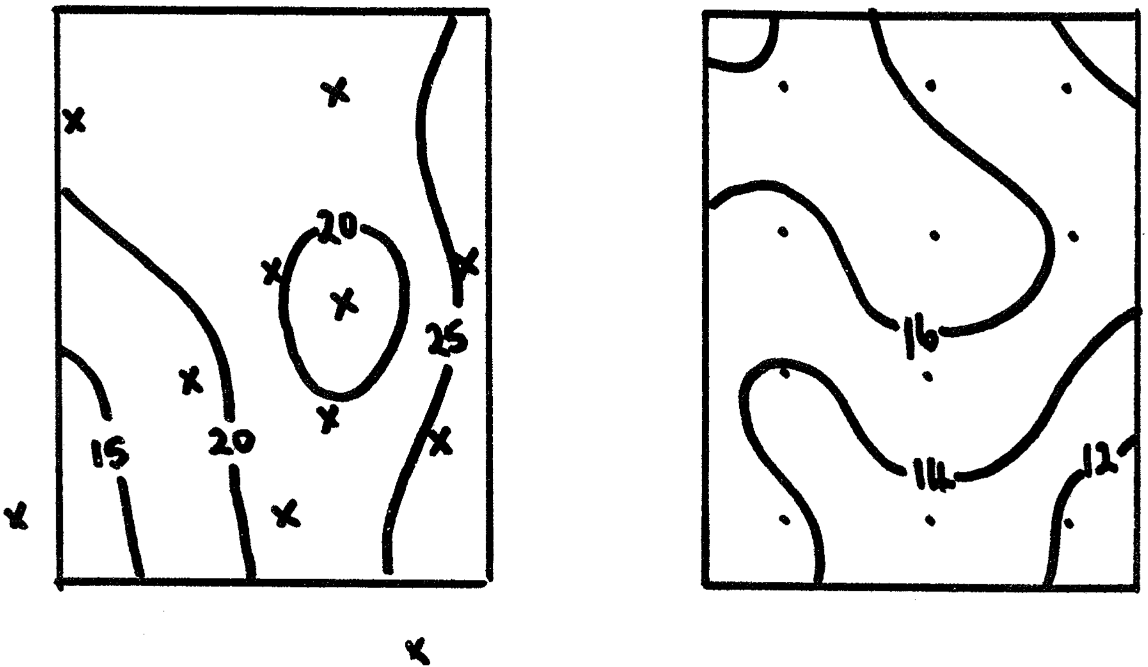


(c) radar using standard Z-R relation.

Fig. 4. Isohyets (unit .01") for period 0910-1020 NZST on 6/10/66, in unstable NW flow.

Mean areal falls.

Raingauges	1.3 ± 0.1
Radar (using standard Z-R)	1.7
Radar (using drop samples)	1.4
Radar adjusted for central gauge (standard Z-R)	1.7



(a) raingauge network; gauge locations shown with cross.

(b) radar using drop samples, and 2 n.m. grid.

Fig. 5. Isohyets (unit .01") for period 1520-1630 NZST on 23/4/67 in unstable NW flow.

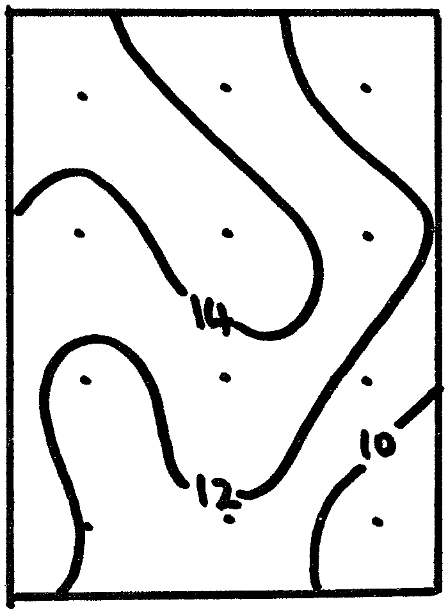
Mean areal falls:-

Raingauges 21.4 ± 1.9

Radar (using standard Z-R) 12.5

Radar (using drop samples) 14.8

Radar adjusted for central gauge 18.3 (standard Z-R)



(c) radar using standard Z-R.

