Report of the National Research Center for Disaster Prevention, No. 5, March 1971

551.579.1:551.577.21:551.501.7/.8

A System Composed of a Central Computer and Weather Radars for Measuring Areal Precipitation

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Abstract

The only way to measure the areal precipitation directly at present is to use the weather radar. Unfortunately, however, the relation between radar echo and precipitation varies with conditions so much that it is difficult to use the radar as rain gauge. One of the ways to overcome this difficulty is to calibrate the measurement of radar by rainfall telemeters. For this purpose, it is possible to construct a system composed of a central computer, weather radars and rainfall telemeters, but there arise other difficulties, because the transmission of the high-frequency radar signals necessitates a very expensive communication system and the data processing of the computer becomes difficult. In consideration of the very low frequency of hydrological phenomena, such a communication of the radar signal itself seems to be somewhat superfluous, and an idea is proposed and discussed with regard to the integration of the radar signal at the site to cut off its high-frequency components.

With gate circuits and integrators it is possible to construct an analog device which gives local averages of radar signals on polar coordinate meshes. It is necessary to rotate the antenna slowly in order to make the communication density low, and thus the data can be transmitted by usual telephone line at low cost. The processing has another important merit in making the information density low, so that many radars can be controlled with one central computer. In this system the radars need not be powerful and of long range. The aimed region can be covered with circles of radar ranges, so as to avoid the interruption of mountains. The results of experiment show that this system is promising.

1. Purpose and Outline of the System

1.1 One of the most important and difficult problems in water balance is the measurement of areal precipitation. We can only estimate it from a set of rain gauges, and as we cannot measure directly areal precipitation itself, the error of estimated areal precipitation must be a theoretical one, that is, the error is derived from some hypotheses, and cannot be evidently proved.

1.2 We consider that the only way of measuring the areal precipitation directly at present is to use the weather radar. Unfortunately, however, the relation between the intensities of radar echo and precipitation varies with conditions so much that it is very difficult to use the radar for rain gauge. One of the ways to overcome this difficulty is to calibrate the measurements of radar by rainfall telemeters. For this purpose, we can use the central computer connected with the radar and rainfall telemeters. Moreover, with the use of a central computer we can construct a system for flood forecasting, heavy rain warning, dam-gate control, etc. (M. Sugawara *et al.*, 1968; M. Sugawara, 1968).

1.3 There lies in communication another difficulty that the radar signal requires very high frequencies, and so the communication system becomes expensive and moreover the data processing of the central computer becomes difficult. As the hydrological phenomena are of very low frequency, there must be some superfluousness to communicate radar signal itself. And we have got an idea of integrating the radar signal at the radar site by cutting off its high frequency components (M. Sugawara, 1968; E. Kessler and K. E. Wilk, 1968).

1.4 If we integrate the radar signal at each of sequential intervals with the use of gate circuits and integrators for time duration Δt, setting the radar antenna in a fixed direction, we obtain the local integral of radar echo in time and space, where the integral domains are as shown in Fig. 1, in which Δr is determined by the time interval of gate opening and $\Delta\theta$ is the width of radar beam.

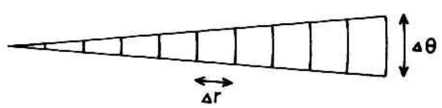

Fig. 1.

1.5 By stepwise rotation of the radar antenna with rotating angle $\Delta\theta$, after fixing it for time interval Δt, we can get the local integral of radar echo on polar coordinate meshes.

But the stepwise rotation is not essential, and we may rotate the antenna continuously at a constant speed.

1.6 It is important to rotate the antenna slowly, and then we can set the long time interval Δt, which causes the following large merits:

1) The noises with cancel each other during the integration interval Δt, so that the noise level becomes lower by inverse proportion to the square root of Δt.

2) The communication density becomes lower by inverse proportion to Δt.

1.7 For example, let $\Delta\theta$ be 3° and Δt be 1 second, then the rotation period is 2 minutes. If we divide the radar range into 30 intervals, and as each of integral values can be expressed in 7 bits, we can transmit the obtained informations with 210 bits per second or it may be sufficient with 300 bits per second even when other necessary signals are included. Therefore, it is easy to communicate with the usual telephone line at low cost.

1.8 As the result of low communication density, there arises the possibility of controlling many radars with one central computer. In this system the radars need not have long ranges, because our purpose is to cover the area with a set of radar ranges overlapping at their peripheries (M. Sugawara, 1969a and 1969b).

