LETTER

# Bird Migration Echoes Observed by Polarimetric Radar

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**SUMMARY** A C-band polarimetric radar on Okinawa Island successfully observed large-scale bird migrations over the western Pacific Ocean. The birds generated interesting polarimetric signatures. This paper describes the signatures and speculates bird behavior.
***key words:*** *polarimetric radar, weather radar, clear-air radar echo, bird echo, ornithology*

## 1. Introduction

Weather surveillance radars observe clear-air radar echoes (CAE); aerial biota and irregularities in atmospheric refractive index caused the echoes. Using weak returns of atmospheric CAE, the radars have been applied to wind findings in a short radar range in a fair weather, in particular S-band radars. Long wavelength radars perform good to observe air motion, because a detectable turbulent scale depends on the wavelength and large-scale turbulences cause strong refractive index perturbations. C-band radars occasionally observe atmospheric CAE at a cloud edge and the thin layer between the atmospheric boundary layer (ABL) and the free atmosphere, where are characterized by a strong moisture (refractive index) gradient. Sometimes accurate wind estimates are difficult, because biological echoes could contaminate the atmospheric echoes. Conversely, these biological echoes have been applied to monitoring bird migrations and conservations [1]. Polarimetric radars are a powerful tool to discriminate biological echoes using dual polarized returns; the radar measures the differential reflectivity $Z_{dr}$ and the copolar correlation coefficient $\rho_{hv}$ between horizontal and vertical polarized returns, and other parameters [2]. $Z_{dr}$ represents a mean axis ratio of scatterers; spherical scatterers are characterized by a value of zero dB and horizontally (vertically) long scatterers generate positive (negative) signatures. Atmospheric CAE mostly generate signatures of $|Z_{dr}| \leq 1.5$ dB. In this paper, we classify the signatures of $Z_{dr}$ exceeding (below) 1.5 dB as P-type (N-type) and $|Z_{dr}| \leq 1.5$ dB as A-type. $\rho_{hv}$ expresses a stability and regularity of scattering cross-sections; atmospheric echoes indicate almost unity (stable and uniform cross-sections), whereas biota indicate small values due to their wing beat and various attitudes. An S-band radar demonstrated that birds indicated $Z_{dr}$ of −1–3 dB and $\rho_{hv}$ of 0.3–0.5 [3].

On 29 June, 2005, the C-band polarimetric precipitation radar operated at Okinawa Island observed large-scale bird migrations coming over the Pacific Ocean along the East Asia-Australasia flyway. In this region, the islands exist on an arc-line stretching for 1200 km from the main islands of Japan to Taiwan. Biota preferably choose migration route along the lands, but some species migrate over the Pacific Ocean from Australia. This paper focused on the migratory birds passing over and landing on Okinawa Islands on 29 June. We display the polarimetric signatures and speculate bird behaviors.

## 2. Radar Observation

The C-band full polarimetric precipitation radar (COBRA; C-band Okinawa Bistatic polarimetric RAdar) (5.3 GHz, 250 kW), operated by the National Institute of Information and Communications Technology of Japan, is located at the center of Okinawa Island (26.59°N, 128.06°E, 363 m elevation) [4].

Okinawa Island is located at the southwestern subtropical region in Japan, where is in a region transporting oceanic moist air toward the seasonal rain front stagnating above the main islands of Japan. COBRA frequently observes atmospheric CAE within 12 km radar range during warm and humid seasons. We conducted an intensive observation for understanding the structure of the moist ABL using COBRA, a vertical pointing wind profiler radar (WPR) and radio sondes during 1–9 July, 2005. In the observational campaign, COBRA principally observed vertical cross-sections including the vertical profile of the WPR, and we expected southwest wind being parallel to the cross-section to investigate initiations of a shallow cumulus convection. COBRA acquired 3-scan of plane position indicator (PPI) at 1.4, 7, 8 degrees in elevation-angle (EL) and 14-scan of range height indicator (RHI) at 41.2 degrees in azimuth-angle (AZ) every 10 minutes. The beam width of COBRA is 0.9 degrees and the range resolution was set to 75 m (300 m to the PPI at 1.4 degrees EL). COBRA was operated in the campaign mode from 28 June to 10 July.

