551. 501. 81
551. 577

ON THE ACCURACY OF RADAR RAINFALL MEASUREMENTS

by

ERKKI JATILA and TIMO PUHAKKA

Department of Meteorology
University of Helsinki

Abstract

Radar rainfall measurements were carried out by using an X-band radar (Selenia Meteor RMT-1L) during summer 1969 (16 storms) near Helsinki, Finland. Simultaneously rainfall was observed by 15 recording rain gauges over an area of 180 sq.km. The purpose of the study was to determine the accuracy of radar measurements by comparing radar observations with the corresponding recordings by the network using various densities.

Two types of equivalent gauge density (EGD) for radar measurements were defined:

EGD 1: the number of gauges per area leading to a mean error in daily precipitation amount equal to the same error obtained by radar. The mean daily error was calculated as the mean of the absolute percentage daily errors in the precipitation amount weighted by the daily amount of areal rainfall.

EGD 2: the number of gauges per area required to give the same number of »correct» 15 minute observations of areal average rainfall rate as obtained by radar. A »correct» observation was the one which lies between the error limits of ±50 % of the »true» (measured by 15 rain gauges) average 15 minute intensity.

EGD 1 describes the accuracy of radar measurements to estimate daily amounts of areal rainfall, while EGD 2 gives an approximation of the accuracy of radar measurements to estimate average rainfall rates over shorter periods of time. The following equivalent density values were obtained: EGD 1: <1 gauge/180 sq.km for continuous rains applying any radar measurement method and for showers 1 gauge/30 sq.km calibrating radar with a reference gauge or applying the mean Z-R relationship obtained for showers ($Z = 360\,R^{1.6}$). EGD 2 values attained were: 1 gauge/46 sq.km for continuous rains utilizing the Marshall-Palmer relation and for showers 1 gauge/36 sq.km applying the reference gauge technique or using the relationship $Z = 360\,R^{1.6}$.

1. *Introduction*

1.1 General

Rainfall amount over an area is conventionally measured by a rain gauge network. The density of the routine rain gauge network in Finland is from 1 gauge/500 sq.km to 1 gauge/1000 sq.km being denser in Southern Finland than in the northern part of the country. This network sends the information of daily rainfall amount once a month to the hydrometeorological authorities. The observations are then used for climatological purposes. Essentially a less dense network (1 gauge/6500 sq.km) transmits the observations twice a day. Based on these observations it is assumed that it fulfills the requirements of agriculture and water regulation of basins.

At present we realize that scarcity of clean water will become current during this decade, because watercourses are more and more polluted by industry and settlement. For this reason we will have to pay more attention to the careful regulation of clean basins. Successful regulation requires a better knowledge of areal rainfall than can be obtained with the existing gauge network. Areal rainfall measurement can be improved in two ways: either the density of the rain gauge network (with real time transmission) must be increased or a better method for estimating the areal rainfall must be developed.

For more than ten years the accuracy of radar rainfall measurements has been under serious investigation throughout the world. Some authors [7] have concluded that the accuracy of radar measurements is equal to the accuracy of the gauge network with a density of 1 gauge/500 — 1000 sq.km. Some others have, on the other hand, stated that the network may be of any density and the radar measurements will still give better estimates of areal rainfall [3]. The utilization of radar gives one extra advantage: the areal rainfall can easily be measured in real time and the regulation of basins can be optimized.

The purpose of the present study was to determine, using data obtained during one summer, how dense a rain gauge network over an area of 180 sq.km should be in order to get as accurate estimates of areal rainfall as can be obtained with radar. To achieve this the network observations were compared with measurements by radar (X-band Selenia Meteor RMT-1L). The material was the same used by JATILA and PUHAKKA [4] to find out the best radar method for estimating rainfall intensities in various rainfall types in Finland.

1.2 Equivalent gauge density

Some of the radar meteorologists have determined the accuracy of radar rainfall measurements by computing the s.c. equivalent gauge density. This is defined as the number of rain gauges per area which leads to an equivalent estimate of areal rainfall with radar measurements. The equivalent gauge density can be calculated considering the total amount of precipitation measured by the radar and by networks with various densities during a certain time period. The standard deviation of the observations has also been used. In some papers the percentage of the observations which lie inside certain error limits has been computed for radar and network observations.

