New approach for grand-based radar calibration by Radar-Rainfall- altitude relationships

Abstract

Weather unipolar ground-based radar measurements can experience momentous changes by using other effective parameters that directly compromise the accuracy of the hydrometeorology applications. These radar measurements, however, need to be calibrated for more accurate rainfall estimation. In addition to the radar-rainfall relationship (Z-R), this is a pragmatic approach based on careful analyses of other parameters, including distance from the radar, altitudes, and rainfall time duration. This article introduces a new calibration approach using altitude parameters and time-stepwise processing of reflectivity-rainfall rate (Z-R) relationship. Based on previous work utilizing the radar-rainfall relationship; this article hypothesizes that the rainfall measurement from ground- based radar are affected by other parameters. This Research leads to introduce a new effective parameter and generate two new empirical coefficients (a/b and c) in radar-rainfall relationship. The study analyzed two consecutive years of unipolar ground-based radar data from 43 stations, totaling 190 occurrences of rainfall within a three-hour calibration window. Additionally, the corresponding rainfall was measured using registered rain gauges.The results indicated that the radar-rainfall relationship is improvised with altitude effect (H) and empirical coefficient (c). The radar-rainfall relationship is denoted by R2min= 58, R2max=98; when the altitude effect (H) is considered, the relationship is better improvised (R2min=71, R2max =98). The results revealed that employing other effective parameters (distance from the radar, altitudes, and rainfall time duration) leads to the optimum accuracy of the Z-R relationship.**Keyword**; Radar-rainfall relationship, Z-R, calibration, altitude

1. Introduction

Rainfall forecasting and flood prediction involve using ground-based radar and are dealt with as the most essential topics in hydrometeorology, civil engineering, and natural resources management. The reflectivity data from ground-based radar provides high spatial and sequential information about the volume and amount of rainfall. However, radars cannot accurately estimate the amount of rainfall before being calibrated due to various sources of error arising from ground topography and the atmosphere. Many studies have been conducted on radar-rainfall estimation but, there has been less focus on the accuracy of the output at different altitudes [1], distance from radar [2],[3], and rainfall duration times [4],[5]. Significant differences exist between the amount of real rainfall and the predicted amounts. While the fluctuations in rainfall predictions may not be critical during light rainfall, they can lead to considerable damage during heavy precipitation, especially in mid-latitude regions. The main factor in forecasting errors is the multiplicity of uncertainty sources in the atmosphere. The greatest way to achieve an ideal radar prediction is the calibration and adjustment of radars by effective parameters such as; altitudes, distance from radar, rainfall types, etc.

In this paper, we investigate the effects and properties of the altitude and rainfall time duration in radar-rain gauges relationship for ground-based radar calibration. Since 1948, after the Second World War, weather ground-based radars have been used in predicting rainfalls based on Marshal-Palmer's proposed relationship [6]. According to this universal relationship, there is a strong correlation between the rate of radar reflectivity (Z) and the rainfall amount (R), known as the Z-R relationship. Return signals from atmospheric targets are dimensionless information called dimensionless radar output (DRO). The DRO value is the 8-bit alteration of audio-visual motion that ranges between 0-255 dimension integer [7],[8]. There is a strong relationship between Z and R in the equation. However, this does not mean that reflectivity from radar equals the amount of rainfall [9], [10]. The A and b are empirical coefficients that refer to climatological characters, location of rainfall, rainfall seasons, geographic latitudes [11], [12] and rainfall time duration[13], [14]. The empirical coefficients depend on climate characteristics in each area [15] and are used to determine Z-R relationships and relevant regional coefficients [16]. More than 100 relationships are available for different rainfall forms such as straight form, tropical, convective, thunderstorm, shower, monsoon, and hurricanes [9]. The sensitivity variation of Z–R relationships is an uncertainty source [17], especially in rainfall calculation based on DSD. Because radar measurements carry many uncertainty sources depending on dissimilarities of radar reflectivity in the atmosphere. Radar calibration is unavoidable to estimate the amount of rainfall [18], [19]. Consequently, the values of A and b coefficients vary from place to place, season to season, and time to time.As most improbability occurs farther from the radar, the distance from the radar is a main factor in all the uncertainty sources [20]. Most errors are found away from the radar [21]. This means that most of the uncertainty is related to dimensions from the radar [22]. The distance (d) between overshooting reflectivity (radar station) and the location of drop raining (DSD) is a critical parameter to ground-based radar calibration. Previous studies have shown that this calibration can further improve radar-rainfall estimation by use of multiple Z-R relationships [23], [24], [25] rainfall types [26], distance from the radar[27], [28], and other parameters [29]. These parameters vary with different weather situations such as rain types, rain duration, and seasons in which rain occurs.

