Time Domain Signal Simulation of Weather Clutter for an Airborne Radar Based on Measured Data

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Abstract

An airborne radar simulator for an X-band radar echo signal was implemented and numerically verified. The simulator can consider weather conditions over a large area and can use measured S-band data as input. A scheme is presented for the conversion of the S-band data to the X-band one. The amplitude and time delay due to weather particles can be theoretically calculated on the basis of reflectivity. The dynamics of the platform and clutter particles were modeled using the Doppler frequency shift in the echo signal. As the simulated weather area was very large, an efficient approximation method was designed for use in calculating the attenuation and time delay, which was also numerically verified. Finally, a scheme for extracting the reflectivity from the echo signal was formulated and was verified by comparing it with the input data.

Key Words: Radar clutter, weather radar, radar return signal, attenuation, weather map.

I. INTRODUCTION

Airborne radar modeling and simulation (M&S) methods have been developed and used for decades, especially in military research. One reason for this is that obtaining real field data is difficult and not economically efficient [1–3]. For the wide application of M&S techniques, sophisticated and accurate simulation data are required, which might include echo signals from not only a target but also radar clutter.

There are many types of radar clutter, such as surface or volume clutter from objects such as forests, vegetation, lakes, and weather particles. Among these, weather clutter is usually distributed over a wide area, and its properties are strongly dependent on weather conditions or types of weather particles, such as rain, snow, and hail. At a higher radar frequency, the echo signal is strongly affected by weather conditions, which may be attenuated or delayed in the time domain [3–5].

Therefore, estimating the effect of various weather conditions on the echo signal is important for radar M&S techniques.

In general, weather conditions are continuously monitored by many ground-based weather radars throughout the world. One example of a ground-based weather radar is NEXRAD, which is operated by the National Weather Service (NWS) and the National Oceanic and Atmospheric Administration. The operating frequency of the ground-based radar is the S-band. The measured data are available to the public [6–9] and are categorized into three levels.

The Level I data are raw time series I and Q data. The Level II data consist of some processed data from Level I data, such as reflectivity ($Z_{H,V}$) and mean radial velocity. The Level III data are more processed data, such as hydrometeor classification, instantaneous precipitation, and tornadic vortex signature [6,8].

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Among these three-level datasets, Level II data can be used for the generation of echo signals. The X-band frequency has become popular of late for airborne radars, but the available measured weather data in this band are very limited. In addition, to estimate the minute dynamics of the target or clutter, micro-Doppler techniques have been studied [10]. Therefore, to simulate an X-band radar echo signal, weather data are numerically generated by a numerical weather prediction code or converted from the available S-band data [11,12].

A computational scheme is proposed to generate an echo signal on the basis of the measured S-band data. First, the data transformation from the S-band to the X-band is addressed in section II. Then the signal calculation scheme is explained. In section III, a method of extracting reflectivity from the generated signal is proposed, and its numerical verification is presented.

II. TIME DOMAIN SIGNAL GENERATION

1. Weather Data Preparation

Ground-based radar data are collected in spherical coordinates centered at the radar, and their range resolution is 250 m. The operating frequency of the radar is the S-band (2.8 GHz), and its polarization is horizontal polarization (h-pol). Data from the radar located in Kunsan, Korea, were used in this study. The data were collected at 00:05 on 08/11/2020. We adopted the Level II data in the measured dataset, which included the h-pol reflectivity \( Z_H \), differential reflectivity \( Z_{DR} = Z_H - Z_V \), radial wind velocity, and wind spectral width, as summarized in Table 1 [13,14]. The subscripts \( H \) and \( V \) indicate the h-pol and vertical polarization (v-pol), respectively. The v-pol reflectivity is calculated as \( Z_V = Z_H - Z_{DR} \).

We generated an X-band airborne radar echo signal on the basis of the measured S-band data. Therefore, data conversion from the S-band to the X-band was required. As reflectivity is generated by many small weather particles, such as rain droplets, it may be dependent on the radar frequency. However, on the basis of known experiments and simulations [12,15,16], the ratio of the reflectivity for the S-band to that for the X-band is almost unity. It can thus be directly adopted for X-band simulation without conversion. To partially consider the shape of the weather particles, we considered the canting angle effect, which could improve the accuracy of the other required quantities, such as the phase shift.