Many factors influence on the equivalent gauge density: 1) the size of the area under investigation, 2) the topography of the area, 3) the type of rainfall, 4) the accuracy of the measurement of the radar reflectivity factor Z (which is related to the rainfall intensity R through the equation $Z = aR^b$, a and b being coefficients), 5) the Z-R relationship used, 6) the data collection frequency, and 7) the length of period for which the equivalent gauge density is calculated.

AOYAGI [1] used an X-band radar and measured rainfall over an area of 638 sq.km during 9 storms. He applied the Z-R relationship given by Marshall and Palmer (abbreviation in the present paper M-P) $Z = 200\,R^{1.6}$ in each case except with diffuse rain (1 case) when the equation $Z = 100\,R^{1.4}$ was used. He compared the radar estimates of areal rainfall with recordings from 27 gauges distributed over the area. Aoyagi computed the equivalent gauge density by comparing the daily amounts of areal precipitation derived by radar with the corresponding amounts measured by the network with various densities. He found that the radar estimates were equal to the observations of network with a density of 1 gauge/210—28 sq.km. When Aoyagi used the standard deviation of 10 minute rainfall amounts measured by radar in comparison to those obtained from the 10-minute isohyetal gauge patterns, the same material provided 1 gauge/200—59 sq.km for the equivalent gauge density.

More extensive data were used by WILSON [7], [8]. His investigation was based on 28 storms (years 1964—1968) and the area of the check site was 4200 sq.km containing about 175 gauges. He proved that the accuracy of radar measurements increases with increasing area and data collection frequency. On the average Wilson gave an equivalent gauge density of 1 gauge/640 sq.km provided that the radar is calibrated with at least one reference rain gauge located in the check site. The equivalent gauge density was computed by applying RMS errors. In one of his earlier studies, WILSON [6] calculated the equivalent gauge density utilizing the percentage of observations within error limits of ±50 % in rainfall rate. Using 7 storms he obtained the value 1 gauge/100 sq.km. He used various values of the Z-R relationship for each storm also in this study.

MUCHNIK *et al.* [5] attained a very high value for the equivalent gauge density: 1 gauge/6 sq.km calculated from standard deviations of 1 hour radar and network observations over an area of 512 sq.km. The result was based on measurements made during one summer (12 storms) in the Ukraine, USSR. BOROVIKOV *et al.* [2] used more extensive material from the Valdai region of the USSR for a period comprising two summers. They stated that the equivalent gauge density is 1 gauge/100 sq.km over an area of 100 sq.km, 1 gauge/300 sq.km over an area of 400 sq.km, and a density of 1 gauge/1300—1400 sq.km over an area of 8600 sq.km. In both Soviet studies an average value of the coefficient a was applied to all the storms.

2. *Data and method used*

The present material consists of observations made during the summer of 1969 in Helsinki, Finland. 16 storms were investigated. The total amount of areal precipitation measured was 59.4 mm. The material has been classified into 3 types of rainfall: continuous rain (8 cases), showers (6 cases), and drizzle (2 cases). The results are given for each rainfall type and for the combined material.

The radar measurements of the radar reflectivity factor were carried out applying the stepped gain method (6 dB steps) at intervals of 5 minutes. The corresponding rainfall rates were computed by applying Z-R relationships obtained in four different ways. The Marshall-Palmer relationship $Z = 200\ R^{1.6}$ was used as the first approximation. Secondly, the value of the coefficient a was computed, which led the total radar-measured rainfall amount of all the storms belonging to a rainfall type to be equal to the network-measured rainfall amount of corresponding storms. The following values were obtained: continuous rain: $a = 196$, showers: $a = 360$, and drizzle: $a = 56$. The values were applied to the measurements of each rainfall type, assuming further, that the exponent b is always equal to 1.6. Thirdly, the radar measurements were calibrated so that the daily amount of precipitation measured by a fixed reference rain gauge in the middle of the check site was equal to the rainfall amount measured by radar directly over the gauge. Finally, during some storms the drop size distribution was determined by applying the filter paper technique in three places within the check site. When the drop size distribution is known it is easy to compute the Z-R relationship. The coefficients obtained in this way were then applied to the radar measurements. For further details see [4].