In addition to the above calibration, this study also hypothesizes a new improvement of the universal Z-R relationship, regarding the effects of altitude (H) and distance from radar (D) and other new coefficients c. Thus producing a new improved algorithm for the relationship is such that. The radar zones are defined in circular shape from the center of the radar station. The effects of distance in rainfall estimation are investigated in 0-50 km (zone 1), 50-100 km (zone 2), 100-150 km (zone 3) and

150-200 km (zone 4) from the radar. The hourly rainfall products from the registered rain gauges were used in this study.

2. Material and method

2.1. Unipolar ground-based radar

Unipolar ground-based radar in Tabriz, Iran (latitude: 37˚ 55 N, longitude: 46˚ 10' and 1700 m height) is used in this study. Figure 1 shows the location and configuration of Tabriz's radar station with the zones of data acquisition. The coverage area by this radar footprint is between 36˚ 01' and 39˚ 20' in the cold semi-arid zone in the northern hemisphere. Tabriz radar is a C-band radar that is located close to Tabriz city at 37˚ 50' N with 3.75 cm wavelength and 5.6 GHZ that is serviced by 250-kilowatt transmitter power. The antenna diameter is 6.7 m. The Doppler range is 200 km, the non-Doppler range is 400 km, and the spatial resolution is 1x1 km. Details are shown in table 1. The station can produce RHI, PPI, CAPPI, and SRI. This study, however, only used a plan position indicator (PPI). The entire Tabriz radar station is managed by the Iran Meteorological Organization (IMO) and is under the national weather radar network. The main radar data acquire reflectivity numerical amount per decibel (dB) unit. These data are processed using the RAINBOW software, converting radar reflectivity into decibel units. The rainfalls are typically in a reflectivity range between 5-75 dB; light rain begins at 5 dB and hails at 80 dB, respectively. Four zones surrounding the radar station are introduced, as this radar zonation can show distance changes between reflectivity and rainfall location.

2.2. Rain gauges network

A total of more than 190 rainfalls occurred in East Azerbaijan and West Azerbaijan providence during the period of study from 1st January 2011 to 30th December 2012. The rainfall is regulated based on an hourly basis. We investigated 3 hours of rainfall from the moment the rain started. Two types of rain gauge stations were employed, namely: synoptic and climatological stations. There are 43 stations (12 climatology stations and 31 synoptic stations) under Tabriz radar. These stations are equipped with registered rain gauges, scattered in the radar-introduced zones. Figure 2 shows these rain gauge locations surrounding Tabriz radar. These rain gauges are pluviometers with registered pens extracted from a special graph based on one-hour observation. The minimum and maximum hourly registered rainfall is 0.1 – 2.2 mm in this weather period.

