### RADAR OBSERVATIONS AND RADAR MODEL COMPUTATIONS OF

### BIOLOGICAL SCATTERERS

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### 1. Introduction

Polarimetric Doppler radar measurements of biological scatterers show distinct characteristics. Biological scatterers can be identified as a fine line polarimetric of enhanced radar Typically echoes signatures. from biological scatterers are present between ground and 1 km AGL. Reflectivity values typically vary between 5 and 20 dBZ and they are directly proportional to size and number concentration. Differential polarimetric measurements. namely, differential reflectivity  $(Z_{DR})$ and differential backscatter phase ( $\delta_{HV}$ ) sensitive to shape and size. are Polarimetric measurements of biological scatterers can be separated into signatures of insect and birds based on radial velocity,  $Z_{DR}$ ,  $\delta_{HV}$  (Zrnic and Ryzhkov, 1998).

In this paper radar observations and model computations of biological scatters are shown. An overview of NEXRAD radar observations of biological scatterers and its application to tracking their movement and monitoring them can be found in Chilson et al. 2012. As radar measurements are sensitive to orientation and size of biological scatterers. scattering computations of biological scatters are compared with radar measurements for

inferring size, type and orientation of biological scatters. Radar scattering computations of a small and large biological scatterers that correspond to insects and birds are shown as a function of orientation angle of the scatterer with respect to radar beam. When the scatterer size is small as compared to wavelength, the radar cross-sections vary smoothly as a function of aspect angle and is proportional to physical cross-section of the biological scatterer. At large non-Rayleigh sizes, radar cross sections vary by more than order of magnitude as a function of orientation angle.

## 2. A Technique for Computing Scattering Cross Section

cross-sections of Radar biological scatterers of various sizes are computed using a rigorous scattering program. Computations in this paper are valid for S-band wavelength and at frequency 2.725 GHz. i.e. radar transmit wavelength of 11 cm. As sizes of the biological target range between 0.1 and 30 cm, rigorous scattering program, namely T-matrix (transition matrix), is used for computing radar cross-section. Overall shape of a biological scatterer is approximated as prolate spheroid of axis ratio 3, i.e. ratio between major and minor dimensions. Average refractive index of scatterer is assumed to be 6.7 +j1 (Schaefer 1968).

When particles are comparable or larger than wavelength, Mie Scatering Theory is used for computing backscattering cross section. Mie scattering applies only to spehrical shapes. For non-spherical shapes (i.e., oblates and prolate spheroids) transition matrix

(T-matrix) method is computationally efficient (Waterman 1969; Barber and Yeh 1975). T-marix method could be used for computing small and large size particles (Vivekanandan et al. 1991). In this paper, the T-matrix is used for computing scattering characteristics of biological scatterers.

The T-matrix essentialy relates the unknown scattered field to the known incident fied or electromagnetic field transmitted by radar. Incident, scattered, and internal electric fields are expanded in terms of vector spherical harmonics functions. Vector spherical harmonic functions are composed of associate Legendre functions, sinusoidal functions and Bessel funcytions (Morse and Fishback 1953). The extended boundary condition method and analytic continuity are used to formulate the surface integral equations. The unkown scattered field is obtained from surface integral equations.

The T-matrix for a particular size, shape and composition of a bird is computed once with its symmetry axis along Zaxis. To obtain scattering properties of an arbitrarily oriented scatterer, depending on orientation of scatterer with respect to incident field direction, rotations of polarization unit vectors of incident and scattered are performed for computing scattering cross section of arbitrarily oriented scatterer (Wang 1979). The scattering code is calibrated by performing backscatter computation for a known target as shown in Figure 1. The refelctivity for 2 mm raindrop of concentarion 1 per m<sup>3</sup> is 18 dBZ and  $Z_{DR}$  is less than 1 dB. Figure 2 shows T-matrix-based scattering refelctivity and  $Z_{DR}$  as a function of polar angle. Polar angle of 90<sup>0</sup> correspond to zero degree elevation angle in the case of radar scan geometry. As expected, horizontally polarized refelctivity is 18 dBZ and there is almost no change in dBZ as a function of polar angle.