1.9 The use of a set of short-range radars has several merits as follows:

1) The radars need not be powerful because of their short range.

2) The interruption by high mountains can be avoided by appropriate distribution of radars.

3) An inadequate height of radar beam, which is caused by the curvature of the globe or by the elevation angle of radar antenna, does not occur in the cases of short-range radars.

4) The radar beam widths need not be so small because of short range, and the radar antenna need not be so great.

1.10 Although there may be a problem of cost in setting up a system of radar net, we consider that such system is desirable because the communication system is not expensive, and the radars also are not so expensive from the following reasons:

1) Radars need not be powerful because of their short range.

2) As the final data from the radars are the integrated value, the noises will cancel each other during the integration. Therefore, the radar apparatus may have rather large noises.

3) Because of the short range, the radar beam widths need not be so small.

4) As we use the data from radars after calibration with rainfall telemeters, the radar apparatus may have some drift or fluctuations of low cycles whose periods are much longer than the time interval of calibration.

5) Each apparatus of the system, such as radars, integrators, etc., must be made by the same specifications, and the production cost per unit may become lower.

2. Results of Our Experiments

2.1 The first trial was to connect the computer with the radar directly. Using the analog-to-digital converter, it was tried to convert the radar signal itself into digits for obtaining the distribution of radar echo intensity on polar coordinate meshes in digital forms. Then we can transform them into the precipitation distribution on polar coordinate meshes after calibration with the rainfall telemeters (M. Sugawara *et al.*, 1968; M. Sugawara, 1968). After some successful experiments, a conclusion that it would be better to integrate the radar signal at the radar site before the transmission to computer was obtained, and an apparatus was made for the test of that possibility (M. Sugawara, 1968).

2.2 The radar which was used for our experiment had many weak points.

1) The radar was made several year before and was too old for reconstruction.

2) The radar was made at first for the detection of artificial rainfall and its wave length is 3 cm, being not suitable for rainfall measurements which require longer wave lengths.

3) It is important to rotate the radar antenna slowly for our purpose, but our radar antenna rotates 10 times per minute.

4) Our radar is situated at the center of a small plain surrounded by mountains in all directions as shown in Fig. 2. It is the worst situation for rainfall measurement.

5) In our new system with integrators, the noise level becomes low by integration, but our radar apparatus is made to cut off the radar signal under original noise level. Therefore, we cannot utilize the weak radar signal which may become useful in our new system.

2.3 The outline of the analog devices with gates and integrators is as follows:

1) The radar range of 60 km is divided into 20 sections by gate circuits which open for 20 μsec successively. The first section nearest to the radar is not used because of noises.

2) Each of dissolved radar signals through the gates is integrated by the incomplete integrator (the linear filter of first-degree lag system) of time constant of 0.1 second, during which the radar antenna rotates by 6° in azimuth.

3) Each integrator is sampled and held simultaneously at the interval of 0.1 second, in other words at the interval of 6° in azimuthal angle.

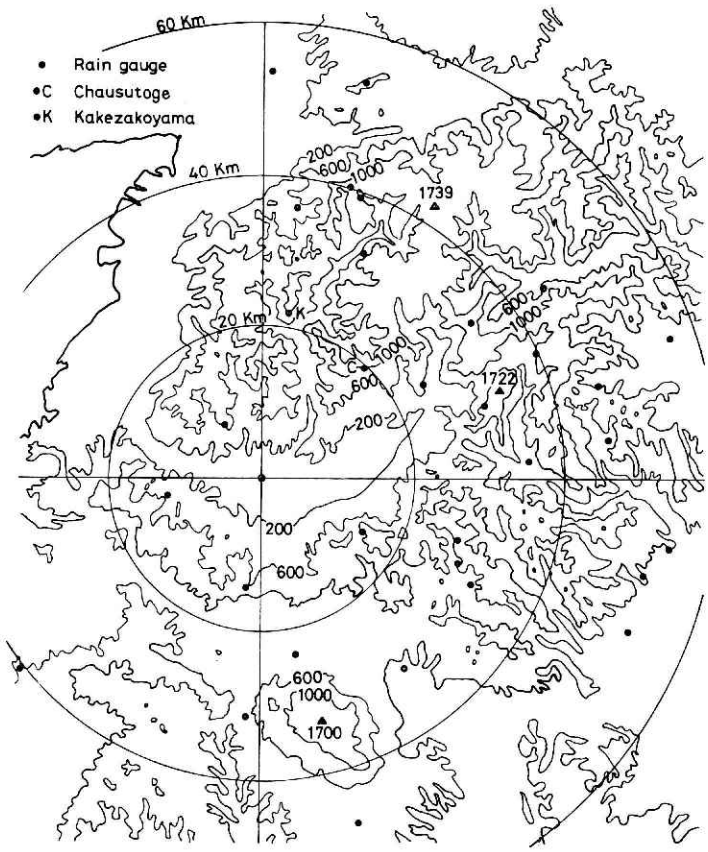

Fig. 2.