2.3. Radar-rainfall relationship

It is assumed that raindrop shapes are spherical, and their sizes are smaller than the radar wavelength. There are certain equations between reflectivity and the characteristics of raindrops. It is essential to qualify radar reflectivity (Z) because the reflectivity depends on the number and diameter of raindrops on the radar sample volume [30]. The reflectivity (Z) depends on the number, diameter, and velocity of raindrops.

$$Z = \sum_i N_i {D^6}_i = \int_0^\infty N(D) D^6 dD \qquad (1)$$

$$R = \frac{\pi}{6}\int_0^{\infty} N(D)D^3V_t(D)dD \qquad (2)$$

Where Z is reflectivity, R (mm/h) is the rainfall rate, N (D) dD is the mean sum of raindrops, D (dD) (mm) /m3of air (is the number of drops with the diameter of the *i*th element), and (cm/second) is the droplet terminal velocity. If the above equations (1, 2) concerning the similarity parameters are equivalent to each other, then equation (3) will be: $Z \ \alpha \ R$

(3)

It means there are strong relationships between reflectivity and the amount of rainfall. According to this strong relationship, the A and b coefficients have been found as the consequence of improving the equation (3);

$$Z = AR^b \qquad (4)$$

It is assumed that heights (altitudes) are more effective parameter in radar-rainfall estimation.

$$Z = AR^b\, H^c \qquad (5)$$

Here we try to improve equation 4 and corroborate equation 5.

2.4. Calibration process

The theoretical background of this theory is that, for each altitude, one can estimate the Z-R relationship. Also, the Z-R relationship changes are considerable in each step time of rainfall duration. Accordingly, the relationships were investigated based on multiple regression analyses. At first, the relationship started with a simple mode, between one independent and one dependent variable. Rainfall (mm/h) in all equations is the independent variable, and radar reflectivity (dB) is the dependent variable. The variable is arranged based on time hourly. According to the general relationship (Marshal- Palmer), the equation is: $Z \ = a \ R^{\ b} + e$ (6)

This relationship is extended for all stations in 3 three hours of rainfall in all four zones surrounding the radar.$Z_{t_i \ z_j} \ = a_i \ \ R_{t_i \ z_j}{}^{\ b\mathrm{i}} + e_{t_i \ z_j}$ (7)

Where Z is radar reflectivity, R is rainfall amount, is the rainfall time duration, 1st - 2nd - 3rdhours of rainfall; here were investigated 3 times of rainfall from rainfall start until 3th time of rainfall based hourly. The four zones are: zone 1 (0-50km), zone 2 (50-100km), zone 3 (100-150km), and zone 4 (150-200km). The coefficients are the empirical coefficients and are partial errors in each zone and time, respectively. Taking into account all of the data in a coordinate system, we can reach equation (8): $Z_t = a\ R_t{}^{b} + e$
(8)

The (t) is the mean, using all data in the entire rainfall region in one coordinate.

The second relationship investigated is to find a new matrix mode of data with the effects of altitude differences. This parameter was first introduced in this paper. When the factor H is considered in the second relationship, the coefficient c is generated; created as a novel empirical coefficient dependent on the geomorphology of rainfall locations. Hereafter, the c coefficient is called the "altitude coefficient". The new relationship is then introduced in equation (9): $Z = a\ R^{b} H^{c} + e$ (9)

This relationship is experimented with in 3 hours of rainfall occurrences in 4 defined zones centered about the Tabriz radar station. $Z_{t_i\, z_j} = a_i\ R_{t_i\, z_j}{}^{b\mathrm{i}} H_n + e_{t_i\, z_j}$ (10)

Equation (10) parameters are the same as in equation (7), the only difference is. The altitude changes at each point where the rainfall is measured. Taking into account all of the data in a coordinate system, and t is the total of data, then the equation can be expressed as: $Z_t = a\ R_t{}^{b} H_n{}^{c} + e_t$ (11)

As a result, equation (11) presents the relationship between reflectivity and all parameters and coefficients in all data in all places and all times of precipitation, respectively. However, previous studies have determined the relationship between reflectivity and rainfall amount based on power regression [3], [4], [14], [17], [24], [25], [27], [31]–[34]. However, the relationship could be expressed in other matrix forms such as logarithmic or exponential regression. All earlier works based on Marshall-Palmer relationships have, however, used only the power-based function in the regression analysis for all the parameters involved. The present study used ArcGIS v9.3 to locate rain gauges and related distances to form the radar zones. MATLAB was used in all the numerical data analysis.

