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Study of Z-R relationship over Gadanki for different rainfall rates

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In this paper, Z-R relationship for different rain fall rates over Gadanki has been studied over a period of four years 1998-2001. The basic data set consists of rainfall rates and reflectivities derived from disdrometer during this period. The study has been carried out for rainfall rates $R\leq 0.5$ mmh^{-1}, $0.5<R\leq 4.0$ mmh^{-1}, $4<R\leq 10$ mmh^{-1}, $10<R\leq 50$ mmh^{-1} and $R>50$ mmh^{-1}. The study shows that Z-R relationship varies for different rainfall rates. The various functional relations between reflectivity and rainfall rate are obtained.

Keywords: Rainfall rate, Reflectivity, Drop size distribution
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1 Introduction

Knowledge of rainfall is necessary in agriculture, hydrology, climatology, weather forecasting and weather modification. Communities in many countries often experience flood. The flash floods following rains or heavy thunderstorms cause serious damage to human property and threat to life. In communication and link designing, high frequencies are being deployed. However, at high frequencies the atmospheric components, viz. rain, snow, atmospheric gases, hail, dust particles, etc. attenuate the signal. Of all these components, rain is the most hazardous. Above 10 GHz, the attenuation effect is potentially significant leading to failure of the link. Hence, the study of rainfall is important in link designing and defense.

Closely spaced rain gauges are needed for forecasting flash floods and weather modification. Installing and maintaining very closely spaced rain monitoring stations is not practically possible. Hence, use of radar as an alternate tool to estimate rainfall is justified. However, radar does not measure rainfall rate directly, rather radar estimates back scattered energy from rain drops using a parametric relation of the form:

$$Z = \alpha R^{\beta} \quad \dots (1)$$

where, Z, is reflectivity factor; R, rainfall rate; parameters α and β, are to be determined. Equation (1) shows that estimation of rain fall is affected by the variability in the relationship between back scattered energy and precipitation rate. Hence, a wrongly chosen relationship will lead to serious error in rainfall estimation. The parameters, α and β, in conventional Z-R relationship as given by Eq. (1) are obtained by matching radar estimated reflectivity values with rainfall rates measured by rain gauges. However, the radar sampling volume is located at an altitude of 1-2 km, with significant time displacement whereas rain gauges measure surface rainfall rate which creates non synchronization of space and time of the two measurements.

All over the globe, the above conventional power law is used to estimate rainfall rate from reflectivity factor irrespective of geographic locations, climatological conditions, rainfall rates, types of precipitation and instruments used. As a matter of fact, a universal Z-R relationship does not seem to hold in all conditions. Reflectivity depends on the back-scattered energy by the target. As rainfall rate increases the back scattered energy reduces because of attenuation of the signal by rainfall. Hence, at high rainfall rates, a conventional Z-R relation may not be valid. Moreover, at high rainfall rate, rain events consist of various drop sizes. The study by Radhakrishna & Narayana Rao points out that on occasions, the shape of rain drop size distribution show bi or tri modal peaks[1]. As reflectivity depends on drop size distribution[2], at high rainfall rates concept of a single Z-R relationship may not be appropriate. Besides, while developing such relationships, the instantaneous surface and upper air meteorological elements such as temperature, pressure, etc. were not taken into consideration. The back scattered signal suffers bending because of variations of refractive index in the atmosphere. The variation of refractive index is attributed to pressure, temperature, dew point temperature, etc. Hence, reflectivity and in turn Z-R relation is supposed to be affected by the meteorological elements. It has been found by Sen & Uma[3] that rainfall is affected by meteorological elements. Hence, it is necessary to search for a suitable model for Z-R relationship instead of assuming one.

