Inference of Spatial Correlation Characteristics of Rainfall Intensity from the Data of Satellite-Borne Precipitation Radar and Ground-Based Rain Gauges

Takeshi Manabe and Ryohei Jozaki

Osaka Prefecture University, Gakuen-cho 1-1, Naka-ku, Sakai, Osaka 599-8531, Japan,
manabe@ieee.org, jozaki@ieee.org

Abstract

Spatial correlation characteristics of rainfall are crucial in predicting rain attenuation statistics and various diversity characteristics for wireless communication links operating at frequencies above 10 GHz. In this paper, we propose a method for estimating the spatial correlation coefficient of rainfall intensity from the ground rainfall intensity data measured by a satellite-borne precipitation radar and a ground-based rain-gauge. By applying this method to the data measured by the Precipitation Radar of the Tropical Rainfall Measuring Mission satellite and those of ground-based rain-gauges provided by Japan Meteorological Agency, the estimated spatial correlation characteristics for Kanto region around Tokyo are found to be consistent with those reported in literatures. In addition, the result revealed that the spatial correlation characteristics showed regional dependence in central and western Japan. dependence.

1. Introduction

It is important to know the spatial correlation characteristics of rainfall for predicting rain attenuation and diversity characteristics on terrestrial and satellite communication links in micro- and millimeter-wave bands. In particular, for predicting site or route diversity characteristics in broadband FWA (Fixed Wireless Access) systems such as Local Multipoint Distribution Systems (LMDS), spatial correlation characteristics within a range of less than several kilometers are indispensable [1]. In order to get the statistical information about the spatial correlation of rain of such a spatial scale, in general, long-term data obtained by a dense network of rain gauges is required for the area of interest, and requires great cost and effort.

In this paper, we propose a method to estimate the spatial correlation characteristics of rainfall from cumulative statistics obtained by a satellite-borne rain radar and those obtained by a ground-based rain gauge at one point on the ground surface. It is well known that the rainfall rate measured by satellite-borne rain radars such as the Precipitation Radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite underestimates actual rainfall intensity for intense rain due to the effects of nonuniform beam filling of the radar footprint by intense convective rain cells [2, 3]. In other words, some information about the spatial inhomogeneity of rainfall should be contained in this underestimation in radar estimated surface rainfall intensity. The approach of our proposed method is to infer the spatial correlation characteristics of rainfall by comparing rainfall intensity measured by a satellite-borne radar with that measured by a ground-based rain gauge of on a cumulative statistical basis. In what follows, we present the outline of the theory behind the proposed inference method and apply the method to cumulative statistics of rainfall intensity measured by TRMM/PR and the ground-based rain gauges.

2. Inference Method

Rainfall intensity $\Re$ measured by a satellite-borne rain radar is an area-averaged rainfall intensity weighted by the round-trip antenna-gain pattern $G(\boldsymbol{r})^2$ as given by

$$\Re = A^{-1} \int_S G(\boldsymbol{r})^2 R(\boldsymbol{r}) d\boldsymbol{r}, \tag{1}$$

where $G(\boldsymbol{r})$ and $R(\boldsymbol{r})$ are the antenna-gain pattern and the rainfall intensity at a point $\boldsymbol{r}$ on the ground surface, respectively, and A is the normalization factor given by $A = \int_S G(\boldsymbol{r})^2 d\boldsymbol{r}$. If we assume that the statistical properties

978-1-4244-6051-9/11/$26.00

of rainfall are statistically homogeneous over the ground surface, we can show that the statistical mean $\langle \Re \rangle$ of the radar-measured rainfall intensity $\Re$ is identical to the statistical mean of the point rainfall intensity $\langle R \rangle$ as

$$\langle \Re \rangle = \langle A^{-1} \int_S G(\boldsymbol{r})^2 R(\boldsymbol{r}) d\boldsymbol{r} \rangle = A^{-1} \int_S G(\boldsymbol{r})^2 \langle R(\boldsymbol{r}) \rangle d\boldsymbol{r} = \langle R \rangle. \quad (2)$$