The areal rainfall measured by radar, applying each of the 4 methods described above, was compared with the rainfall amounts obtained with a rain gauge network in an area of 180 sq.km. This check site had 15 recording rain gauges corresponding to a gauge density of 1 gauge/12 sq.km. Thus the distance from one gauge to another was3 —4 km on the average. The »true» areal rainfall was assumed to be obtained with this network and applying the s.c. Thiessen's method. If one of the gauges was temporarily out of order, the mean value of all the other gauges was considered the missing observation. Naturally even this dense network cannot give absolutely correct values. According to [2] the error in the daily amount of precipitation is less than 10 % in 75 % of the cases, when the area and the network density are equal to ours. This must be remembered when examining the results given in the present paper, because the errors were computed as deviations from areal rainfall measured by the whole network.

Two types of equivalent gauge density (EGD) have been defined as follows:

EGD 1: the number of gauges per area leading to such a mean error in the daily precipitation amount equal to that obtained by radar. The mean daily error was calculated as the mean of the absolute daily percentage errors in the precipitation amount weighted by the daily amount of areal rainfall.

EGD 2: the number of gauges per area required to give the same number of »correct» 15 minute observations of areal average rainfall rate as obtained by radar. A »correct» observation is the one which lies within error limits of ±50 % of the »true» (measured by 15 rain gauges) average 15 minute intensity.

Chapter 3 deals with the EGD 1. The absolute errors in the daily and seasonal amount of areal rainfall were also calculated for radar measurements and for networks with various densities. The EGD 2 is discussed in Chapter 4.

3. *Accuracy of storm totals measured by radar*

3.1 Material classified according to rainfall type

Table 1 shows the error (%) in the amount of precipitation of each storm measured by the network with various densities or by the radar, applying various measurement methods. The contents of the table is fully explained by the following example: on 12 July the areal rainfall amount measured by the whole network (15 gauges) was 6.58 mm. The rainfall amount in the same area but measured by 12 gauges was 2.3 % less than 6.58 mm. Using 9 gauges a 0.6 % greater amount was obtained etc. Applying the Marshall-Palmer coefficients (column M-P) the rainfall amount measured by radar was 16.7 % greater than 6.58 mm. Computing the radar rainfall amount using the value of coefficient $a = 196$ (the mean for all continuous rains) an overestimate of 18.1 % was obtained. The radar, calibrated with a reference rain gauge, underestimated the areal rainfall by 13.4 %. The underestimation was 32.0 %, applying the coefficients obtained from the drop size distribution measurements.

The error in the total seasonal amount of precipitation from storms belonging to a rainfall type is presented on the line $100 (\Sigma Q_n - \Sigma Q_{net}) / \Sigma Q_{net}$, where Q_n is the daily rainfall amount measured by various network densities or by various radar measurement methods. In continuous rains the total rainfall amount does not depend significantly on the network density. Radar measurements have also led to a total that is almost correct when the M-P coefficients have been applied (2.0 % underestimate). Somewhat greater errors have been obtained

Table 1. Error in precipitation amount (%) for various network densities and radar measurement methods per storm and per rainfall type. Mean daily error (%) for each rainfall type is the mean of the absolute daily errors (%) weighted by the daily precipitation amounts.