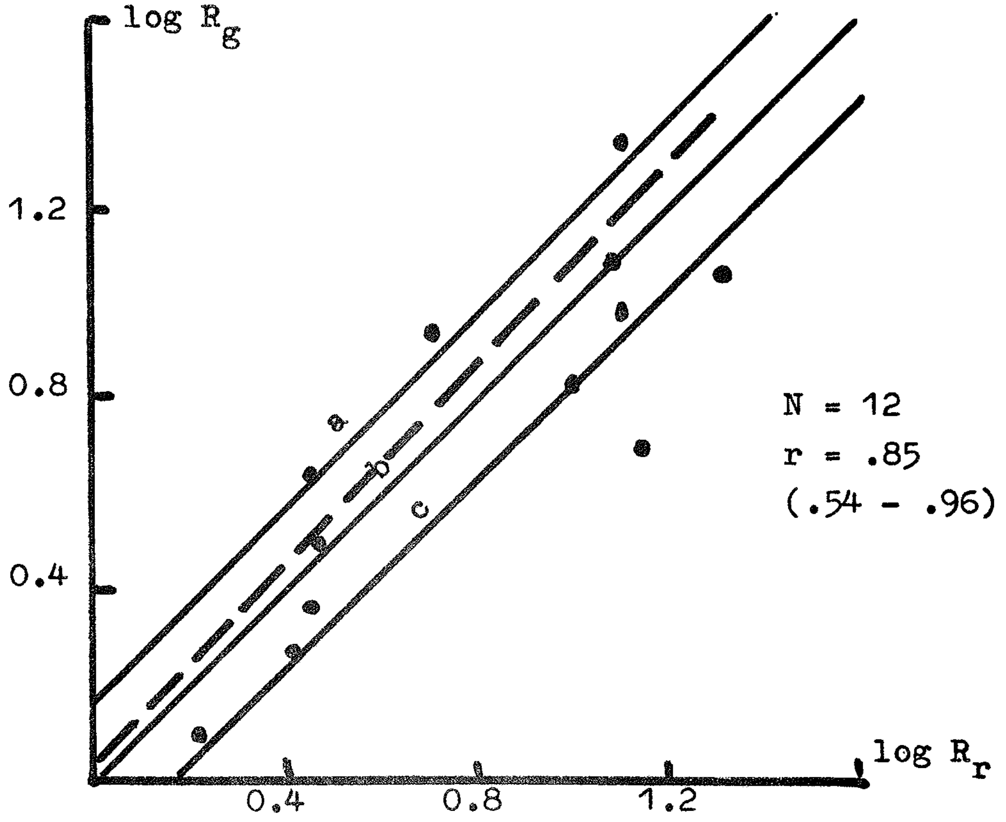


Fig.6.(a) using standard Z-R relation.