COBRA luckily observed migratory echoes approaching to Okinawa Island on 29 June, 2005. During the observation, COBRA additionally observed line-form biologi-

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cal echoes moving northeastward above the southeast ocean of COBRA at night on 5 July and two cellular biological echoes moving northeastward above the Okinawa Island within 20 km radar range in the daytime on 5 and 7 July.

## 3. Meteorological Condition

Figure 1 shows the surface weather chart at 0900 JST on 29 June, 2005. The Pacific high pressure and clear sky covered over Okinawa Islands. The southeast wind occurred untill 1 July, after that the wind direction was changed to southwest along the northwestern edge of the Pacific high having lost the strength. The sounding above Okinawa Island at 0900 JST showed southeast wind of 6 m s$^{-1}$ up to 5 km altitude, but a thin layer of strong south wind of 10 m s$^{-1}$ appeared at 1 km altitude. The migratory birds coming over the Pacific Ocean caught the southeast wind, and they arrived at Okinawa Islands before the strong southwest wind domination.

## 4. Migratory Echoes on 29 June, 2005

### 4.1 Low Altitude Migratory Shorebirds

Terns appear at Okinawa Islands in early summer. Recently, roseate terns carrying Japanese leg-bands marked at Okinawa Island were captured at the eastern Australia in January, and it proves that the birds migrate over the Pacific Ocean [5]. Although terns are a little bird with a body length of about 25 cm and wing span of 55 cm, they can migrate at 2 km altitude [6]. Small and medium-size birds fly by alternating flapping and pausing phases, but they continuously beat the wings to sustain their flight level during a large-distance migration [7].

COBRA observed some biological echoes over the ocean. Figure 2 shows the PPI of radar reflectivity factor $Z$ and $\rho_{hv}$ at 1.4 degrees EL; two distinct biological echoes indicating smallest $\rho_{hv}$ below 0.6 at the 50 km south and northeast of COBRA. The smallest $\rho_{hv}$ represents continuously flapping birds characterized as changeable cross-sections. The south echo northwardly migrated over the Pacific Ocean. It began to appear at a range of 90 km corresponding to 2.5 km altitude; note that a beam coverage considerably widens at a large distance from the radar. Finally the echo passed over Okinawa Island and gathered as surrounding the Izena and Iheiya Islands denoted the symbol A and disappeared to (birds landed on) the islands at 1700 JST. Figure 3 shows the azimuthal dependence of $Z_{dr}$ from 1200 to 1700 JST and the echo mostly indicated P-type $Z_{dr}$. In particular the birds facing toward the radar; approaching from 200 degrees AZ until 1300 JST; generated distinct P-type $Z_{dr}$ varying between 5 and 15 dB. At 1500 JST, the birds passed over COBRA and showed the azimuthal dependence; the solid line, which indicates the logarithmic axis ratio of the projected cross-section of a plane object (length:width:height = 3:7:1) flying toward north with 10 degrees roll angle (left-wing down), seems to match with the observations.

The migratory echo appeared on the RHI during 1400-1500 JST. Figure 4 shows the appearances of $Z_{dr}$ and $\rho_{hv}$ when the main part of the echo passed over the RHI. The figure shows that most of the echo appeared below 1.5 km altitude, and they indicated P-type $Z_{dr}$ and the smallest $\rho_{hv}$; the peak in the $Z_{dr}$ distribution appeared at 5 dB and 80% echoes fall in the $\rho_{hv}$ range below 0.6. Thus, the birds migrated over the Pacific Ocean below 1.5 km altitude with continuous wing beat, and they may catch the strong follow wind at 1 km altitude.