	Date 1969	Q_{net} (mm)	Number of gauges per 180 sq.km.					Radar measurement method			
			12	9	6	3	1	M-P	Mean value of a	Reference gauge technique	Coeff. from drop size measurem.
Continuous rain $\Sigma Q_{net}=$ 34,91 mm)	12 July	6.58	−2.3	0.6	2.6	0.6	−8.5	16.7	18.1	−13.4	−32.0
	18 July	4.31	0.0	0.5	2.3	−0.2	6.7	−32.5	−31.7	−35.0	−37.3
	26 Aug.	0.75	0.0	6.7	2.7	−22.7	−25.3	27.8	28.9	−47.5	−14.3
	6 Sept.	1.86	3.2	5.9	4.8	4.8	3.2	−0.3	1.0	10.4	—
	13 Sept.	0.44	2.3	2.3	13.6	9.1	27.3	54.9	56.9	22.8	6.4
	14 Sept.	11.11	0.8	−0.1	2.6	4.4	14.3	1.1	2.3	21.0	9.7
	15 Sept.	1.51	−1.3	3.7	6.7	2.5	−4.8	−28.2	−27.3	23.4	—
	22 Sept.	8.35	−0.7	0.8	3.0	2.3	0.7	−6.3	−5.1	52.3	—
$100\frac{\Sigma Q_n - \Sigma Q_{net}}{\Sigma Q_{net}}$ (%)			−0.2	1.0	3.1	2.0	3.7	−2.0	0.0	13.1	−11.7
Mean daily error		(%)	1.1	1.0	3.1	3.1	8.4	11.5	11.9	28.9	21.2
Showers (ΣQ_{net} =12.91 mm)	25 July	4.33	2.7	11.1	−4.6	3.8	−34.4	58.2	9.5	−46.0	114.3
	23 Aug.	2.00	−2.5	−6.5	0.5	8.0	88.5	73.3	20.0	−21.1	85.1
	25 Aug.	5.12	0.6	6.6	44.3	107.0	179.3	13.0	−21.8	5.8	91.1
	30 Aug.	0.56	0.0	−1.8	−1.8	−21.4	−42.9	80.7	25.1	−1.8	86.1
	2 Sept.	0.66	−3.0	10.6	10.6	−1.5	−72.7	31.2	−9.2	−71.2	—
	3 Sept.	0.24	−41.7	−37.5	−25.0	−100.0	−100.0	93.4	34.0	—	—
$100\frac{\Sigma Q_n - \Sigma Q_{net}}{\Sigma Q_{net}}$ (%)			−0.2	5.1	16.8	42.1	65.8	42.9	0.0	−20.4	98.2
Mean daily error		(%)	2.5	8.7	20.3	47.8	103.8	42.9	17.1	25.2	98.2
Drizzle	27 Aug.	2.37	−0.4	−0.8	2.5	9.3	0.0	−85.3	−67.5	−3.8	−56.4
	16 Sept.	9.19	−0.4	−0.8	1.7	11.0	32.8	−49.2	12.6	60.1	—

using other radar methods in continuous rains. Applying the mean value of a, the error in the total rainfall amount is naturally equal to zero due to the method used to obtain the average seasonal value for a. In showers the errors are remarkably larger both with less dense network and with radar methods than they are in stable rains. One should note that with the M-P coefficients, the radar overestimates the rain on each shower. This means that the M-P coefficients are not applicable in showers. The same is also valid for drizzle, where use of the M-P coefficients causes clear underestimates on both days.

In Table 1 on the row »Mean daily error», the mean of the absolute daily percentage errors weighted by the daily amounts of areal precipitation is presented for each rainfall type. Weighting is necessary in order to reduce the influence of stroms with small amount of precipitation. Figure 1 provides a graphic representation of the mean daily error as a function of the network density for stable rain and for showers. The symbols in the figure denote the mean daily errors for various radar methods. The figure has been drawn to help to estimate the equivalent gauge density EGD 1. In continuous rains EGD 1 is less than 1 gauge/180 sq.km applying any of the radar methods. In other words on the average even one gauge (located in the middle of the check site) measures the daily amount of areal precipitation better than the radar in continuous rains.