Radial wind velocity is the kinetic quantity of the weather particles, which might be independent of the radar frequency [13]. Hence, reflectivity and radial wind velocity can be directly used for X-band simulation. As the wind spectral width \( \sigma_v \) is related to the dynamic of the weather clutter, it is also independent of the frequency. However, it determines the spread of the Doppler spectrum \( \sigma_f \) of the echo signal [17], which is dependent on the radar frequency:

\[
\sigma_f = \frac{2 \sigma_v}{\lambda},
\]

where \( \lambda \) is the wavelength of the radar signal.

2. Three-dimensional Clutter Model and Simulation Scenario

Fig. 1 shows the simulation geometry and antenna coordinates that were used. The entire weather area was modeled by a large box that was discretized into many smaller sub-boxes. Each box represented a different weather clutter at a specific point, and the properties were assumed to be uniform over a sub-box. The measured data were assigned to the center of the sub-boxes.

The airborne radar beam scans in the horizontal (azimuth) direction, with a fixed elevation angle and a v-pol wave. Four pulses were transmitted to measure the weather conditions at each azimuth direction. The range resolution of the NWS data was 250 m, but the size of the small box was set at 125 m to improve the final signal accuracy and to simulate a large weather area covering dozens of kilometers. In one horizontal scan, the boxes inside the half-power beam width (HPBW) of the radar antenna were selected to generate the return signal.

The return impulse’s location in the time domain could be precisely calculated using the distance between the radar and the sub-box centers, which would be slightly perturbed due to the weather particles. The amplitude of the impulse was calculated using the radar equation based on the given reflectivity. For the

| Parameter         | Symbol | Unit |
|------------------|--------|------|
| Reflectivity (H)  | \( Z_H \) | dBz  |
| Differential reflectivity | \( Z_{DR} \) | dBz  |
| Reflectivity (V)  | \( Z_V \) | dBz  |
| Radial wind velocity | \( v_{Radial} \) | kt   |
| Wind spectral width | \( \sigma_v \) | kt   |

Fig. 1. Simulation scenario and three-dimensional weather clutter model.
simulations in this study, the radar was located at (0, 0, 3) km in Cartesian coordinates. The center point of the clutter box was (20, 0, 3) km, and its dimensions were 30 km $\times$ 0.5 km $\times$ 0.5 km.

Fig. 2 shows the mean, maximum, and minimum values of the measured data of the sub-boxes in the identical range bin for $\theta = 90^\circ$ and $\phi = 0^\circ$. The vertical line shows the maximum and minimum values in a range bin. The data were spread within a wide range.

3. Signal Amplitude and Attenuation

The amplitude of the impulse from each box could be independently calculated with the assigned properties of the box using the radar equation, as follows:

$$P = \frac{P_t G \lambda^2 \sigma}{(4\pi)^2 R^4}$$

where $P_t$, $P_r$, and $G$ are the transmitted power, received power, and antenna gain, respectively; $R$ is the range from the radar to each box center; $\sigma$ is the range from the radar to the radar cross-section (RCS) of the box (expressed as $\eta dV$); $dV$ is the volume of the sub-box; and $\eta$ is the RCS per unit volume, which is directly related to reflectivity [13], as follows:

$$\eta = \frac{\pi^2 |K| Z_{\text{H,V}}}{\lambda^4}$$

where $K$ is a complex dielectric constant [18]. Therefore, the signal amplitude could be formulated as follows:

$$A_{\text{amp}} = \sqrt{\frac{P_t G^2 \lambda^2}{(4\pi)^2 R^4} \sqrt{\eta dV}}$$

Due to the randomness of the weather clutter, the return signal was also random. A Gaussian distribution was assumed over the pulses, and the mean and variance were assumed to be 0 and $A_{\text{amp}}^2$, respectively. To verify the signal amplitude of the radar echo signal, we compared the received power calculated using Eq. (2) with that calculated using the well-known Probert-Jones (PJ) equation [13,14]. For a simple comparison, we assumed a homogeneous clutter with constant reflectivity ($Z = 30$ dBz). The PJ equation approximates the antenna beam as an elliptical Gaussian pattern, and the received power is calculated over the entire angle range (0–2$\pi$), not only over the HPBW [13,14]. Hence, a power beam width of 9 dB was assumed for the calculation using Eq. (2), for comparison with the calculation using the PJ equation in Fig. 3.