4) The integrated radar signals held in analog memories are sent out for transmission. In our case they are recorded in a magnetic tape recorder for the reproduction at the computer.

5) Thus, we can obtain the local integral of radar signals on polar coordinate meshes, where $\Delta r = 3\,\text{km}$ and $\Delta\theta = 6^\circ$. Smaller meshes of $\Delta r = 1.5$ to $2\,\text{km}$ and $\Delta\theta = 2^\circ$ to 3° were wanted, but we could not get them because of expense.

2.4 The data recorded on analog magnetic tapes are reproduced and turned into digits which are summed up on polar coordinate meshes for some time intervals, usually of ten minutes. Then we get a map of radar echo distribution in digital forms.

2.5 Distribution of radar echo intensity is transformed into rainfall distribution in a digital computer.

2.5.1 The first correction is the compensation of radar echo intensity weakened by mountains. We assume that the effect of mountain shadow decreases exponentially with distance. Therefore, we multiply the echo density by the compensation factor.

$$A = 1 + c \sum_{r_i < r} g_i \exp\{-\alpha(r - r_i)\},$$

where α is a decreasing coefficient, c a constant, g_i the intensity of ground echo of a mountain which lies at the distance r_i from the radar, and r the distance of the point which lies behind the mountain. The constants α and c are so determined by trials as to give the good final results.

The corrected echo intensity on the mesh domain where the ground echo exists must be corrected again by eliminating the ground echo.

2.5.2 Then the corrected radar echo must be turned into rainfall. The relation between rainfall intensity $R(r)$ and radar echo intensity $P(r)$ is given as

$$\log R(r)=\beta\left[\log P(r)+2\log r+A+B\int_0^r \exp\{c\log R(r')\}\mathrm{d}r'+Dr\right],$$

where r is the distance from the radar, β, A, B, C, D constants, and D among them negligible in our case of the radar of 3-cm wave length.

2.5.3 In our system we use the integral $\overline{\log P(r)}$ instead of $\log P(r)$, so there appears a problem of putting $\overline{P(r)}$ and $\overline{R(r)}$ instead of $P(r)$ and $R(r)$ in the above radar equation, because both of the logarithmic and exponential functions are not linear.

There exists also a more difficult problem in our system in which the weak radar signals below the noise level are cut off previously. If the weak radar signal is fluctuating above and below the noise level during the integration interval, the integral value with the cut-off signal must become greater than the integral of original signal. Even the noise itself cannot cancel each other in this case.

Therefore, if we put the integral of the cut-off signal into the radar equation without correction, we will get far greater values than the actual when the signals are weak and the distance is large or the damping effect of the rain is large.

2.5.4 The correction for the bias of this type must be statistical, and it is rather reasonable to add the statistical correction to the radar equation which has also a statistical origin in its main part. As we use the radar equation on polar coordinate meshes, we put integer i instead of distance r, where i corresponds to the i-th radial interval. Thus the radar equation turns into the following form, where P_0 is the noise level.

$$\log R(i)=\frac{1}{\beta}\left[\log\frac{P(i)}{P_0}+A(\log i+B)+C\sum_{i'=1}^{i-1}\{R(i)\}^{\alpha}\right].$$

As this formula gives much larger rainfall than actual when the radar signal $P(i)$ is small and the second and third terms of the formula are large, we must multiply correction factors F and G to the second and third terms, respectively.

$$\log R(i)=\frac{1}{\beta}\left[\log\frac{P(i)}{P_0}+F\cdot A(\log i+B)+G\cdot C\sum_{i'=1}^{i-1}\{R(i)\}^{\alpha}\right].$$

The correction factors are given as

$$F=\begin{cases} f(i)\log\dfrac{P(i)}{P_0}+k\cdot c\displaystyle\sum_{i'=1}^{i-1}\{R(i)\}^{\alpha}, & (\text{when } F<1)\\ 1, & (\text{otherwise})\end{cases}$$

