POLARIMETRIC PROPERTIES OF CHAFF

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1. INTRODUCTION

Chaff is made of aluminum coated thin fibers and is released by the military to create widespread echoes and thus confuse non cooperating tracking radars.
To maximize backscattering cross section chaff length is chosen to equal one half the radar wavelength. As predominant wavelengths for military surveillance and tracking are 3, 5, and 10 cm, the standard chaff lengths are 1.5, 2.5 and 5 cm. Because chaff is employed by the military as part of routine training in the USA, it is often observed as echoes on weather radars (Maddox et al. 1997). Although the reflectivity is relatively weak it is sufficient to contaminate precipitation estimates (Vasiloff and Struthwolf 1997). Thus it is desirable to recognize returns from chaff and censor these from precipitation products.

It has been argued (Zrnic and Ryzhkov 1999) that polarimetric radar offers simple and effective way to identify chaff. The argument is rooted in common sense logic and experimental evidence gained with circularly polarized radars (Martner et al. 1992). Polarimietric signatures of chaff in linear horizontal and vertical basis have not been reported. Moreover, because chaff is a nuisance (as far as observation of weather is concerned), little or no theoretical results about its polarimertric properties are available. In few years the National Weather Service will add polarimetric capability to its network of WSR-88D radars. Therefore it will soon be beneficial to have a simple automated procedure for censoring chaff. Our purpose here is to present scattering models of chaff that capture the essential polarimetric properties as well as some data to support these properties.

In laminar airflow chaff is mostly horizontally oriented and slowly falls with respect to air. Turbulence and differential air motion will cause wobbling. In either case differential reflectivity Z_{DR} is expected to be relatively large. Linear depolarization ratio L_{DR} will increase compared to the value in precipitation and the cross correlation between co polar returns ρ_{hv} will decrease. These polarimetric variables do not depend on the absolute values of returned power or backscattering cross section, yet they are the most significant discriminators. It is the insensitivity to cross section that simplifies model development.

Two simple models for computing polarimetric properties of chaff come to mind. In one the chaff is approximated with the Hertzian Dipole so that standard formulas (i.e., for prolate spheroids with induced field along the axis and no field perpendicular) could be applied to compute the elements of the covariance matrix. This approximation is applicable for chaff lengths much shorter than the wavelength. But, for polarimetric variables that are independent of concentration and backscattering cross section we show that the model can be extended to half wavelength sizes.

A more realistic approach is to model chaff as thin cylindrical antenna and apply standard formulas to obtain scattering coefficients. This second approach is also explored herein. Then, once the scattering coefficients are determined the geometrical transformations as done for the spheroids (Bringi and Chandrasekhar 2001, Ryzhkov 2001) can be used for computation of the polarimetric variables.

Both our models can be applied to determine chaff concentration within the resolution volume. This is significant for studies of diffusion in the atmosphere (e.g., Hildebrand 1977). Whereas such and similar studies (Martner et al. 1992) relied on resolution volume weighted averages over the chaff field the polarimetric method allows much finer resolution. It is possible to achieve about a km in the radial direction (sufficient for estimating specific differential phase) whereas the intrinsic beam width dictates the transverse resolution.

A relation between volume reflectivity η (m^2m^{-3}) and specific differential phase K_{DP} is suitable for estimating the chaff concentration N_o.

2. MODELS

2.1 Hertzian Dipole

Patterned after a prolate spheroid, this model in general can be thought of as composed of two orthogonal dipoles. One has fixed orientation along the chaff axis, the other is induced perpendicular to the axis. The dipole along the chaff axis is dominant and will be used initially to compare this simple model with a thin wire model.

2.2 Thin cylindrical antenna

In this model chaff is represented as a thin cylindrical antenna of length L and radius a (Kraus 1950). The antenna is illuminated by a plane wave, the angle between the antenna axis and the propagation direction is ψ, and the electric field, the antenna, and the propagation vector are in common plane.