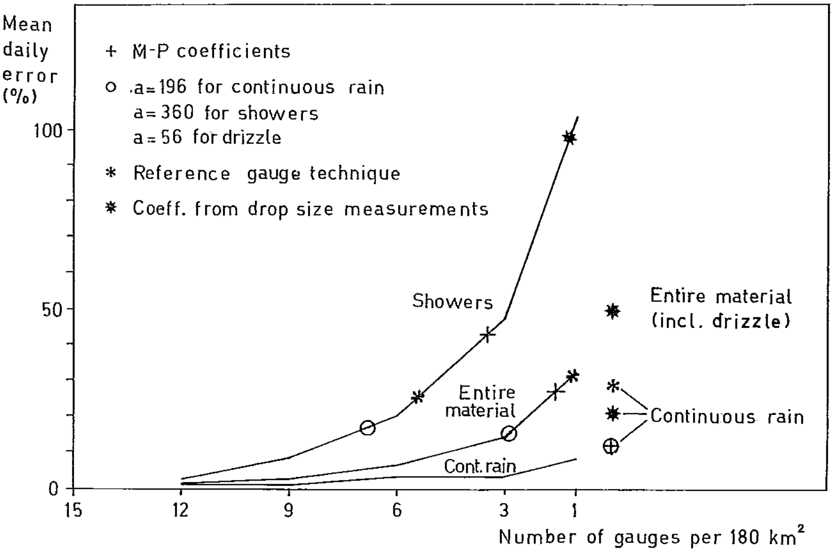

Fig. 1. Mean daily error as a function of network density. Symbols indicate the various radar measurement methods. The symbols outside of the lines present radar methods which gave greater errors than 1 gauge/180 sq.km.

The mean daily error increases rapidly as the network density decreases in showers. The mean error in radar estimates applying the M-P coefficients is 42.9 % corresponding to the EGD 1 value of 3.5 gauges/180 sq.km (equal to 1 gauge/51 sq.km). Utilizing the mean value for the coefficient a in showers ($a = 360$) the EGD 1 is 6.8 gauges/180 sq.km (1 gauge/26 sq.km). The reference gauge technique leads to a value of 5.5 gauges/180 sq.km (1 gauge/33 sq.km) whereas when applying the dropsize distribution coefficients the EGD 1 is nearly 1 gauge/180 sq.km.

The influence of the network density in drizzles was small on 27 August (see Table 1.). On that day the only radar method in which the error was as small as in the network observations, was the reference gauge technique. On the other day with drizzle (16 Sept.), the error increased stronger with decreasing network density. Nevertheless, only the application of the mean value of a for drizzle ($a = 56$) obtained radar measurements superior to those with 1 gauge/180 sq.km. Due to the small number of cases with drizzle, no combined results for drizzle were calculated.

3.2 Combined results

The error in the total amounts of precipitation during the whole summer and the mean daily error for various network densities and radar measurement methods appear in Table 2. All the radar methods did a better job of measuring the total rainfall amount than a rain gauge located in the middle of the check site. The mean daily error also appears in Figure 1 (curve »entire material»). Of the radar methods, only the utilization of the coefficients obtained from drop size measurements led to greater error than the one for 1 gauge/180 sq. km.

Table 2. Error (%) in total precipitation amount and mean daily error (%) for the whole summer.

	Number of gauges per 180 sq.km.					Radar measurement method			
	12	9	6	3	1	M-P	Mean value of a	Reference gauge technique	Coeff. fr. drop size measure.
$100\,\dfrac{\Sigma Q_n - \Sigma Q_{\mathrm{net}}}{\Sigma Q_{\mathrm{net}}}$ (%)	−0.2	1.5	5.8	12.4	21.6	−2.9	0.0	12.1	20.6
Mean daily error (%)	1.3	2.7	6.6	14.3	32.5	27.1	15.3	31.9	48.1

4. *Accuracy of 15 minute rainfall amounts by radar*

For certain applications (water budgeting in real time, attenuation in microwave telecommunication systems etc.) data on the rainfall rate integrated over short intervals of time is essential. The average rainfall rate for several hours (usually 12 or 24 h) is no longer applicable. In principle radar can measure rainfall in real time. It was not possible to determine the instantaneous rainfall rates in the present study, because no reference meter for recording instantaneous values of rainfall intensity was available. The recording rain gauges used are not suitable to measure reliable average intensities for time periods of less than 15 minute in duration. Hence the rates measured by radar are also the average value for a quarter of an hour. The accuracy of the radar measurements was worked out by computing the number of »correctly» measured intensities (error $\leq \pm 50\ \%$). The corresponding numbers have been calculated for various network densities, too.

Table 3. Percentage of »correct» 15 min. observations (error in rainfall rate $\leq \pm 50\ \%$) for various network densities and radar measurement methods.