![Fig. 2. Mean, maximum, and minimum values of the weather data in each range resolution bin. (a) Reflectivity, $Z_V$ (dBz). (b) Wind radial velocity, $v_{\text{Radial}}$ (m/s). (c) Wind spectral width, $\sigma_v$ (m/s).](image-url)

![Fig. 3. Comparison of the power ratios of the proposed scheme and of the PJ equation.](image-url)
The power ratio of Eq. (4) to the PJ equation is shown in Fig. 3. It approaches 1 as the range profile increases. In the short range, some discrepancies can be observed due to the difference between the volume of the box for Eq. (2) and the volume of the cylinder for the PJ equation in a range bin. However, the discrepancies quickly decreased over the range profile.

Due to the particles inside the weather clutter, the signal is attenuated as it propagates through the clutter. For long-range propagation, the attenuation effect may be significant, especially in the X-band [19,20]. The weather clutter was highly inhomogeneous, so the attenuation was strongly dependent on the signal path inside the clutter. Estimating the exact path length over many small boxes is very time consuming. Therefore, we approximated the exact path length as the size of a box, \( dL = 125 \text{ m} \), which resulted in a very small attenuation error for a sub-box.

The specific attenuation \( \gamma_R \) of a sub-box recommended by the ITU Radiocommunication Sector (ITU-R) is as follows:

\[
\gamma_R = \kappa \alpha \beta \frac{r^2}{\text{dB/km}},
\]

where \( r \) is the rain rate in mm/h and \( \kappa \) and \( \alpha \) are constants equal to 0.008853 and 1.2636, respectively, for the X-band and v-pol. The rain rate can be estimated on the basis of the reflectivity and weather clutter type shown in Table 2, which are given by the NWS and a previous study [21]. Thus, the attenuation for the round trip was approximated as follows:

\[
2 \int_{R_0}^{R_1} \gamma_R dR = 2dL \sum_i \gamma_R(k_i),
\]

where \( R_0 \) and \( R_1 \) are the start and end ranges of the clutter, respectively. Finally, the value obtained from Eq. (6) was multiplied by the value obtained from Eq. (4) for each impulse.

### Table 2. Relation between reflectivity and rain rate

| Surface precipitation type | Z-r relation                     |
|----------------------------|----------------------------------|
| Rain                       | \( Z = 75r^2 \) (\( Z \leq 40 \text{ dB} \)) |
| Snow                       | \( Z = 200r^{2.4} \) (\( Z > 40 \text{ dB} \)) |
| Hail                       | \( Z = 75r^2 \)                  |
| Kunsan Rain (k1)           | \( Z = 300r^{2.4} \)             |
| Kunsan Rain (k2)           | \( Z = 69.91r^{1.69} \)         |
|                            | \( Z = 89.77r^{1.79} \)         |

4. **Time Delay (Phase Shift)**

The weather particles also decrease the signal velocity, which results in time delay and phase shift in the time and frequency domains, respectively, as shown in Fig. 4. We analytically calculated the phase shift and then converted it to the time delay. The frequency shift can be calculated as follows [22]:

\[
\Delta k = e^{i\beta k r(N_\alpha \alpha \beta + 1) \Gamma(\beta_k + 1) \text{rad/m}},
\]

where \( N_\alpha, \alpha_k, \beta_k \) are constants based on the type of clutter [23]; \( \Gamma(\cdot) \) is the Gamma function; and \( \Lambda \) is a slope parameter related to reflectivity \( Z \), as follows:

\[
\frac{\alpha_k}{\pi} = N_\alpha \Lambda \left( -2^{2.5} \right) .
\]