3. Results

The radar-rainfall relationship improvement is to find the other effective parameters defined as the determining factor between real rainfall and the corresponding radar rainfall estimates. In this study, a radar-rainfall relationship has been developed for processing and analyzing two years of consecutive rainfall data from unipolar ground-based radar in middle latitudes. The results indicated that the altitude effects can be added as a new parameter in the radar-rainfall equation. The Z-R relationship was investigated with the introduction of new additional effective parameters. In the following stages of the study, we achieved two main results: (i) demonstrating the strength Z-R relationship and, (ii) detecting the effects of altitude in a radar-rainfall relationship and introducing a new equation Z-R-H in a radar-rainfall relationship. *2.1.* Determination of relationship between (R) and (Z);

There is a strong relationship between radar reflectivity and rainfall amount in the cold semi-arid zone in the middle latitudes and the relevant coefficient. Z-R relationship is investigated in all zones and 3 times rainfall time duration. Table 2 shows the empirical coefficient (a, b) and relationship between variables in 4 zones and 3 times of rainfall. There are no significant differences between the value obtained and other research in middle geographic latitudes. We found the range of coefficients of variation; ($68 < a < 104$) and ($0.81 < b < 1.85$). Table 2 tabulates the detailed results, where a new coefficient a/b is introduced to enable changes in coefficient a concerning b more clearly. Both the empirical coefficients (a, b) were strongly dependent, at increasing coefficient (a), the (b) coefficient decreases and vice-versa. To better exhibit both changes of variables, we introduce the a/b parameter. This ratio could manifest the changes of variables better than separate variables. Table 2 shows the values of the a/b variable at different times and zones. We noted that the range of a/b coefficients is between (37.2 to 118.5). The (a/b) coefficient changes are attributed to different distances from radar stations (zones). Figure 3 clearly shows the changes in the new empirical coefficient (a/b) in various zones. It is also found that (a/b) changes with different times of rainfall.

2.2. Exploration of strong relationship was evident among altitudes (H), radar reflectivity (Z) and rainfall amount (R); Z-R-H;

According to equation (11), there is a strong relationship between Z-R-H. In the new hypothesized relationship, upon entering the H parameter, the c coefficient is generated. The c coefficient changes show the condition and characteristics of the altitude parameter. The value of this new empirical coefficient is a negative numeric, which infers that reflectivity (Z) with altitude (H) has an inversely proportional relationship. Also, at higher elevations, much less radar reflectivity is noted. It can be interpreted based on the convective precipitation at height. The Z-R-H relationship is investigated in all zones and three different times of rainfall time duration. Figures 5 and 6 show the new empirical coefficient and the relationship between 3 variables in 4 zones and 3rd times of rainfall. Table 3 shows the value of coefficient c concerning other related parameters in all locations (zones) far from the radar station. We found that coefficient c varies between (-0.094) to (- 0.363), with significant changes in distant zones. The amount of reflectivity is less in distant zones. But, the third zone is different due to the mountainous conditions. It can be explained and justified. This result is not unexpected. Obtained graphs demonstrate that whatever the precipitation time passes, the numerical value of coefficient c has a sinusoidal shape.

Further research will show that for more rainfall time duration, the sinusoidal trend will continue or change. To sum up, the Z-R relationship at different heights and various distances from the radar station, even when rainfall begins from moment to end rainfall, is very changeable. Based on this theory, other parameters are effective and can be entered into the Z-R equation. The altitude parameter (H) was entered and confirmed throughout this study. Changes of RMSE, in simple mode (Z-R) and when using altitude parameter (Z-R-H), show that the new improved algorithm has more fits. Figure 7 demonstrates changes in RMSE from 4 introduced radar zones and three times rainfall duration before and after applying the altitude parameter (H). The amount of RMSE in new mode (Z-R-H) at four zones of radar and three times of rainfall is lower than before applying the altitude parameter in the equation. Figure 8 fits the previous equations (Marshall-Palmer, Rosenfeld, and WSR 88) and our research with and without altitude parameters. The amount of RMSE confirms that the new Z-R-H equation can be replaced with a universal Z-R equation (see Table 4).