	Date 1969	No of obs.	Number of gauges per 180 sq.km.					Radar measurement method			
			12	9	6	3	1	M-P	Mean value of a	Reference gauge technique	Coeff. fr. drop size measure.
Continuous rain	12 July	20	100	100	95	90	65	80	80	85	95
	18 July	13	100	100	85	54	46	85	85	85	69
	26 Aug.	10	100	100	100	70	40	70	70	70	80
	6 Sept.	7	100	100	100	100	86	86	86	71	—
	13 Sept.	6	100	100	83	67	67	33	33	50	83
	14 Sept.	39	100	100	100	74	69	90	90	82	90
	15 Sept.	4	100	75	75	75	75	75	100	100	—
	22 Sept.	16	100	100	100	94	94	88	88	88	—
	Total	115	100	99	96	78	68	82	83	81	86
Showers	25 July	14	100	100	100	57	36	36	43	50	36
	23 Aug.	10	100	70	60	10	10	30	80	70	20
	25 Aug.	6	100	83	33	0	0	67	83	83	0
	30 Aug.	6	100	83	67	50	50	50	83	67	50
	2 Sept.	6	100	100	100	33	33	50	33	17	—
	3 Sept.	4	50	25	25	0	0	50	75	—	—
	Total	46	96	83	72	30	24	45	63	52	28
Drizzle	27 Aug.	14	100	100	100	100	100	0	0	100	29
	16 Sept.	11	100	100	100	91	64	54	100	18	—
Entire material		186	99	95	90	69	59	65	73	73	65

The percentage of »correct» 15 minute observations appears in Table 3 for various network densities and various radar methods.

Figure 2 shows the percentage of »correct» observations as a function of network density for continuous rains, showers and for the entire material. No curve for drizzle is presented due to insufficient observations. In the figure the percentage of »hits» with various radar methods was marked with symbols on the lines to define values for the EGD 2. As expected, the number of »correct» observations decreases as the network density decreases. During continuous rains the EGD 2 for all the radar methods ranged between 3.5—4.3 gauges/180 sq.km (1 gauge/51—42 sq.km) giving an approximated average of 1 gauge/46 sq.km.

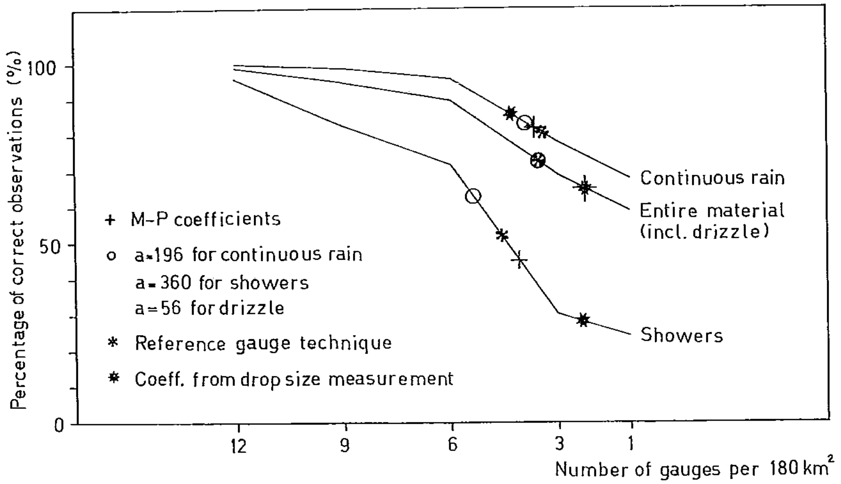

Fig. 2. Percentage of »correct» 15 minute observations (error in precipitation rate $\leq \pm 50$ %) as a function of network density. The number of »hits» for various radar measurement methods are marked on the lines with symbols.

In showers the EGD 2 depends greatly on the radar method. The M-P coefficients led to a value of 4.1 gauges/180 sq.km (1 gauge/44 sq.km), the drop size distribution coefficients to 2.3 gauges/180 sq.km (1 gauge/78 sq.km), the mean value of *a* for showers ($a = 360$) to 5.4 gauges/180 sq.km (1 gauge/33 sq.km) and finally the reference gauge technique to a value of 4.6 gauges/180 sq.km (1 gauge/39 sq.km).

When the material is combined (including drizzle cases) the M-P and the drop size coefficients provide an EGD 2 of 2.2 gauges/180 sq.

km (1 gauge/82 sq.km) and the two remaining radar methods a value of 3.5 gauges/180 sq.km (1 gauge/51 sq.km) for the EGD 2.