The canting angle effect is more important for the X-band than for the S-band due to the shorter wavelength. Using Eq. (8), \( \Lambda \) can be estimated by considering the frequency property of the radar, and then \( \Delta k \) can be computed using Eq. (7). The overall phase shift can be approximated as follows:

\[
2 \int_{R_0}^{R_1} \Delta k dR = 2dL \sum_i \Delta k_i,
\]

![Fig. 4. Time shift description converted from phase shift.](image)
The phase shift \( \phi \) is directly converted to the time delay, as follows:

\[
\Delta \tau = \frac{\Delta \phi}{2\pi f_c} = \frac{2\int_{k_i}^{k_f} \Delta k dR}{2\pi f_c} = \frac{\int_{k_i}^{k_f} \Delta k dR}{\pi f_c},
\]

where \( f_c \) is the carrier frequency [24,25]. Fig. 5 compares the exact and approximated estimations of the time delay and attenuation, which are cumulatively calculated values along the line of sight (LOS) for \( \theta = 90^\circ \) and \( \phi = 11.6^\circ \).

### 5. Time Domain Signal

The echo impulse responses from many sub-boxes in an identical range bin (\( \Delta r \)) are coherently integrated. Fig. 6 shows the generated time domain signal for the input data in Fig. 2. It shows the magnitude of the one-dimensional (1D) signal with and without an attenuation effect for rain clutter. As expected, the amplitude of the signal is proportional to the reflectivity in Fig. 2(a).

Due to the dynamics of the platform and clutter particles, successive pulses are slightly distorted and can be modeled using the Doppler frequency shift. The power spectrum density of the Doppler frequency can usually be assumed to be a Gaussian probability density function (PDF) [17], given by:

\[
S(f) = \frac{1}{\sqrt{2\pi\sigma_f^2}} \exp \left[ -\frac{(f - f_D)^2}{2\sigma_f^2} \right],
\]

where \( \sigma_f \) is calculated using Eq. (1) and \( f_D \) is the mean Doppler frequency of the clutter related to the radial wind velocity. Eq. (11) is converted to the correlation between the pulses in the time domain, which is also written in terms of the Gaussian function with the assumption of \( f_D = 0 \), as follows:

\[
\rho(n) = \exp \left[ -2(\pi\sigma_f n T_s)^2 \right],
\]

where \( n \) and \( T_s \) are the indices of the pulse and the pulse repetition interval, respectively. The correlating Gaussian random variable can be generated through the Cholesky decomposition method and the mean Doppler frequency in Fig. 2(b), and the platform velocity is consecutively applied to the signal, as described in other studies [17,26].

The accuracy of the Doppler shift can be examined on the basis of the range–Doppler (RD) maps. To generate a fine RD map, 256 pulses were transmitted and processed for the situation in Fig. 6, with an attenuation effect. Fig. 7 shows a simulated RD map with a 180 m/s flight velocity toward the positive x-axis. In the calculation for Fig. 7(a), only the flight Doppler effect was included (the wind effect was not included). From the RD map, the peak Doppler shift is around 444 Hz, which can be converted to 179.4 m/s. This agrees well with the 180 m/s flight velocity. In Fig. 7(b), the wind effect is included. The radial velocity of the wind in each sub-box is also applied with the flight velocity to the signal, which decreases the peak frequency if the wind direction is identical to that of the flight. Hence, the Doppler frequency is decreased, as shown in Fig. 7(b).