2.3 Results of computations

For both models we assume that the chaff is randomly oriented in the horizontal plane (i.e., azimuth angle φ is between 0 and 2π), the radar elevation is 0 deg (a good approximation for surveillance radars), and the angle between axis of chaff and horizontal plane is uniformly distributed between θ_1 and $\pi/2$ (angle θ is measured with respect to the true vertical). Henceforth this angle ($\pi/2$ - θ_1) will be referred to as "flutter angle". Thus, a probability density function that represents a uniform distribution of orientation within the above prescribed limits is given by

$$p(\theta, \varphi) = \sin(\theta)/[2\pi\cos(\theta_1)].$$

This probability density function is used for computing scattering coefficients and thereafter the following three polarimetric variables (Doviak and Zrnic 1993).

Differential reflectivity
$$Z_{DR} = 10\log(<|s_{hh}|^2>/<|s_{vv}|^2>),$$

Copolar cross correlation coefficient
$$\rho_{hv} = <s^*_{hh}\, s_{vv}> /(<|s_{hh}|^2><|s_{vv}|^2>)^{1/2},$$

Linear depolarization ratio
$$L_{DR} = 10\log(<|s_{vh}|^2>/<|s_{hh}|^2>).$$

Under the assumption that the induced field transverse to the chaff axis is negligible these three variables are related via

$$L_{dr} = \rho_{hv}\, (Z_{dr})^{-1/2},$$

wherein L_{dr} and Z_{dr} are expressed in linear units.

Two variables Z_{DR} and ρ_{hv} are plotted in figures 1 and 2, for both models. The fluttering angle in these figures is between the chaff axis and the horizontal plane (equal to $\pi/2$ - θ_1). Also three lengths of chaff are used in the antenna model. A glaring conclusion is that the difference in Z_{DR} for the two models is insignificant. The slight difference in the ρ_{hv} (at small flutter – wobbling) is inconsequential for the purpose of identifying chaff.

Comparison of the three variables from the two models suggests that the simple dipole is quite adequate to explain the dependence on the wobbling (fluttering) angle. This dependence is mostly due to the orientation of the chaff needles (or dipole moments) and is not affected by the angular dependence of the scattering coefficients. This independence is expected for chaff lengths that produce one lobe of the backscattered pattern. Although this lobe is sharper for the thin antenna than the dipole, on the average it makes little difference to the variables.

The rather large values in Z_{DR} predicted for fluttering angles between – 40 and 40 deg require some explanation. Without direct measurement we speculate that four factors at play might prevent such large values. One, it could be that natural wobbling is larger. Two, induced field transverse to the chaff axis might be present. Three, there could be some flexing of the chaff as it falls. Four, the weaker signal (in the vertical channel) is below noise level.

3. CHAFF DENSITY

Next we present formalism for computing chaff density. This can be achieved by measuring the specific differential phase and volume reflectivity.

It can be shown that for the Herzian dipole model of chaff

$$K_{DP} = 180\, \lambda\, f_a\, N_o \sin^2(\theta_1)/(2\pi) \quad (\text{deg m}^{-1})$$

where the units for wavelength λ and forward scattering amplitude f_a are meters and concentration N_o is per m^3. Further, it is assumed that the imaginary part of f_a is zero.

The volume reflectivity η (at horizontal polarization) is related to the scattering coefficients by

$$\eta = 4\pi\, N_o <|s_{hh}|^2>.$$

For the Herzian dipole substitute and the considered geometry closed form solution for $<|s_{hh}|^2>$ can be obtained. Then the following equation

$$\frac{(K_{DP})^2}{\eta} = \frac{2025\sin^4(\theta_1)}{\pi^3[\sin^4(\theta_1) - 4\cos^2(\theta_1)/3 + 4]}\lambda^2 N_o$$

relates concentration of chaff to the flutter angle.

Clearly this ratio depends on the radar wavelength, flutter angle ($\pi/2$ - θ_1), and concentration. Computations for the thin antenna model requires similar steps. Note units in (17) are mks, and K_{DP} is in (deg m^{-1}). It happens that the result is the same if units of K_{DP} are changed to the more representative (deg km^{-1}) and η is in ($mm^2\ m^{-3}$).