An attempt has been made to obtain reflectivity-rainfall rate relationships for large data set considering different rainfall rate ranges. Witold[4] has pointed out that large data set of over 10,000 samples is required to obtain valid estimates of Z-R parameters. He also pointed out that the results of estimation are sensitive to the selection of threshold of rainfall rate and reflectivity data. The objective of the study is to find out whether Z-R relations vary with rainfall rate and which model exactly suits Z-R relations over Gadanki. For this purpose, rainfall rate intervals $R \leq 0.5$, $0.5 < R \leq 4$, $4 < R \leq 10$, $10 < R \leq 50$ and $R > 50$ have been chosen. The validity of the model is judged by F test at 5% level of significance.

2 Data

In the present study, reflectivity and rainfall rate data obtained from disdrometer installed at National Atmospheric Research Laboratory, Gadanki have been used over a period of 1998-2001 for all the rainy days. The number of data points are 5388, 13935, 19391 and 11392 for 1998, 1999, 2000 and 2001, respectively. The study has also been performed in each rainy month, the number of data points varying from a minimum of 537 to a maximum of 5730. The study has been repeated by considering 20 data points. The purpose of using small as well as large data set is to check whether the proposed model, suited for short range, is valid for long range and vice versa. The negative reflectivity values corresponding to very small rainfall rates have been neglected. The rainfall rate data have been divided in to various classes, viz. $R \leq 0.5$; $0.5 < R \leq 4$; $4 < R \leq 10$; $10 < R \leq 50$; and $R > 50$. This may be noted that dead correction is not applied to rainfall rate.

3 Results and discussions

In the present study, monthly and yearly analysis of reflectivity and rainfall rate has been carried out. The data has been tested against a cubic (Cub), growth (Gr), logarithmic (Log), logistic (Logs), exponential (Exp), S-curve (S), linear (Lin), quadratic (Quad), inverse (Inv), compound (Comp) and power (Pow) model. The study shows that in the range $R \leq 0.5$ mmh^{-1}, the reflectivity-rainfall rate relation fits a cubic curve for certain months and logarithmic curve for certain months of all the years studied [Figs 1 (a)-(d)].

The results of Z-R relationship analysis for all rainfall rate intervals: $R \leq 0.5$, $0.5 < R \leq 4$, $4 < R \leq 10$ and $10 < R \leq 50$ are presented in Tables 1(a)-(f). Table 1(a) depicts monthly Z-R relationship over Gadanki in the year 2001 for $R \leq 0.5$. It is seen from Table 1(a) that in the rainfall rate interval $R \leq 0.5$, during February-September, the Z-R relation over Gadanki mostly suits cubic curve. Table 1(b) presents the monthly Z-R relationship over Gadanki in 1999 during May - December in the rainfall rate interval $0.5 < R \leq 4$. The Z-R relationship mostly suits cubic curve, whereas, power law is suitable in July and December 1999 and logarithmic law is suitable in October 1999. In the rainfall interval $4 < R \leq 10$, no model is suitable in most of the months over the period of study except in May and September 2000 when a power and S-curve are respectively suitable. In July and September 2001, a power curve is suitable as shown in Table 1(c).

From the analysis, it is also found that in 1998 in rainfall rate interval $R \leq 0.5$, a logarithmic curve is suitable in April; a cubic curve in July and September; and an S-curve in May. In 1999, in the same rainfall rate interval, a logarithmic curve is suitable in May, June, July and November, whereas, a cubic curve is suitable in August, September and October. In 2000, a logarithmic curve is suitable during April-July and in September and November. In August, October and December, a cubic curve is suitable in the same rainfall rate interval.

In the rainfall rate interval $0.5 < R \leq 4$, a cubic law is suitable in July, whereas an S-curve is suitable in September in 1998. In the same rainfall rate region in 2000, a power law is suitable in May and July; a cubic law in January, June, August and December; and a logarithmic curve in September and November. In 2001 in the rainfall rate interval $0.5 < R \leq 4$, a power law is suitable in April and May; a cubic law in July and August; and a logarithmic curve in September.