![Fig. 6. Magnitude of one-dimensional time domain signals with and without an attenuation effect.](image1)

![Fig. 7. Range-Doppler map of a two-dimensional signal showing (a) the flight Doppler effect and (b) the flight and clutter Doppler effects with a 180 m/s flight velocity and the clutter velocity shown in Fig. 2(b).](image2)
12 km, the mean wind velocity decreases, and beyond 20 km, it increases. Thus, the Doppler frequency decreased beyond 12 km and increased again beyond 20 km. Over the 20–25 km region, the Doppler frequency was distributed over 50–500 Hz on the RD map, which is attributed to the variance of the wind radial velocity in Fig. 2(b) for each sub-box at 20–25 km (~1 to 6 m/s). This velocity could be converted to -388 to 64 Hz and was added to the flight Doppler frequency of 444 Hz. Then, it became 56–508 Hz, which is very similar to the estimated variation in the RD map (50–500 Hz).

III. REFLECTIVITY ESTIMATION

To simulate the weather map, reflectivity $Z_V$ should be extracted from the generated two-dimensional (2D) signal. Then the weather map was constructed from the rain rate using the colors in Table 3. The amplitude of the 1D signal at a time point might be random because it is affected by the reflectivity of many sub-boxes inside the identical range bin. Due to the central limit theorem, the amplitude can be approximated using a Gaussian PDF. Hence, an estimator of reflectivity was developed on the basis of the Gaussian PDF assumption. The signal amplitude in a range bin is the summation of Eq. (4) over the sub-boxes, as follows:

$$X = \sum_{k} \sqrt{Z_{V_k}},$$  \hspace{2cm} (14)

where $N_c$ is the number of sub-boxes in a range bin. The constants $P_a, \lambda, \pi, K, \text{ and } dV$ can be simply removed by dividing them out from the received signal.

The antenna gain $G_k$ and the range between the radar and each box $R_k$ are different for each box. Only the boxes inside HPBW were considered, and all were in the far-field region. Thus, the gain and distance could be approximated by the mean gain and distance ($R_{mid}$) of all the sub-boxes and were removed. After this algebraic manipulation, Eq. (13) was reduced to the following:

$$X^2 = \sum_{k} Z_{V_k},$$  \hspace{2cm} (15)

Finally, by taking the expectation, $E[\cdot]$, the estimator of reflectivity can be formulated as $E[X^2]$. To compute the reflectivity for a box, we divided $E[X^2]$ with the box number estimated using the assumption that the volume was an elliptical cylinder [13,14].

Fig. 8 shows the estimated reflectivity from the generated 2D signal with and without an attenuation effect for the simulation case in Fig. 6. The estimation result was compared with the mean input reflectivity in each range bin. The two results were in excellent agreement, but if the attenuation effect were included, the discrepancy would become larger with increasing range.

Fig. 9 shows the weather maps extracted from the 2D signal and the input data, which also agree well. The weather map from the input data was calculated from the mean reflectivity inside the identical range bin. For this simulation, seven azimuth angles, from -11° to 11°, were scanned. The attenuation effect decreased the reflectivity from around 20 km, and the reflectivity was reduced by 10 dB compared with that for the S-band at 35 km. These results agree well with the previous simulation results [15].

Table 3. Weather map color definition with rain rate

| Level   | Rain rate mm/h | Color |
|---------|----------------|-------|
| Level 0 | -1             | Black |
| Level 1 | 1–4            | Green |
| Level 2 | 4–12           | Yellow|
| Level 3 | 12–50          | Red   |
| Level 4 | 50–100         | Magenta|

![Fig. 8. $Z_V$ and $Z_{DR}$ estimation with signals in Fig. 6 and the assumption of rain clutter.](image-url)
For a final verification, we compared the estimated rain rate with the instantaneous rain rate in the Level III data. The Level III data were processed by the data provider through the dual polarization measurement, and the azimuth resolution was different from that of the Level II data: the instantaneous rain rate was given every 1°. Hence, three instantaneous rain rates along the azimuth range were averaged for comparison with the estimation results.

For the aforementioned comparison, rain clutter was assumed. Three rain rates were computed from the reflectivity estimated using the NWS equation, and were denoted as “Estimated.” Two equations were used to fit the Kunsan region data [21], and the results were denoted as “Estimated-k1” and “Estimated-k2,” respectively, in Fig. 10. The explicit equations are given in Table 2. The $Z-r$ empirical relation is generally developed on the basis of the $Z_H$ parameter; thus, the rain rate estimated using $Z_H$ is also shown in Fig. 10. The two estimated reflectivities are shown in Fig. 8.