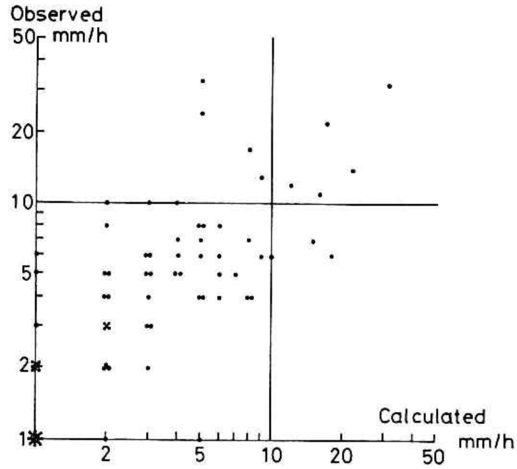

Fig. 3. Before calibration (Kakezakoyama).

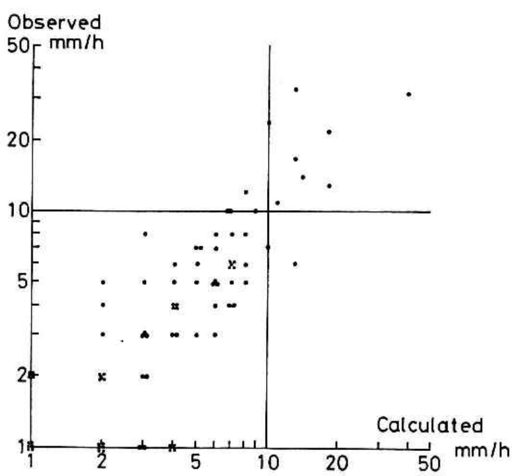

Fig. 4. After calibration (Kakezakoyama).

$$G=\begin{cases} f(i)\log P(i)\,, & \text{(when } G<1) \\ 1\,, & \text{(otherwise)} \end{cases}$$

$$f(i)=1/(a+bi)\,,$$

where k, a, b are constants. Meaning of the function $f(i)$ may be probably a simple approximation of logarithmic function ($k'\log i+B'$).

The forms and constants of the correction factors are determined by trials, so as to obtain good final results, but there remain still many ambiguities.

2.5.5 One of the results obtained by the above corrected formula is shown in Fig. 3. The correlation between the observed and estimated rainfall values becomes bad, while the distance from the radar increases. Without the above correction, however, there is scarcely any correlation at distant spots.

2.5.6 The relation between radar signal and precipitation may fluctuate with time partly from the variation of distribution of rain drops, and partly from the fluctuation of the power of radar, etc. These fluctuations can be corrected by multiplying the correction factor that varies with time. These values can be determined by comparing the derived rainfall with the observation.

There may be also local fluctuation which can be corrected by local factor. After these corrections we get slightly better results as shown in Fig. 4.

2.5.7 More important method to obtain better results must be the repeated calibration with short time intervals. For example, if we repeat the calibration at 15-minute intervals, then we get hourly precipitation as the sum of four calibrated values. We will get better results than in the case when we calibrate one time per hour.

Unfortunately we can use hourly precipitation data only, and therefore, instead of using the precipitation data of 15 minutes, we sum up the successive four calibrated hourly data and compare the sum with the observed precipitation of four hours. The results show better correlation as shown in Fig. 5, but we consider them to be not sufficient for use.

2.5.8 One reason why the correlation is not good is that the value derived from the radar data is the estimate of areal precipitation on polar cooridinate

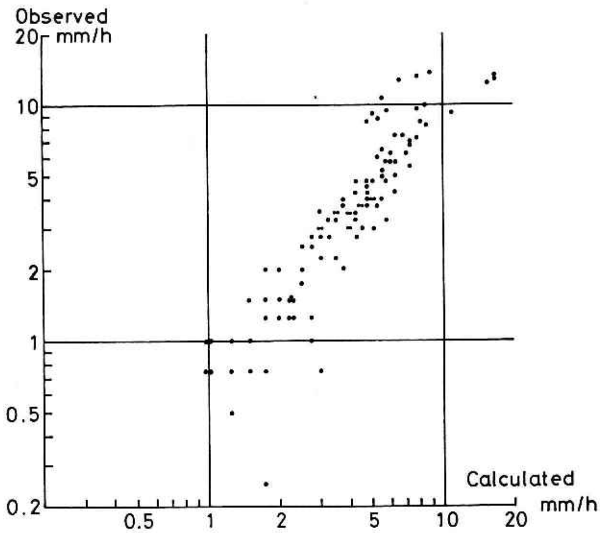

Fig. 5. Average for 4 hours (Kakezakoyama).