### 4.2 High Altitude Migratory Shorebirds

COBRA observed a biological echo at 4 km altitude. Since

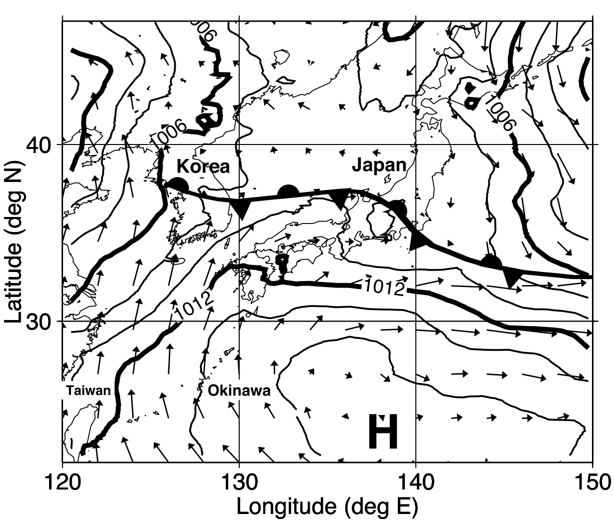


**Fig. 1** Surface weather chart at 0900 JST on 29 June, 2005. The contours indicate the pressure every 2 hPa and the vectors indicate horizontal wind (5 m s$^{-1}$ per degree on the abscissa).

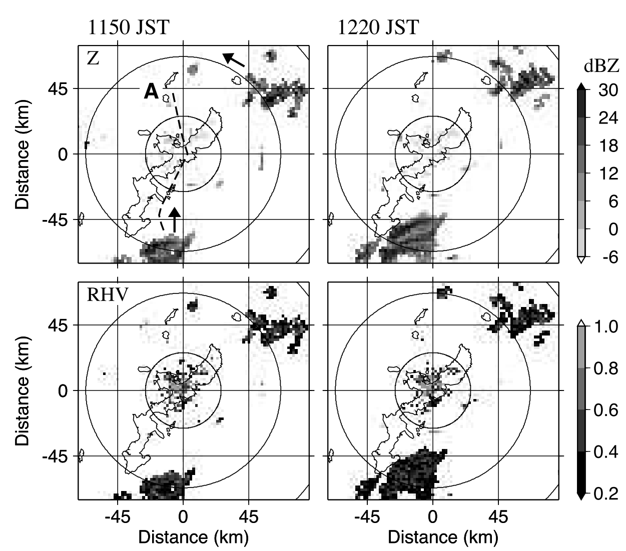


**Fig. 2** PPI of $Z$ and $\rho_{hv}$ at 1.4 degrees EL at 1150 and 1220 JST on 29 June, 2005. The circles denote the radar ranges corresponding to 1 and 2 km altitudes. The dashed line denotes the locus of the echo.

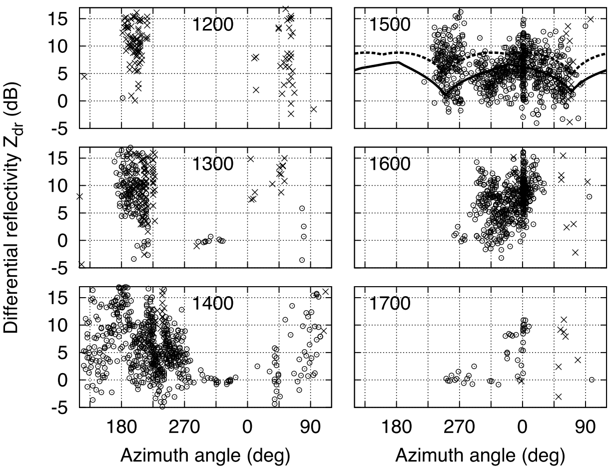


**Fig. 3** $Z_{dr}$ azimuthal dependence from 1200 to 1700 JST on 29 June 2005. The circle (cross) indicates the echoes within (beyond) 45 km radar range. The solid-line indicates the axis ratio of the plane object flying toward 340 degrees AZ with 10 degrees rolling. The dashed-line indicates the ratio without rolling.