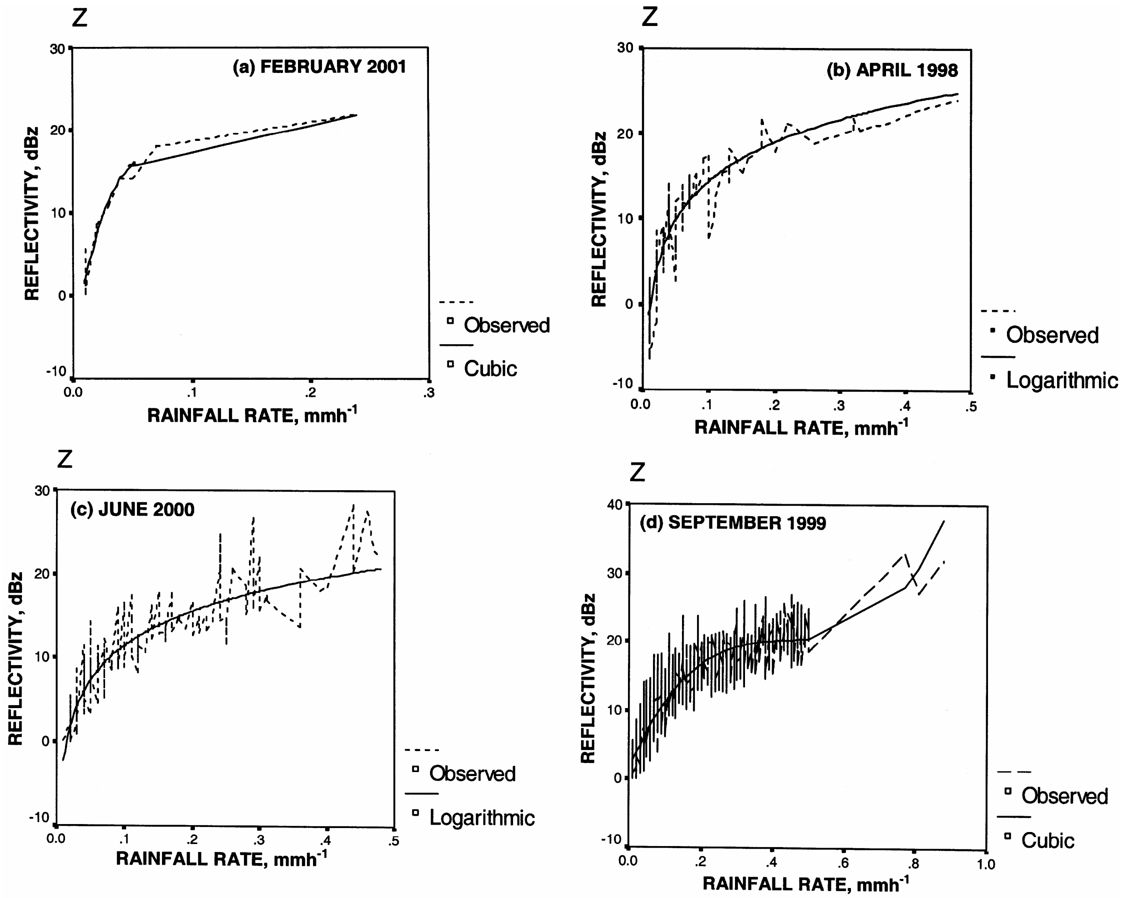

Fig. 1 — Reflectivity *vs* rainfall rate over Gadanki for R<=0.5: (a) February 2001; (b) April 1998; (c) June 2000; and (d) September 1999

Table 1 (a) — Monthly Z-R relationship in the year 2001 for R≤0.5

Month	Model	Equation
Feb 2001	Cub	$Z=4.77+762.72R+8160.5R^2+22687.41R^3$
Mar 2001	Cub	$Z=0.768+213.11R+724.86R^2+807.41R^3$
Apr 2001	Comp	$Z= 0.017(1.161)^R$
May 2001	Log	$Z=23.92+4.778 \ln R$
Jun 2001	Cub	$Z=0.96+104.33R+169.86R^2+62.87R^3$
Jul 2001	Cub	$Z=0.34+112.75R+274.29R^2+249.29R^3$
Aug 2001	Linear	$Z=R$
Sep 2001	Cub	$Z=30.10+0.873R+0.021R^2+0.0002R^3$