On the other hand,the statistical variance $\sigma_\Re^2$ of of the radar-measured rainfall intensity $\Re$ is reduced by a factor of K as compared with the statistical variance σ_R^2 of point rainfall intensity R as

$$\sigma_\Re^2 = \langle (\Re - \langle \Re \rangle)^2 \rangle = A^{-2} \int_S \int_S G(\boldsymbol{r}_1)^2 G(\boldsymbol{r}_2)^2 \langle R(\boldsymbol{r}_1) R(\boldsymbol{r}_2) - \langle R \rangle^2 \rangle d\boldsymbol{r}_1 d\boldsymbol{r}_2 = K\, \sigma_R^2 \quad (3)$$

where the reduction factor K is given by using the spatial correlation function $\rho_R(\boldsymbol{r}_1, \boldsymbol{r}_2)$ as

$$K = A^{-2} \int_S \int_S G(\boldsymbol{r}_1)^2 G(\boldsymbol{r}_2)^2 \rho_R(\boldsymbol{r}_1, \boldsymbol{r}_2) d\boldsymbol{r}_1 d\boldsymbol{r}_2. \quad (4)$$

If we assume the spatial correlation function $\rho_R(\boldsymbol{r}_1, \boldsymbol{r}_2)$ of point rainfall intensity is horizontally isotropic and is given by a function of the distance d between two points as $\rho_R(d) = \exp(-\alpha\sqrt{d}\ )$, the reduction factor K is given as a function of α as

$$K(\alpha) = A^{-2} \int_S \int_S G(\boldsymbol{r}_1)^2 G(\boldsymbol{r}_2)^2 \exp(-\alpha\sqrt{|\boldsymbol{r}_1 - \boldsymbol{r}_2|}) d\boldsymbol{r}_1 d\boldsymbol{r}_2. \quad (5)$$

The spatial correlation function of this type is widely used in predicting rain attenuation in the micro- and millimeter-wave bands in Japan [4, 5, 6].

If we assume a Gaussian pattern with a half-power footprint diameter of 5 km for $G(\boldsymbol{r})$ of TRMM/PR in (5), the reduction factor K is given as a function of α as shown in Fig. 1. By using this relationship, we can infer the parameter α which characterizes the spatial correlation characteristics of rainfall for the area of interest by comparing the statistics of rainfall intensity measured for ground surface by a satellite-borne radar with those of point rainfall intensity measured by a ground-based rain gauge in terms of their variances.

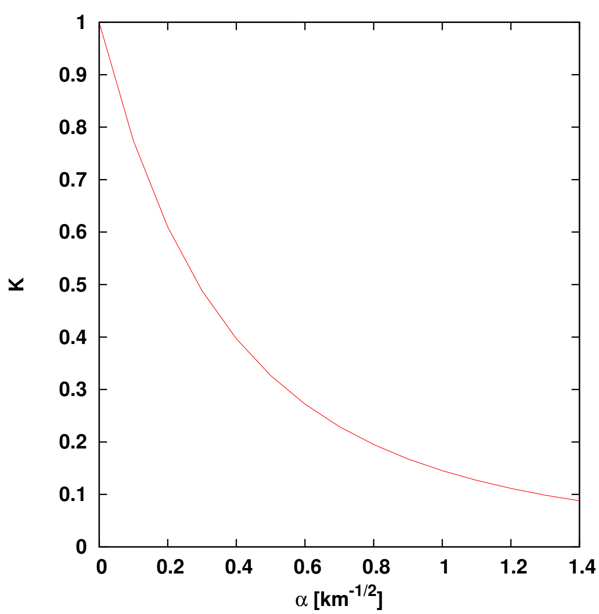

Figure 1: Reduction factor K versus α.

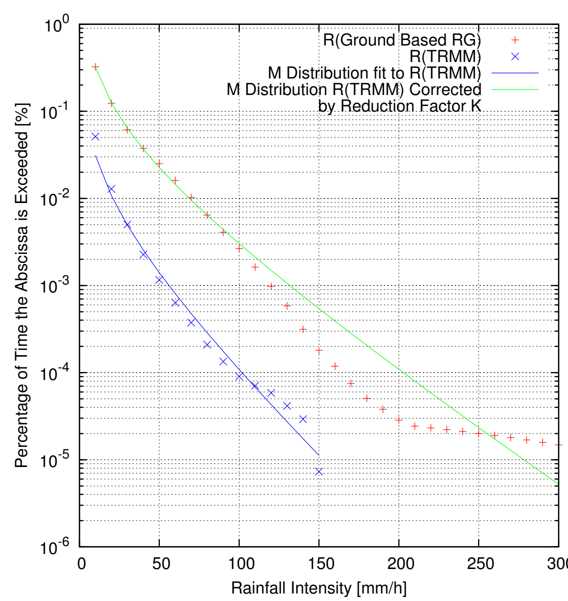

Figure 2: Cumulative distributions of rainfall intensity at Choshi (140.86°E, 35.74°N).