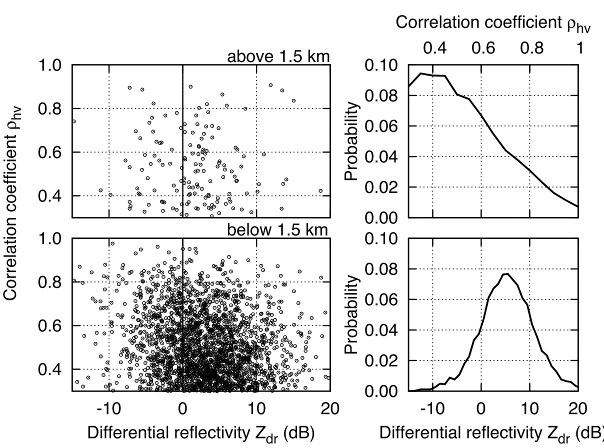


**Fig. 4** The scatterplot between $Z_{dr}$ and $\rho_{hv}$ below and above 1.5 km altitude (left panels), and the appearances of $Z_{dr}$ and $\rho_{hv}$ below 1.5 km altitude (right panels); $Z_{dr}$ appearance is classified every 1 dB and $\rho_{hv}$ is every 0.05. The figure derives the data from the 6 RHI during 1420-1440 JST on 29 June, 2005 and the sample number is halved.

the sounding result showed the zero temperature level at 5 km and a moist layer at 6 km altitude, the birds flew in the cold air just below clouds. Large species can climb up to more than 6 km and the migratory altitudes concentrate above and blow the clouds. The birds take a soaring-gliding flight during more than 95% of their migrations, because of an energy-saving strategy in good thermal conditions; however they compensate for lack of thermals by additional wing-flapping at low altitudes [7].

Figure 5 shows that the line-form biological echo appeared at 30 km south of COBRA at the altitudes of 3–6 km. The echo was consisted of two flocks; the northwardly approaching to Okinawa Island at the grid of (15, −20) and the westward flock at the grid of (10, −30). The echoes showed P-type $Z_{dr}$ at the edge parts of the flocks and N-type $Z_{dr}$

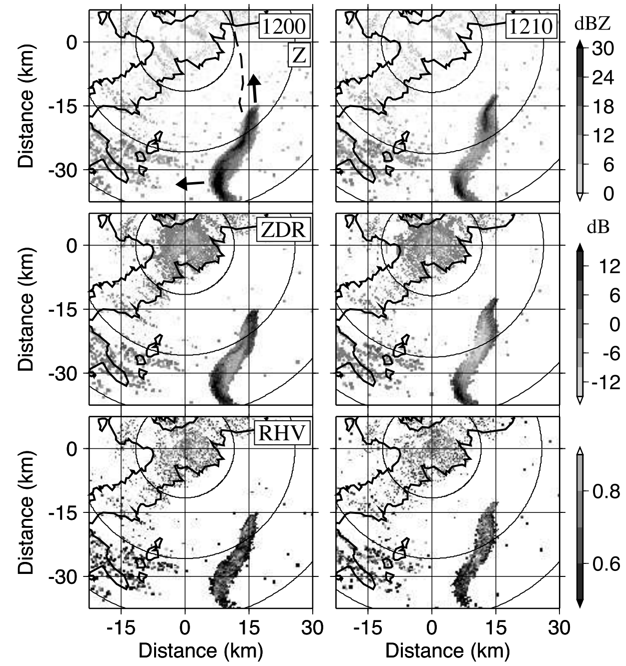


**Fig. 5** PPI of $Z$, $Z_{dr}$ and $\rho_{hv}$ at 8 degrees EL at 1200 and 1210 JSTon 29 June, 2005. The circles denote the radar ranges corresponding to 2, 4 and 6 km altitudes. The dashed line denotes the locus of the echo.

around the dividing point of the flocks. For generating the N-type $Z_{dr}$ of −9 dB, long sideway scatterers must deeply roll to change the flight orientation. The $\rho_{hv}$ signatures of the echo concentrated at 0.7 and the values were larger than the aforementioned low altitude echo. Thus the values around 0.7 probably represent soaring-gliding birds.