4. Discussion

Z-R-H methodology for unipolar ground-based radar calibration and vagueness estimation gives beneficial and valuable outcomes. This equation is applied to the radar calibration, which is precisely for unipolar ground-based radar type. The results of this study clearly illustrate that the agreement between radar reflectivity and rainfall amount is highly dependent on altitude effects. Table 4 summarises the comparison of the Z-R relationship obtained with similar previous studies[35]. The value of empirical coefficients from different areas is presented. This study noted a Z-R relationship in cold semi-arid for this region, where the coefficients are uniquely representing the region. Also, considering that the other parameters have been ignored in radar rainfall estimation, this study has focused on three effective main parameters in radar rainfall equation that include: altitude effects, distance from radar, and rainfall time duration. Accordingly, to investigate the effectiveness of distance from the radar, the radar coverage area was divided into 4 zones. To determine the altitude impact, the altitude for all rain gauges was interfered in the equation. The first three hours of rainfall were considered to enable the detection of changes in rainfall in initial precipitation and subsequent periods. According to the previous studies illustrated in Table 4, the amount of empirical coefficient is very changeable in different regions. In many climate zones, these empirical coefficients are still not investigated, and determined. In this study, the empirical coefficients for cold semi-arid areas are defined. Also, the altitude parameter (H) is used to predict rainfall more accurately. Although previous research has identified the value of the empirical coefficient briefly, here the value of the empirical coefficient (a, b, a/b, and c) at different distances from the radar and duration of the precipitation has been determined. This study is one step ahead of the results of previous studies on radar rainfall estimation. Findings obtained from the results are commonly used for meteorology and hydrological applications, hence this is beneficial and particularly important to similar regions. The results of this paper, strongly confirm the use of this improved method (Z-R-H), to achieve accurate results in radar-rainfall for hydrometeorology applications.3.1. Z-R relationship and a/b parameterization

We noted a strong relationship (R2 min =70, R2 max =98) between radar reflectivity and the amount of rainfall (Z-R), in the cold semi-arid zone in the geographic middle latitude of the northern hemisphere. Empirical coefficient changes presented relevant correlations in different situations and locations far from the radar. According to Table 4, the amount of (a and b) coefficients have been separately considered in previous studies. In this study, first-time changes of empirical coefficient are considered (a/b) style, because their changes are dependent together strongly. The new a/b coefficient expressed the changes in empirical coefficient far from the radar. As it is distant from the radar station, the a/b coefficient decreases. Hence, radar echoes rarely return to receivers from far radar stations. This result is not unexpected, because the uncertainty resources have a large impact on the amount of reflectivity. All the empirical coefficients do not change with different times of rainfall. Nonetheless, there are no considerable a/b coefficient changes in the first to third time of rainfall occurrence. There are minor changes, but they cannot be fully interpreted as evidence does not follow a logical sequence. The benefit of the a/b is obvious in that it represents the changes in the amount of rainfall corresponding to radar reflectivity far from the radar (distance) and duration of rainfall time. After this, for radar adjustment, it is better to use the a/b coefficient instead (a), and (b) coefficients independently. Especially in urban areas flood control needs to be more careful. The new coefficient (a/b) can show the region characteristics better than the last empirical coefficients. It can be a strong default for ground-based radar in different geographic latitudes before anticipated operations. The a/b changes at differing times of rainfall and different distances away from the radar, prove this assumption that, for each region and each climatic situation, have to be synthesized exclusively Radar-rainfall (Z-R). We synthesized this relationship for cold semi-arid regions.