Table 1 (b) — Monthly Z-R relationship in 1999 for 0.5<R≤4

Month	Model	Equation
May	Cub	$Z=18.11+14.46R+5.45R^2+0.11R^3$
June	Cub	$Z=15.98+12.87R+3.23R^2+0.25R^3$
July	Pow	$Z= 25.199R^{0.256}$
Aug	Cub	$Z=20.29+3.83R+0.198R^2+0.78R^3$
Sep	Cub	$Z=18.36+9.92R+2.32R^2+ 0.17R^3$
Oct	Log	$Z=24.71+5.56 \ln R$
Nov	Cub	$Z=12.497+13.44R+3.60R^2+ 0.383R^3$
Dec	Pow	$Z=16.903R^{0.332.8}$

Table 1 (c) – Monthly Z-R relationship during 1999, 2000, 2001 for 4<R≤10

Month	Model	Equation
Jun 1999	Cub	$Z=35.97+1.128R+0.0143R^3$
May 2000	Pow	$Z= 21.314R^{0.3261}$
Sep 2000	S	$Z= e^{(3.77+ 1.228/R)}$
Jul 2001	Pow	$Z= 20.31R^{0.261}$
Sep 2001	Pow	$Z= 24.6R^{0.168}$

Table 1 (d) — Monthly Z-R relationship in 1999 for 10<R≤50

Month	Model	Equation
Jul 1999	Cub	$Z=44.96+1.386R+1.712R^2+0.001R^3$
Aug 1999	Pow	$Z= 28.13R^{0.1425}$
May 1999	Cub	$Z=34.3+0.836R+0.014R^2+0.00001R^3$
Sep 1999	Cub	$Z=32.484+0.658R+0.008R^2+0.0004R^3$
Oct 1999	Cub	$Z=39.28+0.283R+0.026R^2+0.0001R^3$
Nov 1999	Cub	$Z=32.68+0.445R+0.003R^2+0.001R^3$
Dec 1999	Cub	$Z=1.34+80.45R+112.9R^2+46.93R^3$

Table 1 (e) — Monthly Z-R relationship in 2000 for $10<R\leq50$

Month	Model	Equation
Apr 2000	Cub	$Z=40.27+0.28R+0.001R^2+0.0001R^3$
May 2000	Pow	$Z= 31.18R^{0.119}$
Aug 2000	Pow	$Z= 27.0R^{0.155}$
Sep 2000	Cub	$Z=28.62+1.284R+0.032R^2+0.0002R^3$
Oct 2000	Cub	$Z=32.39+0.61R+0.00068R^2+0.00002R^3$

Table 1 (f) — Monthly Z-R relationship in 2001 for $10<R\leq50$

Month	Model	Equation
Jun 2001	Cub	$Z=49.3+2.08R+0.14R^2+0.002R^3$
Jul 2001	Cub	$Z=38.87+0.95R+0.09R^2+ 0.002R^3$

Table 2 — Yearly regression relations between reflectivity and rainfall rate over Gadanki for $R \leq 0.5$ considering 20 data

Year	Model	Equation
1998	Cub	$Z=14.279+15.320R-5.115R^2+0.652R^3$
1999	Cub	$Z=- 0.002+210.317R-921.226R^2+1283.587R^3$
2000	Cub	$Z=-2.768+168.671R-521.451R^2+589.009R^3$
2001	Cub	$Z=0.649+195.106R-521.016R^2-3882.17R^3$

Tables [1(d)-(f)] depict the results of Z-R relationship for the rainfall rate interval $10<R\leq50$. In this interval, a cubic law is suitable in May, July, September, October, November and December 1999; April, September and October 2000; and June and July 2001. In the same rainfall interval, a power law is suitable in August 1999; and May and August 2000. In other months in the interval $10<R\leq 50$, no models appear to be suitable.