The northward migratory echo changed the flight orientation to westward and spreaded after arriving at the island. Figure 6 shows the widespread echo moving westward above the north sea of COBRA; however the westward echo included the narrow line-form echo northwardly flying away from the island at 0 degree AZ. The widespread echo clearly showed N-type $Z_{dr}$ and relatively large $\rho_{hv}$ signatures at the near-side to COBRA, whereas P-type $Z_{dr}$ and the smallest $\rho_{hv}$ appeared at the far-side and the leading part. Then P-type $Z_{dr}$ and the smallest $\rho_{hv}$ signatures gradually dominated as the echo moved westward. In addition, the echoes of P-type $Z_{dr}$ and the smallest $\rho_{hv}$ around COBRA are the low altitude migratory echo. Figure 7 shows velocity azimuth display (VAD) at 1410 and 1420 JST; the velocities are aliased to match with the echo movements on the PPI. P- and N-type echoes are derived from the radar range beyond 10 km to separate from the low altitude migratory echoes nearby COBRA, and A-type echoes are derived from the range during 5–10 km corresponding to the ABL top layer, where COBRA frequently observes atmospheric CAE. The westward P- and N-type echoes showed constant radial velocities to AZ at 1410 JST; 10 m s$^{-1}$ going far from the radar at 310–20 degrees AZ and it suggests that the birds turned to the left. The velocities at 1420 JST seemed on the curve of birds flying toward 305 degrees AZ with 11.5 m s$^{-1}$. The velocities

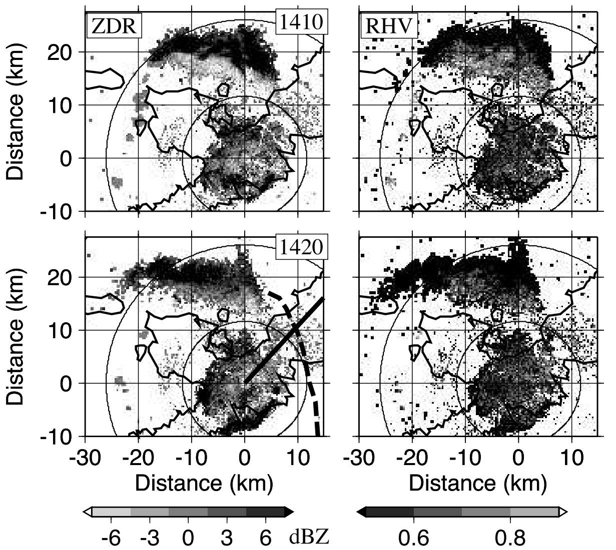


**Fig. 6** PPI of $Z_{dr}$ and $\rho_{hv}$ at 8 degrees EL at 1410 and 1420 JST on 29 June, 2005 as in Fig. 5. The thick solid-line denotes the RHI and the dash-line denotes the locus of the echo.