3.2.Z-R-H approach and introduce c coefficientThe entry of the altitude parameter in the radar equation is a crucial step in this field of study. Given that the other parameters in the Z-R relationship can be effective, the altitude (H) parameter is entered, and for the first time, Z-R-H is defined. In the new hypothesized relationship, upon entering the H parameter, the c coefficient is generated. The c coefficient changes show the condition and characteristics of the altitude parameter. Figure 4 schematically shows the general shape of the Z-R-H genesis, as discussed in this article. As the case study (Azarbayjan province) is relatively mountainous, parameter H with coefficient c changes are explainable in different locations and times. The c coefficient changes show the effect of rainfall types (mountainous and conventional) in a radar-rainfall relationship. The maximum value of R-square and minimum RMSE in different times and locations shows a strong relationship between the three parameters, namely the Z-R-H. The c coefficient change ranges are (-0.094) to (- 0.363). We noted that the c coefficients are negative values. These negative values in the power of altitude parameter ()

display that at higher altitudes the return echo (Z) is lower than in flat areas, and this is agreeable to the amount of precipitation at higher altitudes is more than plain. In other words, negative values of the c coefficient mean that with constant radar reflectivity at higher elevations, precipitation volume increases.

These results can interpret the amount of mountainous precipitation in the radar-rainfall equation. Figures 7 and 8 indicate that an inevitable consequence of the relationship is that the H parameter and c coefficient become the main part of the radar-rainfall equation (Z-R) for future users in hydrometeorology. The ultimate amount of Z-R-H relationship for the cold semi-arid zone is obtained; **Z* =*581* R1.58 H-0.273.**

The results of this study also well indicated that coefficient c alternates from the first time of rainfall to the next time. As precipitation time passes, the numerical value of coefficient c has a sinusoidal shape. The level of this claim is a discussable theory. Further research will show whether for more rainfall duration the sinusoidal trend will continue or not. A notable issue is that there are no a/b coefficient changes in the duration of rainfall times, but coefficient c varies considerably. As demonstrated by RMSE in Figure 7, it is beneficial if the radar rainfall measurement is conducted based on the Z-R-H relationship at different times, which can suggest the use of the most effective parameter. Also, the new relationship is very useful in watershed hydrology management because the duration of precipitation and distance from the location of the precipitation from the basin outlet are crucial, especially in flood routing and flash flood control. Although the authors have considered the new relationship to allow radar calibration, it is not doubtful that any improvement using other effective parameters will be highly rational.

5. Conclusions

The research outcomes demonstrated that the radar relationship is so important exclusively if the data is used in hydrometeorology applications, which require high resolutions in time and space. Therefore, it is concluded that utilizing other effective parameters (distance from the radar, altitudes, and rainfall time duration) leads to the optimum accuracy of the Z-R relationship. A strong relationship between radar-rainfall-altitude is also evident. Moreover, there was a rational correlation between the empirical coefficient, and the new coefficient (altitude coefficient) in different rainfall time durations and different distances from radar (zones). The radar-rainfall-altitude relationship must be treated as an instantaneous method for rainfall estimation. It is highly recommended to apply other effective parameters in different rainfall time situations and locations, especially in mountainous areas to improve a radar-rainfall-altitude relationship, It is necessary to conduct this experiment with more rainfall time duration and more registered rain gauges under radar supervision. Finally, this new contribution is crucial for minimizing uncertainties for accurate rainfall measurement and related-derived hydrological parameters for input into various tasks in sustainable water resource management, especially in ensuring water security and mitigating rainfall-based disasters.

6. Acknowledgments

We are thankful to

7. Author Contributions

In this paper, the authors tried to find more effective parameters in the radar-rainfall relationship (Z-R) of the universal equation. Also, unipolar ground-based radar in cold semi-arid regions was calibrated, and corresponding empirical coefficients were investigated. This Research led to the introduction of a new effective parameter and generated two new empirical coefficients (a/b and c) in a radar-rainfall relationship. Also, the authors have achieved a new approach to ground-based radar calibration by introducing a radar-rainfall-altitude (Z-R-H) relationship to use in hydrometeorology.

8. Conflicts of Interest

The authors declare no conflict of interest.

9.References

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