In the interval $R> 50$, no model is suitable except in June and September 2000 when a quadratic and cubic model seem to suit. Surprisingly, it is found that in the rainfall rate interval $10<R\leq50$ in July 2000, several models appear to be suitable. The present study has been performed using 1-20 data also in the rainfall rate interval $R\leq0.5$ (Table 2). Figure 2 shows that in 1999 in the rainfall rate interval $0.5<R\leq4$, the Z-R relationship appears to suit a growth, logistic and exponential model using 20 data alone.

Figure 3 shows that both a cubic and a quadratic model appear to be suitable in the Z-R relation in November 1999 in the rainfall rate interval $10<R\leq50$.

From Tables 1[(a)-(f) and above discussions, it seems that at low rainfall rate, it is possible to predict a model for Z-R relationship. As rainfall rate increases, ambiguity in the prediction starts occurring and at $R>50$ it becomes impossible to predict a model.

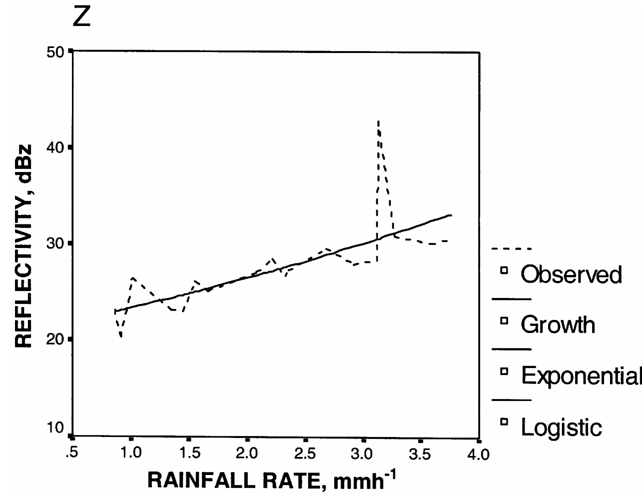

Fig. 2 — Reflectivity *vs* rainfall rate over Gadanki for 1999 for 20 data, 0.5<R<=4

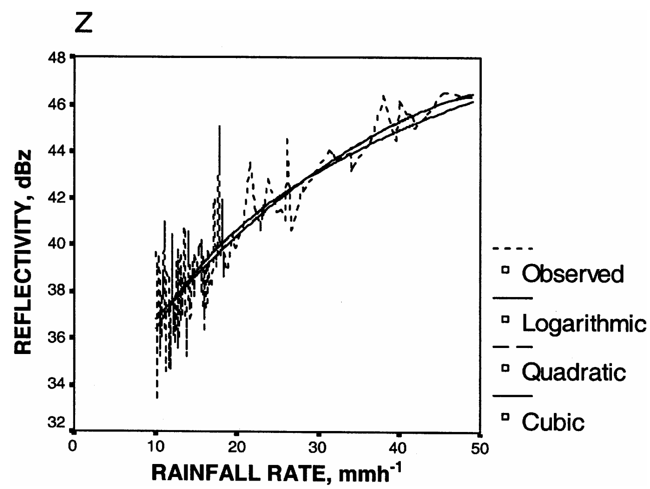

Fig. 3 — Reflectivity *vs* rainfall rate over Gadanki for November 1999, 10<R<=50

Of course, the intermediate rainfall rate interval $4<R\leq10$ shows anomaly. In this interval, no models appear to be suitable except for a few cases. The reason for this anomaly is yet to be found. Yuter & House[5] also have reported the presence of both large and small drops in stratiform rain. Stoct & Mueller[6] have shown that Z-R relationship is very similar in Oregon and Alaska and it is attributed to the similar climatic conditions at two places. Moreover, the Z-R relationships at Florida and Indonesia are also almost similar at low and intermediate rainfall rates except at higher rainfall rates. The departure at high rainfall rates, according to him, is due to the fact that at high rainfall rates different climatological conditions prevail.

