Relationship between Lightning Discharges and Rapid Changes in Cross Polarization Discrimination of the Ka-band Satellite Radio Signal

Yasuyuki Maekawa
Osaka Electro-Communication University, Japan

Abstract — Rapid changes in cross-polarization discrimination (XPD) of the satellite radio wave signal (19.45 GHz) are observed at 1 sec interval in the thunderstorm events. About one third of the rapid changes are found to coincide with the cloud-to-ground lightning strokes which occurred on the south side of our earth station at the distance up to 20 km. The distribution of the lightning location indicates that the center of thunder clouds primarily exists to the westward of the radio wave propagation path. At the moment of the rapid changes, more than half the observed data indicate the decrease in XPD. Also, more than two thirds of them show the changing direction of cross-polar phases toward $-90$ deg, which means the decrease in canting angles of ice crystals possibly causing the depolarization changes. These features seem to be enhanced in the middle stage of each lightning event. The decrease in XPD may be related to cancellation effects of depolarization due to the difference in canting angles between the ice crystals near the lightning and those in other places far from the lightning. Thus, the measurements of XPD and cross-polar phase are shown to be important to reveal the electrification process of thunder clouds and to predict lightning discharges.

1. INTRODUCTION

In satellite communication links, degradation of cross-polarization discrimination (XPD) of the radio wave is caused by raindrops and ice crystals along the propagation paths. In thunderstorm events, moreover, rapid changes of XPD and cross-polar phase relative to co-polar phase are frequently observed at time intervals of less than 1 sec [1, 2]. These peculiar phenomena are considered to be related to the change of electric field due to lightning discharges as well as the aerodynamic forces of convective air flows [3]. Up to now, however, detailed mechanisms of the rapid changes of XPD and cross-polar phase are not understood very well.

In this study, statistical distributions of the changes of XPD and cross-polar phase are examined using the Ka-band beacon signal observations of Japan’s domestic communication satellites [4] which have been conducted for the past 17 years at 1 sec (partly 0.1 sec) interval in Osaka Electro-Communication University. The thunderstorm events are observed more than 70 times from 1990 to 2006, and more than 2500 examples of rapid XPD changes are obtained during these years in our university. The occurrence time and the amplitude of these changes are then compared with the lightning location and time provided by the Kansai Electric Power Company in Osaka area. Also, the decrease and increase in XPD and cross-polar phase are discussed in relation to the alignment of ice crystals due to electrostatic force and convective air flow in thunder clouds.

2. EXAMPLE OF THUNDERSTORM EVENTS

First, an example of the thunderstorm event observed on August 12, 1990 is presented. Fig. 1 shows the variations of (a) XPD and (b) cross-polar phase relative to co-polar phase, respectively. On this day, no rainfall was recorded at the station, and the attenuation did not exceed 2 dB during the thunderstorm event. However, large depolarization with the XPD values down to nearly 25 dB, and rapid changes in (a) XPD and (b) cross-polar phase can be detected almost every minute during 15:10–15:40 LT. Dashed lines indicate the time of cloud-to-ground (CG) lightning strokes near the station recorded by the Lightning Location and Protection System (LLPS) of the Kansai Electric Power Company. Several samples of the rapid changes are thus found to actually coincide with the moments of lightning strokes near the station, while the other considerable samples are seen to occur without CG lightning strokes. It should be noted that these characteristic changes in depolarization are primarily caused by ice crystals above the rain height, since no appreciable rain attenuation occurred in this event. Hence, these rapid changes without CG lightning discharges...
rather seem to be related to inter-cloud (IC) lightning discharges that occur in higher part of the thunder clouds.

Next, Fig. 2 depicts the distribution of mean canting angles of ice crystals inferred from the observed cross-polar phase just before (thin line) and after (thick line) the rapid changes, respectively, for the thunderstorm events observed from 1990 to 1998. Here, positive angles are defined as clockwise rotation seen from the satellite. Thus, the ice crystals are basically canting around 10–30 deg in clockwise even after the rapid changes as shown by the thick line. Moreover, the thin line suggests that the mean canting angles are increased up to 30–50 deg in the “same” clockwise direction before the changes, and then they return to around 10–30 deg after the changes associated with CG or possible IC lightning discharges.

Figure 3 illustrates horizontal distribution of lightning locations which affected the rapid changes of XPD and cross-polar phase observed in thunderstorm events during 1990–1998. The location of our earth station is at the origin of the diagram. The size of symbols is classified according to the amplitude of the phase changes such as more than 20 or 40 deg. It is seen from Fig. 3 that the data points primarily exist on the south side of the station at the distance up to about 20 km. Note that the large data points with conspicuous phase changes are mainly found in southward and westward directions, and that they are centered around a south-west point (−4 km, −6 km) from the station with a radius of approximately 4–12 km. The distribution of these data points seem to indicate the area where the cloud base producing CG strokes stays in each thunderstorm, so the center of the clouds primarily exists to the westward of the propagation path shown by a thick dashed line.

As the elevation angle of the satellite is about 50 deg, the beacon signal radio wave may pass through comparatively higher part of the thunderclouds mostly composed of ice crystals. So, the location of the cloud center being westward from the radio wave path in Fig. 3 may explain the afore-mentioned average clockwise rotation of ice crystals shown in Fig. 2 above the rain height as follows In an “aerodynamic-gravitational” point of view, the small clockwise inclination of ice crystals that still exists after the rapid changes suggests the effects of westerly (eastward) wind

Figure 1: Example of (a) XPD and (b) cross-polar phase observed in the thunderstorm event on August 12, 1990. Dashed lines indicate the time of cloud-to-ground (CG) lightning strokes recorded near the station.

Figure 2: Distribution of mean canting angle of ice crystals before and after the rapid changes.