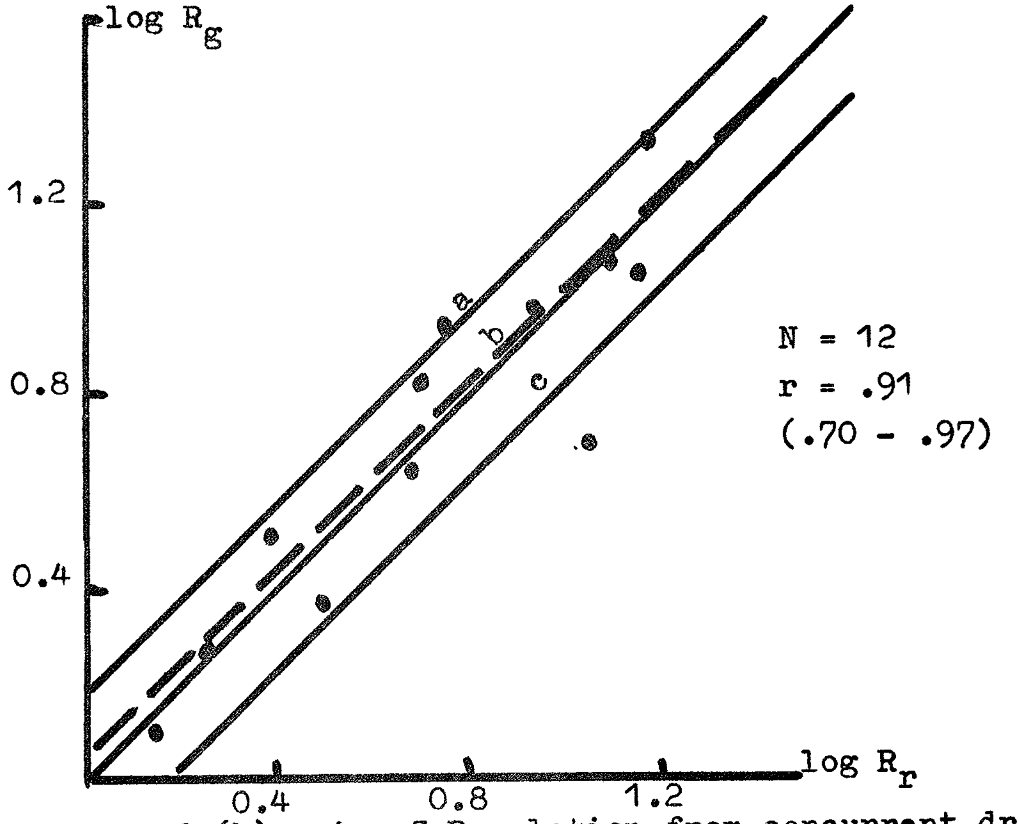


Fig.6 (b) using Z-R relation from concurrent drop samples.

Fig. 6. Comparison of mean areal rainfall from gauges and from radar. Lines a,b,c show respectively, $R_r = 0.67R_g$; $R_r = R_g$, and $R_r = 1.5R_g$. See caption to fig.1.