$Z_{DR}$ was around 1.2 dB; thus, the two estimated rain rates were very similar, but the h-pol estimation was slightly more accurate. The $Z-r$ empirical relation processed on the basis of the Kunsan data could provide more accurate results, while the NWS one, which was developed with US region data, was less accurate. Accordingly, the generated 2D signal can be used for a radar simulation, considering the weather conditions.

Fig. 9. Weather map generated by seven azimuth boresight angle sweeps from -11° to 11° using input data (a) and the estimated $Z$ parameter (b).

Fig. 10. Comparison of the rain rate from Level III data and the estimated rates for both v-pol and h-pol (increased by 50 dB).

IV. CONCLUSION

A calculation scheme was proposed for the generation of a 2D time domain radar echo signal from a large-volume weather clutter in the X-band. Measured Level II data were utilized. As the dataset was measured in the S-band, the data were converted to X-band data. The entire weather area was modeled by a large box discretized into many small boxes. Weather data were assigned to each box center.

Reflectivity was used to compute the specific phase shift and attenuation of the radar signal, as recommended by ITU-R and a known analytical formulation. As the canting angle effect was partially considered, several types of weather clutter could be simulated, such as rain, snow, fog, and hail. The received power and Doppler frequency shift were validated by comparing them with those obtained using known formulations, such as the PJ equation and RD map.

An estimator of reflectivity that could be used to extract the reflectivity from the received signal was proposed, and it was verified by comparing the estimated value and the input data. In addition, a weather map was generated on the basis of the estimated reflectivity, which had excellent agreement with the result based on the input data. The rain rates were calculated and compared with the instantaneous rain rate among the Level III data. The rain rates were computed using three $Z-r$ empirical relations. Their comparison showed that the generated 2D signal could provide accurate results.

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REFERENCES

[1] V. Louf, O. Pujol, H. Sauvageot, and J. Riédi, “Simulation of airborne radar observations of precipitating systems at various frequency bands,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 52, No. 3, pp. 1627–1634, May 2013.

[2] L. Liao, R. Meneghini, and T. Iguchi, “Simulations of mirror image returns of air/space-borne radars in rain and their applications in estimating path attenuation,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 37, No. 2, pp. 1107–1121, Mar. 1999.

[3] Z. Li, Y. Zhang, G. Zhang, and K. A. Brewster, “A micro-physics-based simulator for advanced airborne weather radar development,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 49, No. 4, pp. 1356–1373, Oct. 2010.

[4] O. Pujol, F. Mesnard, and H. Sauvageot, “Effects of melting layer in airborne meteorological X-band radar observations,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 50, No. 6, pp. 2318–2324, Nov. 2011.

[5] O. Pujol and J. F. Georgis, “Degradation of radar reflectivity by cloud attenuation at microwave frequency,” *Journal of Atmospheric and Oceanic Technology*, Vol. 24, No. 4, pp. 640–657, Apr. 2007.

[6] R. M. Beauchamp and V. Chandrasekar, “Dual-polarization radar characteristics of wind turbines with ground clutter and precipitation,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 54, No. 8, pp. 4833–4846, Apr. 2016.

[7] F. Kong, Y. Zhang, and R. Palmer, “Wind turbine clutter mitigation for weather radar by adaptive spectrum processing,” presented at the 2012 IEEE Radar Conference, Atlanta, USA, May 2012.

[8] D. E. Weissman and M. A. Bourassa, “Corrections to scatterometer wind vectors during Hurricane Dennis using high-resolution NEXRAD radar rain corrections,” presented at OCEANS 2006, Boston, USA, Sep. 2006.

[9] Z. Li et al., “Evaluation of the impacts of system modules on polarimetric radar data quality using a phased array weather radar system simulator,” presented at the 2019 IEEE International Symposium on Phased Array System & Technology (PAST), IEEE, Waltham, USA, Oct. 2019.