*Figure 1. Scattering geometrry for an oblate spheroid.* 



Figure 2. Reflectivity and  $Z_{DR}$  for 2 mm raindrop at 3 GHz as a function of polar angle are shown. Polar angle  $0^0$ corresponds to direction of Z-axis. Polar angle of  $90^0$  corresponds  $0^0$  elevation angle.

# **3. Radar Model Computations of Biological Scatterers**

For computing scattering cross-section of a bird, shape is assumed as prolate spheroid of axis ratio 3, i.e. ratio between major and minor dimensions (Wilson et al., 1994). Orientation of prolate spheroid with respect to incident wave is shown in Figure 3 for radar elevation angle of  $0^0$  and azimuth angle of  $90^0$ . At this orientation the major axis of prolate spheroid is parallel to horizontal polarization. Physical and geometrical cross sections of prolate spheroid are large along this direction.



Figure 3. Scattering geometrry for a proate spheroid for  $0^0$  elevation and  $90^0$  azimuth are shown.

Figure 4 shows reflectivity,  $Z_{DR}$  and  $\delta_{HV}$  for a prolate spheroid of equivalent spherical diameter ( $D_{eq}$ ) of 10 mm. This size corresponds to a size of typical insect. Concentration of insect is assumed to be 10000/km<sup>3</sup>. Since radar cross-section of a prolate spheroid is sensitive to orientation of scatterer with respect to the radar beam, radar parameters shown as a function of azimuth and elevation angle. At an elevation angle of 0<sup>0</sup>, and azimuth angle of 90<sup>0</sup>, the radar beam sees the maximum dimension of prolate spheroid



Figure 4. Reflectivity,  $Z_{DR}$  and  $\delta_{HV}$  for an insect of 10 mm equivolume diameter size with an axis ratio of 3 are shown as a function of orientation scatterer. Population of insects is assumed to be 10000/km<sup>3</sup>.

and the corresponding radar cross section is maximum. Reflectivity,  $Z_{DR}$ 

and  $\delta_{\rm HV}$  vary as a function of orientation angle. For a specified size and concentration dBZ varies between 5 to 20 dBZ. Differential polarimetric measurements are nil when major axis scatters are aligned along the radar beam. Differential polarimetric signals are maximum when broadside of scatterer is perpendicular to the radar beam. For elevation angles <  $10^0$  Z<sub>DR</sub> varies between 0 and 10 dB.  $\delta_{\rm HV}$  is smaller than  $2^0$ 

Figure 5 shows radar parameters for a prolate spheroid of equivalent spherical diameter  $(D_{eq})$  of 72 mm. This size corresponds to a size of a typical bird in Indian Ocean near Gan Island. Concentration of bird is assumed to be 10/km<sup>3</sup> i.e. one-thousandth of insect concentration. The corresponding reflectivity and Z<sub>DR</sub> values vary over a larger range than in the case of insects and it exhibits multiple peaks as the orientation of bird changes. However,  $\delta_{HV}$  values are order of magnitude larger than the corresponding values of the insect. Large values of  $\delta_{HV}$  distinguish between bird and insect.

# **3.** S-Pol Observations of Biological Scatterers during the DYNAMO

Figures 6, 7 and 8 show S-Pol Z,  $Z_{DR}$ and  $\Phi_{DP}$  from DYNAMO (Dynamics of Madden-Julian Oscillation) field measurements gathered on 19 Dec. 2011 at 0.5 degree elevation (Zhang, 2013). Several type of data anomalies are marked including a line of biological scatterers. The Z and Zdr for the biological scaterers range from 0 to 25 dBZ and from 3 to 10 dB respectively. Figure 8,  $\Phi_{DP}$ , shows no consistent evidence of  $\delta_{HV}$  corresponding to the biological scatterers. This indicates that the scatterers are most likely insects (Hubbert and Dixon, 2012).