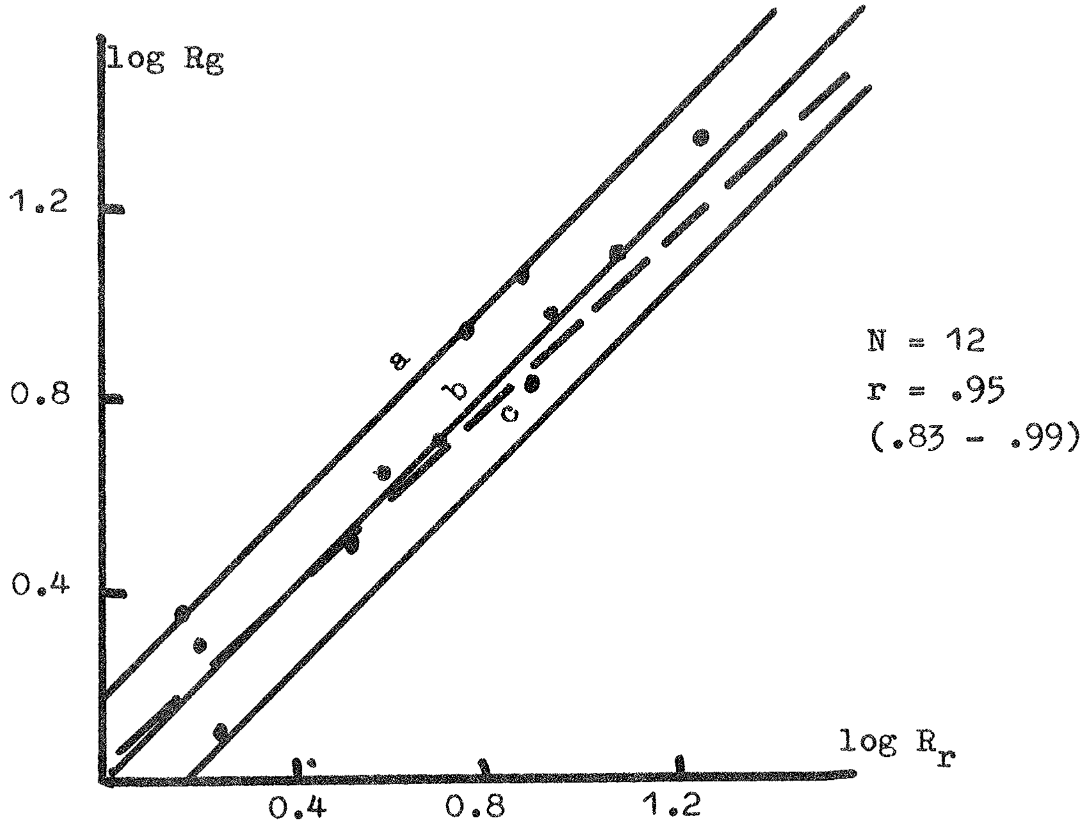


Fig 6.(c) using standard Z-R relation, but corrected for rainfall measured at central gauge (see text). See caption to fig. 1.

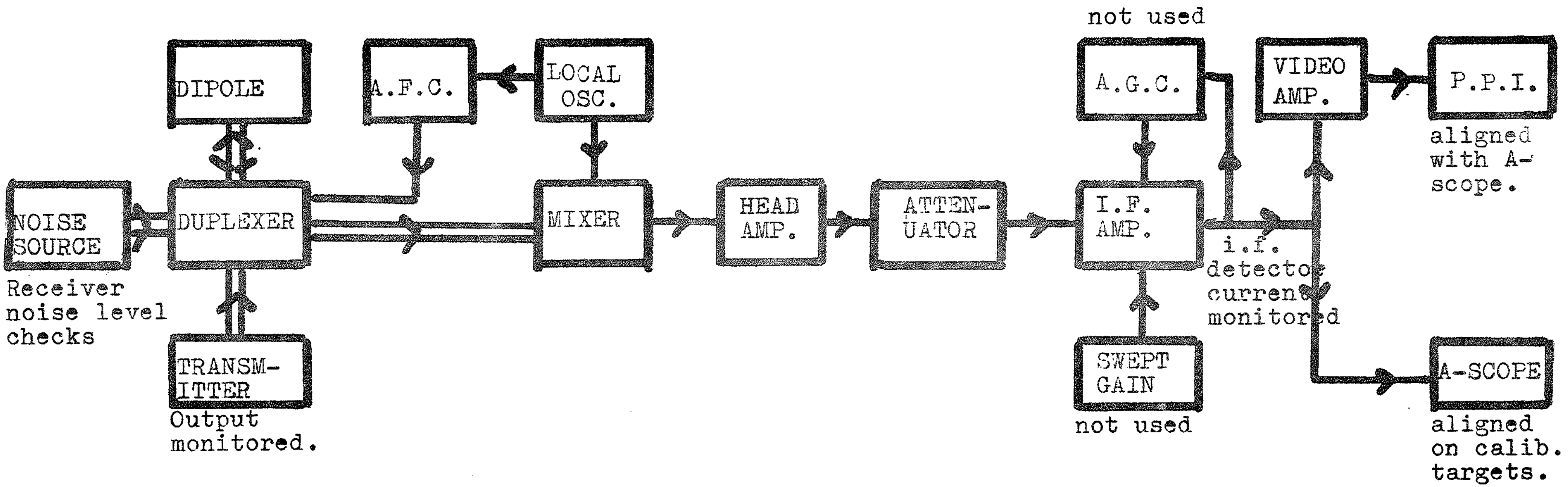


Fig. 7. Block diagram of relevant parts of CR353.