5. *Discussion and conclusions*

When daily rainfall amounts are measured by radar over an area of 180 sq.km and the results are compared with the corresponding recordings of a dense rain gauge network, the mean error in radar estimates of daily precipitation amounts is larger than that obtained with one rain gauge located in the middle of the check site. This is valid for rains of large extent both in time and space (continuous frontal rain). In the case of showers, the ability of a network to measure the areal rainfall decreases rapidly as the network density decreases. In these rains the equivalent gauge density (EGD 1) for various radar measurement methods is as follows:

1 gauge/51 sq.km	applying the M-P coefficients
1 gauge/26 sq.km	applying the mean value of a for showers $(a = 360)$
1 gauge/33 sq.km	applying the reference gauge technique
1 gauge/180 sq.km	applying the coefficients obtained from drop size distribution measurements.

Since the M-P coefficients overestimated the daily amounts of areal rainfall in each convective storm, the utilization of these coefficients in showers is senseless. The coefficients obtained by measuring average drop size distribution for each storm also led regularly to overestimates of rainfall amounts by radar. Neglecting these two radar methods the remaining radar techniques gave an approximation of the EGD 1 for showers: 1 gauge/30 sq.km.

The EGD 1 values for the entire material (including two cases of drizzle) are as follows:

$\sim$ 1 gauge/180 sq.km	applying the M-P coefficients and the reference gauge technique
1 gauge/62 sq.km	applying the mean value of a for each rainfall type
$<$ 1 gauge/180 sq.km	applying the coefficients obtained from drop size distribution measurements.

Defining the equivalent gauge density with the aid of the number of »correct» 15 minute areal intensity observations (EGD 2) all the radar methods gave the approximated value of 1 gauge/46 sq.km for continuous rains. For showers the following EGD 2 values were obtained:

1 gauge/44 sq.km	applying the M-P coefficients
1 gauge/33 sq.km	applying the mean value of a for showers ($a = 360$)
1 gauge/39 sq.km	applying the reference gauge technique
1 gauge/78 sq.km	applying the coefficients obtained from drop size distribution measurements.

Again neglecting other radar methods except the reference gauge technique and the one applying the mean value of a for showers, we obtained the average value of the EGD 2 for showers: 1 gauge/36 sq.km.

For the entire material the M-P coefficients and those from drop size data gave a value of 1 gauge/82 sq.km for EGD 2. The EGD 2 was 1 gauge/51 sq.km when the reference gauge technique or the mean values of a for each precipitation type were applied for the entire material.

REFERENCES

1. Aoyagi, J., 1964: Areal rainfall amounts obtained by a 3.2 cm radar and a raingage network. *Proc. World Conf. on Radio Meteorology* (*11th Weather Radar Conf.*), A.M.S., Boston, Mass., 116—119.
2. Borovikov, A., Kostarev, V., Mazin, I., Smirnov, V., and A. Chernikov, 1970: *Radar measurement of precipitation rate.* Israel Program for Scientific Translations, Jerusalem, 1970, 112 pp.
3. Dimaksian, A., and N. Zotimov, 1965: Results of radar measurements of liquid precipitation. *Tr. Gos. Gidrolog. Inst., No. 130,* 530—537. (See complete translation in Sovjet Hydrology: Selected Papers, 6, 1965).
4. Jatila, E., and T. Puhakka, 1972: Experiments on the measurement of areal rainfall by radar. *Geophysica,* 12,
5. Muchnik, L., Markovich, V., and L. Volynetz, 1966: On the evaluation of accuracy of the radar method of measuring the areal rain quantity. *Proc. 12th Conf. on Radar Meteorology,* A.M.S., Boston, Mass., 216—219.
6. Wilson, J., 1966: Storm-to-storm variability in the radar reflectivity—rainfall rate relationship. *Proc. 12th Conf. on Radar Meteorology,* A.M.S., Boston, Mass., 229—233.
7. —»— 1970: Integration of radar and raingage data for improved rainfall measurement. *J. Appl. Meteor.,* 9, 489—497.
8. —»— 1970: Operational measurement of rainfall with the WSR-57: review and recommentations. *Preprints 14th Radar Meteorology Conf.*, A.M.S., Boston, Mass., 257—263.