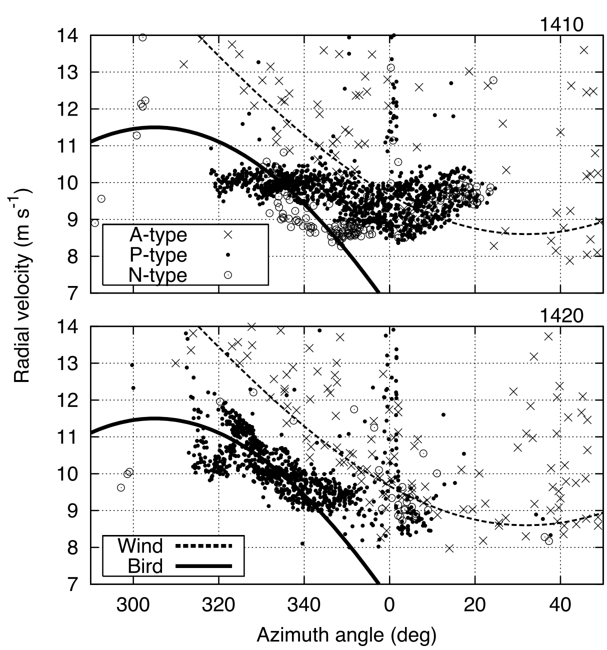


**Fig. 7** VAD at 1410 and 1420 JST on 29 June, 2005 (EL is 8 degrees). The symbols of cross, dot and circle denote the velocities of A-, P- and N-type $Z_{dr}$ echoes, respectively. The velocities are aliased (Nyquist velocity was 7.6 m s$^{-1}$) and the sample number is halved. The solid line shows the velocity curve of birds flying toward 305 degrees AZ with 11.5 m s$^{-1}$. The dashed line shows the wind blowing from 210 degrees AZ with 6.5 m s$^{-1}$ (aliased).

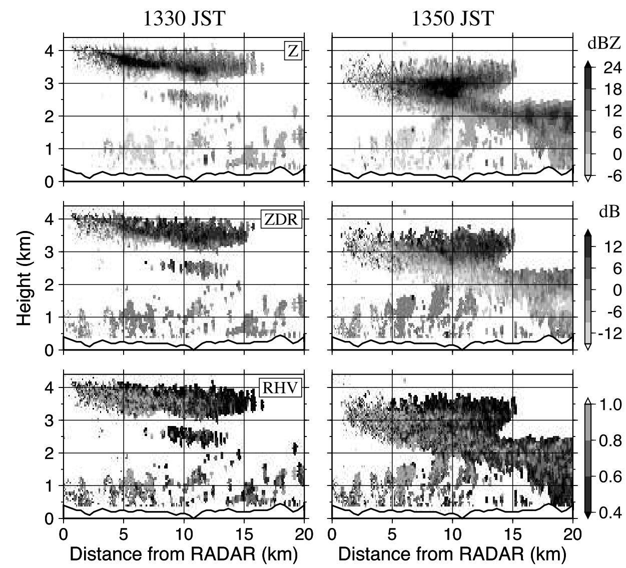


**Fig. 8** RHI of Z, $Z_{dr}$ and $\rho_{hv}$ at 1330 and 1350 JST on 29 June, 2005. The echoes with the velocities slower than 0.5 m s$^{-1}$ are excluded for a ground clutter elimination.

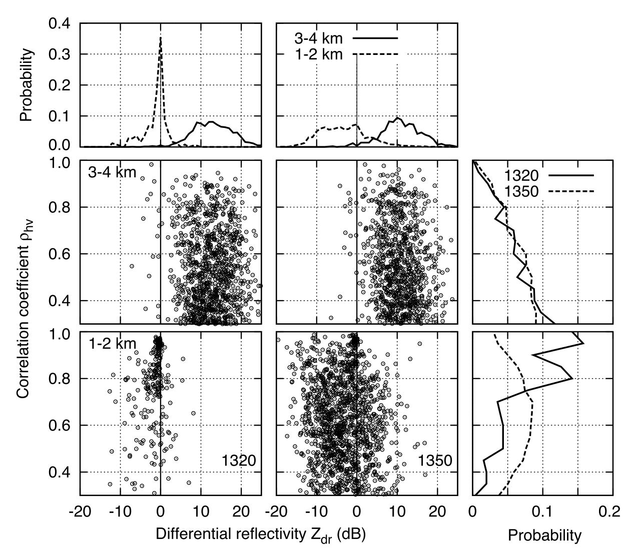


**Fig. 9** The scatterplots between $Z_{dr}$ and $\rho_{hv}$, and their appearances at the altitudes of 1–2 and 3–4 km on the RHI at 1320 and 1350 JST on 29 June, 2005.

around 12 m s$^{-1}$ at 0 degree AZ correspond to the northward narrow line-form echo. Thus the polarimetric signatures and VAD suggests that birds deeply rolled with a few flapping for a left-turn at the near-side, and birds flew westward without rolling at the far-side.