3. Spatial Correlation Characteristics Inferred from the Data of TRMM/PR and Ground-Based Rain Gauges

We applied the proposed method to combinations of surface rainfall intensity data acquired by PR of TRMM as the satellite-borne radar and 1-minute rainfall rate data provided by Japan Meteorological Agency (JMA) as ground-based rain gauges. The JMA 1-minute ground-based rainfall data are those measured by tipping-bucket rain gauges at 52 meteorological observatories shown in Fig. 3, and are converted into 1-minute rainfall intensity by the second-based random distribution process [7, 8]. Red cross symbols ($+$) in Fig. 2 show the cumulative distribution of 1-minute rainfall intensity for Choshi (140.86°E, 35.74°N), one of the 52 meteorological observatories, for an eight-year period between 2002–2009. On the other hand, blue cross symbols ($\times$) in Fig. 2 show the cumulative distribution of estimated surface rainfall intensity compiled from the 2A25 product for the area within a radius of 150 km from the Choshi observatory for 2001–2009.

It is clearly found in Fig. 2 that the cumulative distribution derived from TRMM data significantly underestimate the rainfall intensity as compared with that derived from ground based data. The blue curve in Fig. 2 is the Hosoya's M-distribution fit to the cumulative distribution for the ground-based rain gauge data determined by the mean and the variance of one-minute rainfall intensity [9]. If we assume that the cumulative distribution for the rainfall intensity measured by TRMM/PR can also be approximated by Hosoya's M-distribution, we can determine the reduction factor K so that the M-distribution scaled from the M-distribution of ground-based rain-gauge cumulative distribution by scaling its variance with $1/K$ gives best fit to the cumulative distribution measured by TRMM/PR. In applying this method, we assumed the half-power footprint diameter of the TRMM/PR antenna to be 5 km irrespective of the cross-track scan angle for simplicity. The M-distributed cumulative distribution thus obtained is shown by the green curve in Fig. 2. In this case for the area around Choshi observatory, the best fit value for the reduction factor K is determined to be 0.59 which corresponds to the value of the spatial-correlation parameter α of 0.35.

Figure 3 shows the values of the parameter α inferred for the sites of 52 meteorological stations in the central and southern part of Japan. The values of α for the sites in the Kanto region around Tokyo are found to be around 0.15 km$^{-1/2}$ $\sim$ 0.35 km$^{-1/2}$ which are consistent with those reported for regions around Tokyo in literatures [4, 5, 7]. In Fig. 3, it is found that the value of the parameter α shows regional dependence. In the regions around the Seto Inland