Figure 3: Horizontal distribution of lightning location around the earth station.
shear on ice crystals possibly due to the convection of thunder clouds together with the jet stream that is high-altitude westward winds common in mid latitudes. In an “electrostatic” point of view, on the other hand, the large clockwise inclination of the canting angles just before the rapid changes is certainly caused by a strong vertical electric field, which is expected in the height of ice crystals at the moment of lightning discharges [5].

3. LONG-TERM STATISTICS

In this section, the statistical nature of XPD and cross-polar phase variations is further investigated for the entire observational period from 1990 to 2006. Fig. 4 shows the distribution of (a) coincident rates with cloud-to-ground (CG) lightning strokes, (b) clockwise (CW) and counter-clockwise (CCW) rotations for the canting angles of ice crystals, and (c) increase and decrease in XPD at the moment of lightning strokes, respectively. All the statistics are calculated for the entire observational period and three periods of each thunderstorm event which are equally divided by every one third of the duration time of each event and approximately correspond to developing, mature, and dissipating stages of thunder clouds [5]. As for the comparison with CG lightning strokes shown in Fig. 4(a), however, the statistics are limited up to 1998, since the LLPS data are only available for the duration from 1990 to 1998 near the station.

It is seen from Fig. 4(a) that about one third of the rapid changes of the depolarization coincide with CG lightning discharges near the station. Their percentages are found to increase in the middle stage of thunderstorms, when CG lightning strokes frequently occur. On the other hand, the percentages extremely decrease at the first period when thunder clouds are still developing, since inter-cloud (IC) discharges are, in general, active in this early stage [5].

As was previously shown in Fig. 2, the canting angles of ice crystals inferred from the cross-polar phase variations tend to rotate largely in the clockwise direction seen from the satellite before the lightning discharge and then return to nearly horizontal directions after the discharge. Fig. 4(b) statistically indicates that more than two thirds of the canting angles decrease at the moment of lightning discharges. Also, more than two thirds of the decreased canting angles originally rotate in the clockwise direction, and this tendency is more conspicuous in the middle stage of thunderstorms when their convective air motion is usually most active. Thus, these features of the canting angles are possibly caused by the afore-mentioned combination of both “aerodynamic-gravitational” and “electrostatic” effects.

Finally, Fig. 4(c) shows that there are two different cases in which the XPD values increase (depolarization decreases) and decrease (depolarization increases) at the moment of rapid changes, with decreasing cases slightly larger than decreasing cases. These results are distinct from those of other previous XPD observations using INTELSAT in low elevation angles, which primarily show the decrease in XPD at the moment of rapid changes in thunderstorms [6]. In the present observations, moreover, the XPD values tend to increase when the average XPD is comparatively high such as at the beginning or end of thunderstorms, while they tend to decrease when the average XPD is generally low such as in the middle of thunderstorms, as shown by Fig. 4(c).

Note that if the size of thunder clouds is small such as at the beginning or end of thunderstorms,
XPD values will be only affected by the alignment of ice crystals near the discharging point before lightning. In this case, when the electrostatic force is released after a lightning discharge, the XPD values for circular polarizations can be increased by random orientation of ice crystals. On the other hand, if the size of thunder clouds is large such as in the middle of thunderstorms, XPD values may be rather decreased before lightning by the cancellation effects between ice crystals in other places far from the lightning and those near the lightning. It should be noted that the mean canting angle of ice crystals is extremely increased near the lightning location before a discharge, while it does not seem to be increased so much in other places far from the lightning since “electrostatic” forces can not reach so far. Thus, the difference of their mean canting angles seems to yield depolarization cancellation as the charge is being accumulated. After the lightning occurs, the XPD value then decreases rapidly because their mean canting angles approach and become nearly horizontal direction.

4. CONCLUSIONS

The characteristic rapid changes in XPD and cross-polar phase are presented for the thunderstorm events obtained from the Ka-band beacon signal observations of the Japan’s domestic communication satellites for the past 17 years. About one third of the rapid changes are found to coincide with the cloud-to-ground (CG) lightning strokes, which primarily occurred on the south side of our earth station at the distance up to 20 km. The distribution of the lightning location indicates that the center of thunder clouds that produced these lightning strokes primarily exists to the westward of the radio wave propagation path. At the moment of rapid changes, two thirds of the observed cross-polar phases tend to move toward $-90$ deg, which means the decrease in canting angles of ice crystals inferred from the cross-polar phase. Also, more than half the observed XPD data indicate the decrease in XPD, which is equivalent to the increase in depolarization at their rapid changes. These features seem to be enhanced in the middle stage of thunderstorm events, when the thunder clouds become most developed and their convective motion and electrification are very active.

The average canting angles of ice crystals are considered to become very large in the clockwise direction seen from the satellite before lightning discharges, while they seem to return to nearly horizontal directions. These features of the canting angles are found to be well explained by the combination of “aerodynamic-gravitational” forces due to the eastward wind shear at the high altitude and strong vertical “electrostatic” forces before the lightning discharges. On the other hand, the present observations indicate a number of cases in which the XPD increases at the moment of rapid changes, in contrast to the past low elevation-angle observations using INTELSAT that showed the decrease in XPD for almost all cases. In our high-elevation observations, however, the increase in XPD after the lightning seems to be directly related to the anisotropic effects of ice crystal alignment caused by the decrease in the standard deviation of ice crystal’s canting angles due to electrostatic forces just before the lightning. To contrast, the decrease in XPD after the lightning may be related to cancellation effects of depolarization before the lightning due to the difference in canting angles between the ice crystals near the lightning and those in other places far from the lightning.

ACKNOWLEDGMENT

The LLPS data were supplied by the courtesy of the Kansai Electric Power Company.

REFERENCES