Figure 8 shows the RHI at 1330 and 1350 JST, when the high altitude migratory echo passed across the RHI (Fig. 6 shows the echo locus and the RHI). Thin stratiform echoes appeared at 2.5 and 4 km altitudes at 1330 JST. The upper echo gradually descended to 3 km altitude and it mostly indicated P-type $Z_{dr}$ of 10 dB and the smallest $\rho_{hv}$. Since the soaring-gliding birds tended to generate $\rho_{hv}$ values around 0.7, the birds no longer kept the soaring-gliding strategy over the island. The lower echo rapidly descended as if the echo run away from the upper echo or the echo found and chased something at the lower altitude. At 1350 JST, the descending birds clearly formed a down-sloped echo indicating N-type $Z_{dr}$ and relatively large $\rho_{hv}$ around 0.7. The northeastward descending movement and the polarimetric signatures suggest that rolling birds descended with fewer wing beat and changing the flight orientation. However the N-type $Z_{dr}$ echoes occasionally indicated the smallest $\rho_{hv}$ near the surface. It suggest that descended rolling birds quickly adjusted the roll angles to sustain the flight in turbulences or the birds flapped frequently. At that time, the lowest PPI displayed a cellular echo indicating the smallest $\rho_{hv}$ and moving northeastward along the west coast in the northern part of Okinawa Island. The cellular echo showed N-type $Z_{dr}$ at the later part of the echo locating on the RHI and P-type $Z_{dr}$ at the leading part beyond the range of the RHI. Then P-type signature dominated as the echo moved away from the radar (not shown). In addition, COBRA simultaneously observed scattered cumuliform atmospheric CAE originating from turbulences at cloud edges at 0.5–2 km altitudes; the echoes showed A-type $Z_{dr}$ and $\rho_{hv}$ exceeding 0.8.

Figure 9 shows the scatterplot between $Z_{dr}$ and $\rho_{hv}$ at the altitudes of 1–2 and 3–4 km at 1320 and 1350 JST. The scatterplot derives the echoes below 18 degrees EL to minimize elevational dependences; both signatures of $Z_{dr}$ and $\rho_{hv}$ of the high altitude stratiform echo clearly showed the elevational dependences at the EL higher than 20 degrees; $Z_{dr}$ decreased with a rate of 0.3 dB deg$^{-1}$ and $\rho_{hv}$ increased with a rate of 0.02 deg$^{-1}$ (not shown), simply because the radar viewed open-wing flapping birds from the bottom. The figure shows that the stratiform echo at 3–4 km altitudes showed P-type $Z_{dr}$ around 10 dB and large counts at the smallest $\rho_{hv}$. The descending down-slope echo at 1350 JST showed N-type $Z_{dr}$ and $\rho_{hv}$ concentrated around 0.7. The cumuliform echoes at 1–2 km altitudes showed nearly zero (A-type) $Z_{dr}$ and $\rho_{hv}$ exceeding 0.8, in particular at 1320 JST. The criteria can be useful to atmospheric CAE discriminations.

## 5. Conclusion

On 29 June, 2005, bird activity over the ocean around Okinawa Island was high. COBRA successfully captured large-scale bird migrations along the East Asia-Australasia flyway. The polarimetric signatures were useful not only for biota separations from atmospheric echoes, but also for speculating behaviors of large species birds.

- The criteria of $|Z_{dr}| > 1.5$ dB and $\rho_{hv} < 0.8$ are useful for bird echo separations.
- The low altitude migratory birds generated P-type $Z_{dr}$ and the smallest $\rho_{hv}$ ($< 0.6$) signatures. This species was characterized as long sideway cross-sections and continuously flapped in their migration.
- The large shorebirds flying at the high altitude generated P- and N-type $Z_{dr}$; level flight birds generated P-type and rolling birds showed N-type signatures. The $\rho_{hv}$ suggested that the line-formation birds approaching to Okinawa Island took the soaring-gliding strategy, whereas they frequently flapped around the island.

We expect that COBRA will offer significant contributions to the radar ornithology in Japan, for example, detecting bird density, developing migration maps, mapping roosting areas.

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