[10] S. S. Ram, C. Christianson, Y. Kim, and H. Ling, “Simulation and analysis of human micro-Dopplers in through-wall environments,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 48, No. 4, pp. 2015–2023, Feb. 2010.

[11] Leinonen, Jussi et al., “Mapping radar reflectivity values of snowfall between frequency bands,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 49, No. 8, pp. 3047–3058, 2011.

[12] J. P. Fritz and V. Chandrasekar, “Simultaneous observations and analysis of severe storms using polarimetric X-band SAR and ground-based weather radar,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 48, No. 10, pp. 3622–3637, 2010.

[13] V. N. Bringi and V. Chandrasekar, Polarimetric Doppler weather radar: principles and applications, Cambridge, UK: Cambridge University Press, 2001.

[14] R. J. Doviak and D. S. Zrnić, *Doppler radar and weather observations*, Mineola, NY: Courier Corporation, 2006.

[15] V. Chandrasekar, S. Lim, and E. Gorgucci, “Simulation of X-band rainfall observations from S-band radar data,” *Journal of Atmospheric and Oceanic Technology*, Vol. 23, No. 9, pp. 1195–1205, Sep. 2006.

[16] J. P. Fritz and V. Chandrasekar, “Simultaneous observations and analysis of severe storms using polarimetric X-band SAR and ground-based weather radar,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 48, No. 10, pp. 3622–3637, July 2010.

[17] G. Galati and G. Pavan, “Computer simulation of weather radar signals,” *Simulation Practice and Theory*, Vol. 3, No. 1, pp. 17–44, 1995.

[18] G. Zhang, J. Vivekanandan, and E. Brandes, “A method for estimating rain rate and drop size distribution from polarimetric radar measurements,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 39, No. 4, pp. 830–841, May 2001.

[19] Y. Oh, D. Lee, S. Jung, K. Nam, and G. Lee, “Attenuation correction effects in rainfall estimation at X-band dual-polarization radar: evaluation with a dense rain gauge network,” *Advances in Meteorology*, Vol. 2016, p. 20, June 2016.

[20] R. Meneghini, “Application of a threshold method to airborne–spaceborne attenuating-wavelength radars for the estimation of space–time rain–rate statistics,” *Journal of Applied Meteorology*, Vol. 37, No. 9, pp. 924–938, Sep. 1998.

[21] T. J. Kim, H. H. Kwon, and K. B. Kim, “Calibration of the reflectivity-rainfall rate (ZR) relationship using long-term radar reflectivity factor over the entire South Korea region in a Bayesian perspective,” *Journal of Hydrology*, Vol. 593, No. 125790, 2021.

[22] L. Lei, G. Zhang, B. L. Cheong, R. D. Palmer, and M. Xue, “Simulations of polarimetric radar signals based on particle radar signals,” *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 2016, p. 20, June 2016.

[23] Y. Jung, G. Zhang, and M. Xue, “Assimilation of simulated polarimetric radar data for a convective storm using the ensemble Kalman filter. Part I: Observation operators for reflectivity and polarimetric variables,” *Monthly Weather Review*, Vol. 136, No. 6, pp. 2228–2245, June 2008.
2008.

[24] Y. Wang, and V. Chandrasekar, “Algorithm for estimation of the specific differential phase,” Journal of Atmospheric and Oceanic Technology, Vol. 26, No. 12, pp. 2565–2578, Dec. 2009.

[25] M. Longbrake, “True time-delay beamsteering for radar,” presented at the 2012 IEEE National Aerospace and Electronics Conference (NAECON), IEEE, Dayton, OH, July 2012.

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[26] J. H. Nam, J. W. Rim, H. Lee, I. S. Koh, and J. H. Song, “Modeling of monopulse radar signals reflected from ground clutter in a time domain considering Doppler effects,” Journal of Electromagnetic Engineering and Science, Vol. 20, No. 3, pp. 190–198, May 2020.

[27] P. Z. Peebles and B. Shi, Probability, random variables, and random signal principles, New York, NY: McGraw Hill, 1987.

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