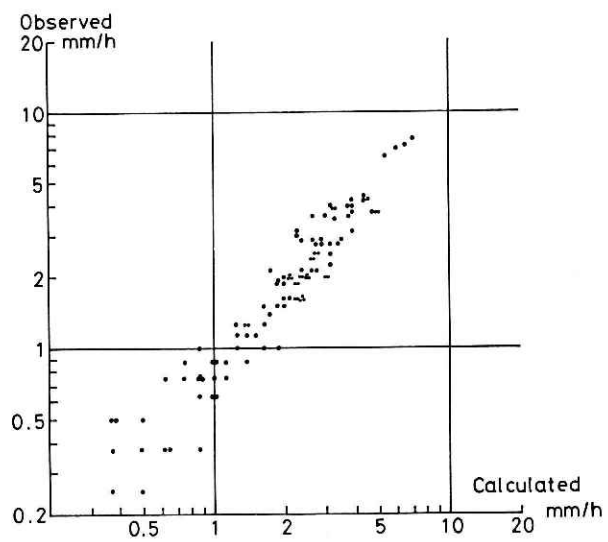

Fig. 6. Average for 4 hours of two spots (Kakezakoyama and Chausutoge).

mesh domains and is different from the value of point precipitation which is measured by a rain gauge at a point.

Unfortunately we cannot measure the areal precipitation directly to compare with the radar data. Instead of areal precipitation we can use the sum of point precipitations of several rain gauges, and the sum is compared with the sum of corresponding values derived from the radar data. One of the results is shown in Fig. 6.

2.6 Though the final results shown in Fig. 6 are not satisfactory, it may be said that our method is promising, in consideration of many bad conditions of our experiments.

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(Manuscript received 27 March 1970)

Report of the National Research Center for Disaster Prevention, No. 5, March 1971

多数のレーダと中央の計算機による地域雨量測定法

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現在，地域雨量を直接測定する唯一の方法はレーダ利用であろうが，困ったことに，レーダエコーの濃さと雨量強度との関係は，雨滴分布で左右される．それを，雨量テレメータの観測値で補正するために，レーダ，テレメータ，計算機の組合せの方式がまず考えられた．そうするとレーダから計算機までの情報伝送が問題になる．レーダ信号は非常な高周波で，その伝送には費用がかかる．一方，大雨とか洪水は，せいぜい15分単位ですむ程度のきわめて低周波現象である．それにメガヘルツ級のレーダ信号が必要であるとすれば，どこかにむだがあるに違いない．そこでレーダ信号をレーダの所で積分することを考えた．ゲート回路と積分回路からなるアナログ機構により，極座標メッシュ上で，レーダ信号の局所的平均値を作り，アナログホールドし，順次送り出していく．

この際，アンテナをゆっくり回転させれば，伝送密度を十分に落とすことができて，普通の電話線にのせることができる．伝送費用は安くなるし，積分によりレーダ信号中の雑音のレベルが落ちるから，レーダをあまり高級にしなくても，精度が得られる．したがって，多数レーダを配置し，それを中央の計算機で支配するシステムを組むことができる．

われわれが行なった実験では，既存の設備を使わざるを得なかったから，アンテナの回転速度を落とすこともできず，極座標メッシュも $\Delta r=3\,\mathrm{km}$, $\Delta\theta=6^\circ$ とあまり小さくできなかったが，それにもかかわらず，昭和44年6月~7月に行なった実験結果はかなり良好であった．

レーダ信号の区分的積分値は，現地（人吉）でデータレコーダにアナログ記録され，東京に持ち帰ってA-D 変換され，計算機に入れられた．

極座標メッシュ上に数値化されたレーダ信号は，まずグランドエコーの補正が施され，次に雨量に変換された．われわれのレーダでは，あるレベル以下のレーダ信号が切り捨ててあるが，それから生じたと思われるかたよりが，このとき補正された．この補正をしても，結果（図3）はあまりよくない．そこで，各時間ごとに全地点に共通な補正係数，各地点ごとに全時間を通じて共通な補正係数を定めて，これを掛けると，結果はいくらかよくなる（図4）．15分ごとに補正をすれば，結果はよくなると思われるが，その資料がないので，1時間ごとの補正をして，4時間の和にして比較したのが図5で，結果はかなりよくなる．元来，レーダで測る雨量は地域雨量であるから，これを地点雨量と比較するのが無理であろう．そこで何地点かの合計にして比較したものが図6で，結果はさらによくなる．

これらの点からみて，レーダ，テレメータ，計算機の組合せ方式は，十分有望であると思われる．