Table 3 — Yearly percentage of occurrence of rainfall during 1998-2001

Rainfall rate (R), mmh^{-1}	1998	1999	2000	2001
$R \leq 0.5$	84.65	62.2	55.19	68.86
$0.5 < R \leq 4$	11.17	29.30	30.45	22.43
$4 < R \leq 10$	1.78	3.80	6.99	3.69
$10 < R \leq 50$	2.11	4.37	6.18	3.83
$R > 50$	0.27	0.43	1.21	0.49

The study by Krishna Reddy *et al.*[7] shows that drop size distribution (DSD) has seasonal dependence. Hence, Z which depends on DSD also appears to have seasonal dependence.

Table 3 shows the percentage of occurrence of different rainfall rates over Gadanki in each year. It is seen that $R \leq 0.5$ has the maximum percentage of occurrence, whereas $R > 50$ has the least percentage of occurrence. Monthly analysis also shows that occurrence of rainfall in the interval $R \leq 0.5$ is very high as compared to higher rainfall rate interval. It is found that as rainfall rate increases, percentage of occurrence decreases which is obvious as high rainfall event is short lived and low rainfall rate lasts for a longer period of time[8].

4 Conclusions

From the above study, it is clear that Z-R relationship varies in different rainfall rate intervals. Moreover, assumption of a conventional power law in all cases irrespective of rainfall type, rainfall rate and season is not justified. It is found that it is possible to predict a model in the rainfall rate intervals $R \leq 0.5$, $0.5 < R \leq 4$ and $10 < R \leq 50$. At $R > 50$ no model is suitable except in September 2000 when both cubic and a quadratic curve seem to suit well. Also, at $R > 50$ in June 2000, all models appear to suit which is an absurd case. The suitability of more than one model in a single case probably points out the necessity of implementing different approach to establish Z-R relationship. In the rainfall rate interval $4 < R \leq 10$, no model can be predicted except in few cases. Over Gadanki, most of the rain events show a very low rainfall rate, i.e. in the range $R \leq 0.5$. A rainfall rate of $R > 50$ is very scanty.

For low rainfall rates, i.e. at $R \leq 0.5$, the reflectivity versus rainfall rate relation suits a cubic model in some months and a logarithmic relation in some other months over Gadanki. However, as rainfall rate increases, the Z-R relationship often diverts from a cubic or a logarithmic curve. It seems that at higher rainfall rates a particular rain event consists of drops of various sizes, i.e. various drop size distributions contribute to a particular rain event. As reflectivity and rainfall rate depend on drop size distribution, hence, at higher rainfall rates, a single Z-R relationship may not be valid. In most of the previous studies, reflectivity and rainfall rate have been assumed to be independent variable. But that may not be reality. Rainfall rate and hence reflectivity seem to be time dependent. As for example, the rainfall rate at a particular time may depend on that at the previous instant. This may be viewed as when it rains from the same cloud for a long time the rainfall rate at an instant depends on that at the previous time or instantaneous climatological conditions, viz. temperature, pressure, etc. at any instant, perhaps depend on that at a previous instant. Hence, one should approach time series analysis to establish a relation between reflectivity and rainfall rate.

The relationship between rainfall rate and the reflectivity seem to be affected by geography and climatological conditions of a place. It seems to have seasonal variation too. It seems that it is not possible to give a universal Z-R relationship. The power law relationships established at other places should be retested considering large number of slots of small data sets. Attention may also be drawn to the fact that rain gauges record surface rainfall rate whereas radar measures reflectivity at an elevated volume. Also study is required considering large number of stations over long period. The authors aim to continue the study further.

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