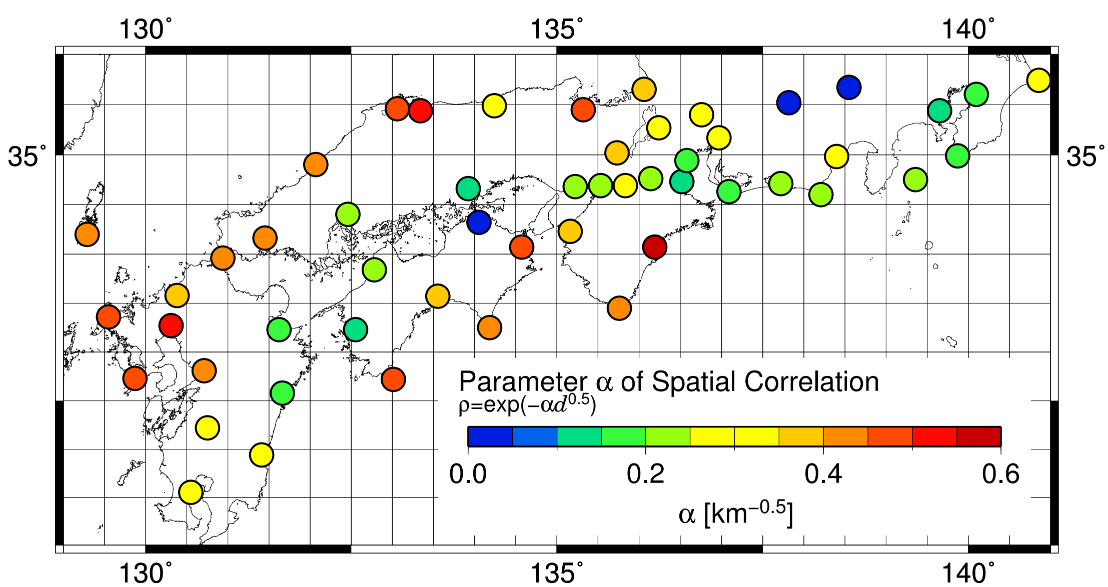

Figure 3: The values of the parameter α for the spatial correlation function $\rho_R(d) = \exp(-\alpha\sqrt{d}\ )$ inferred for the sites of 52 meteorological stations in the central and southern part of Japan.

Sea, the values of α are relatively small indicating that rain in these region is likely to be widespread, while they are relatively large in the coastal regions along the Pacific Ocean and the Sea of Japan indicating that rain in these regions has a tendency to localized within narrow area.

4. Conclusion

We have proposed a method to infer the spatial correlation characteristics of rainfall from the data of a satellite-borne precipitation radar combined with point rainfall data measured by a ground-based rain gauge on a statistical base. By applying this method to the data measured by the Precipitation Radar aboard the TRMM satellite and those of ground-based rain-gauges provided by Japan Meteorological Agency, the estimated spatial correlation characteristics for Kanto region around Tokyo are found to be consistent with those reported in literatures. In addition, the result revealed that the spatial correlation characteristics showed regional dependence in central and western Japan. Although the accuracy of the current estimate for the spatial correlation characteristics is limited by sparse satellite observation, we would be able to get more accurate estimation for the spatial correlation characteristics if we could have further long-term data accumulated.

Acknowledgments

This work was supported by Grant-in-Aide for Scientific Research (C) 21560406 of Japan Society for the Promotion of Science.

References

[1] T. Maruyama, Y. Shirato, Y. Akimoto, and M. Nakatsugawa, “Service area expansion of quasi-millimeter FWA systems through site diversity based on detailed rain intensity data,” *IEEE Trans. Antennas Propagat.,* vol. 56, no. 10, Oct. 2008.

[2] S. L. Durden, Z. S. Haddard, A. Kitiyakara, and F. K. Li, “Effects of nonuniform beam filling on rainfall retrieval for the TRMM Precipitation Radar,” *J. Atmos. Oceanic Technol.,* vol. 15, no. 3, pp. 636-646, 1998.

[3] T. Kozu and T. Iguchi, “Non-uniform beam filling correction for spaceborne radar rainfall measurement: implication from TOGA/COARE radar data analysis,” *J. Atmos. Oceanic Technol.,* vol. 16, no. 11, pp. 1722-1736, 1999.

[4] K. Morita and I. Higuti, “Prediction methods for rain attenuation distribution of micro and millimeter waves,” *Review of the Elec. Commun. Labs.,* vol. 24, no. 7-8, pp. 651-668, July-Aug. 1976.

[5] K. Morita and I. Higuti, “Statistical studies on rain attenuation and site diversity effect on Earth to satellite links in microwave and millimeter wavebands,” *Trans. IEICE Japan*, vol E61, vol. 6, pp. 425-432, June 1978.

[6] T. Manabe, H. Kobayashi, T. Ihara, and Y. Furuhama, “Spatial correlation coefficients of rainfall intensity inferred from statistics of rainfall intensity and rain attenuation,” *Annales des Telecommun.*, vol. 41, no. 9-10, pp.463-469, Sep.-Oct. 1986.

[7] K. Ono, Y. Nishimura, K. Nakama, K. Saito, S. Nomoto, and Y. Karasawa, “An accurate estimation scheme of 1-min Rainfall Rate Statistics from 1-min Rainfall Data Provided by the Meteorological Agency,” *IEICE Trans. Commun.* (Japanese Edition), vol. J88-B, no. 8, pp. 1508-1518, Aug. 2005.

[8] R. Jozaki, T. Manabe, S. Yamamoto, and W. Chujo, “An improvement of the accurate estimation scheme of 1-min rainfall intensity statistics from the 1-min rainfall data provided by the Japan Meteorological Agency,” submitted to *IEICE Trans. Commun.,* (Japanese Edition).

[9] Y. Hosoya, “An estimation method for one-minute-rain distributions at various locations in Japan,” *IEICE Trans. Commun.* (Japanese Edition), vol. J71-B, no. 2, pp. 256-262, Feb. 1988.