Plots of $(K_{DP})^2/\eta$ (Fig. 3) indicate the multiplying factor (in units of $\lambda^2\, N_o$) is relatively insensitive to the chaff length. Further, it changes by less than 20% for small flutter angles (< 20 deg). Thus if chaff flutters less it should be possible to determine its concentration.

4. CONCLUSIONS

Two scattering models have been used to compute polarimetric variables of chaff. The models are Herzian dipole and thin wire antenna. Pertinent polarimetric variables are differential reflectivity, correlation coefficient between co and cross-polar signals and linear depolarization ratio. Chaff is assumed to be uniformly distributed in azimuth. The angle between its axis and horizontal plane (flutter angle) is also uniformly distributed but between zero and a maximum value. It follows that the two models produce very similar results if the chaff length is half the radar wavelength or less. The linear depolarization ratio is uniquely related to the ρ_{hv} and Z_{dr} therefore these two variables are sufficient to separate chaff from precipitation echoes. Nonetheless, chaff could be confused with echoes from insects because these produce similar values of ρ_{hv}.

5. REFERENCES

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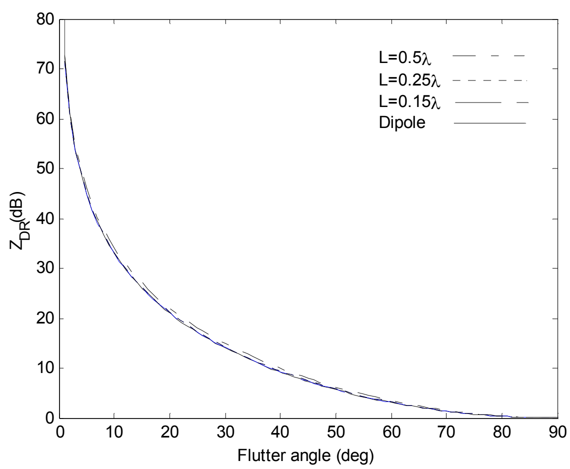

Fig. 1. Differential reflectivity as a function of the wobbling angle, defined as the maximum (positive as well as negative) deviation of the chaff axis from the horizontal plane. The lengths of chaff modeled as a thin antenna are indicated in terms of wavelength.

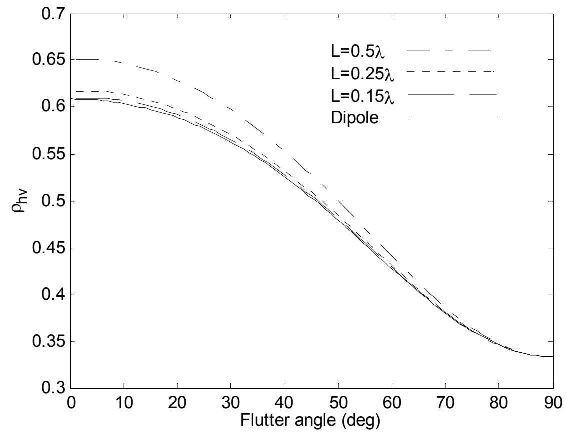

Fig. 2. Cross correlation coefficient for the same models as in Fig. 1.

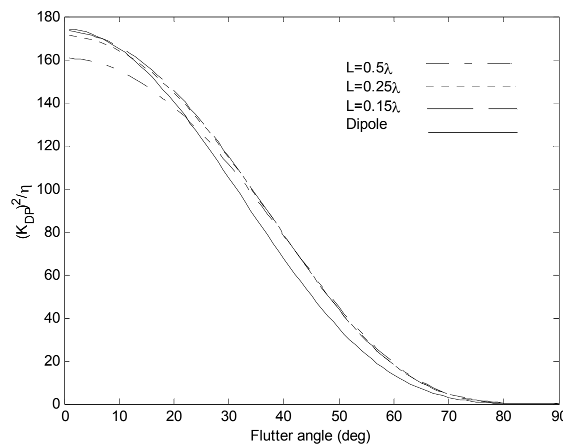

Fig. 3. Ratio $(K_{DP})^2/\eta$ for the thin wire model (lengths as fractions of wavelength are indicated) and the dipole model. The ordinate is in units of λ^2 N_o.