Figure 5. Reflectivity,  $Z_{DR}$  and  $\delta_{HV}$  for a bird of 72 mm equivolume diameter size with an axis ratio of 3 are shown as a function of orientation scatterer. Population of bird is assumed to be  $10/km^3$ .



Figure 6. S-Pol reflectivity from DYNAMO gathered on 19 Dec. 2011 at  $0.5^{\circ}$  elevation. The high reflectivity cores were moving north-east to south-west. In front (south) of the line of storms is a line of biological scatterers likely "caught-up" in the gust front. The reflectivity of the biological scatterers range from about 0 to 25 dBZ.



Figure 7. S-Pol  $Z_{DR}$  from DYNAMO accompanying Fig. 6. The line of high  $Z_{DR}$  values mark the biological scatterers range from about 3 to 10 dB.



Figure 8. S-Pol  $\Phi_{DP}$  from DYNAMO accompanying Figs. 6 and 7. There is no evident line of backscatter phase shift that accompanies the region of high  $Z_{DR}$  values due to biological scatterers. Thus the biological scatterers are most likely insects.

Figures 9, 10 and 11 show S-Pol Z,  $Z_{DR}$ and  $\Phi_{DP}$  from DYNAMO gathered on 22 Dec. 2011 at 0.5 degree elevation. There is an interesting V-shaped echo below the storm core in the center of the images. This is likely due to birds. The reflectivities are typically in the 15 to 30 dBZ range. The left part of the Vshape has positive  $Z_{DR}$  while the right side has more negative  $Z_{DR}$ . From Fig. 11, the  $\delta_{HV}$  of the right and left hand side of the V-shape have a different character. The phase measurements of the bird echoes is quite noisy since the accompanying  $\rho_{HV}$  is very low. Since  $\delta_{HV}$  values in the V-shaped region is  $> 20^{0}$ , the scatterers are most likely birds.



Figure 9. S-Pol reflectivity from DYNAMO gathered on 22 Dec. 2011 at  $0.5^{\circ}$  elevation. The V-shaped line of reflectivity below the storm core in the center of the image is likely due to birds.



Figure 10. S-Pol  $Z_{DR}$  from DYNAMO accompanying Fig. 9. The V-shaped line of reflectivity below the storm core in the center of the image is likely due to birds. Note that the left side of the V-shaped biological echo has positive  $Z_{DR}$  while the right side of the V has negative  $Z_{DR}$ .



Figure 11. S-Pol  $\Phi_{DP}$  from DYNAMO accompanying Figs. 9 and 10. The V-shaped line of bird echo shows a distinct  $\delta_{HV}$ . Note that the left and right sides of the V-shaped biological echo has a different  $\delta_{HV}$ signature. The  $\delta_{HV}$ signature is quite noisy since the  $\rho_{HV}$  of the bird echoes is very low.

## 4. Summary and Discussion

Radar scattering computations of biological scatterers are shown as a function of orientation angle with respect to the radar beam. T-matrix scattering program is used for computing radar parameters. Accuracy of T-matrix scattering program is verified by computing cross sections of a 2 mm raindrop. At small sizes cross-sections smoothly varies as a function of orientation angle. Radar cross-section is proportional to physical size when the size of a biological scatterer is small comparable to wavelength. As size of become large than radar wavelength radar cross section varies by 10 dB as the orientation angle changes. In the case of birds larger than radar wavelength, radar cross-section exhibits multiple peaks and it varies more than 20 dB. Differential parameters, namely,  $Z_{DR}$  and  $\delta_{HV}$  are independent of density of biological scatterers in the case of mono-dispersion. The parameter,  $Z_{DR}$ varies by more than 20 dB as the orientation of scatterer changes and it exhibits multiple peaks. It is interesting note the parameter  $\delta_{HV}$  smoothly varies as a function of size and orientation angle. This parameter can be used to identify average size of biological scatterers and delineate regions that are dominated by insects and birds.

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