A Comprehensive Model for Chaff Characterization

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***Abstract*— The paper is aimed at providing a unified behavioural model for the chaff which takes into account all its fundamental characteristics including the kinematical properties, the statistical properties and the non-stationary behaviour. The aim is to reproduce the chaff behaviour with respect to all the relevant parameters in order to exploit such model in simulated environments, with respect to the radar and jamming domains. Such model is aimed at being representative for both naval as well as avionic situations.**

I. INTRODUCTION

Chaff is a countermeasure designed to reduce the effectiveness of radar. It usually consists of a large number of thin, highly conducting wires dispensed in the atmosphere to form a "cloud" of scatterers. Energy scattered by this cloud and received by a radar would ideally be large enough to mask the presence of some target the chaff is aimed at protecting. The strings composing a chaff may have many forms but typically are cut to a length so that they becomes resonant dipoles at the radar's frequency. The dipoles also will be effective at harmonics of the radar frequency. The idea of using metallic strips to create confusion with radar systems was probably known to all the major powers during the early stages of the Second World War. In the UK the material was called window, although the US term chaff is now most commonly used. Window was first used by the British in a raid on Hamburg on the night of 24th July 1943. The material had been in production since 1942 and at the time consisted of strips 300mm long and 15mm wide assembled in packets of about 1000. The Wurzburg (570MHz) and Lichtenstein (490MHz) radars were rendered almost completely ineffective, and the normal losses of bombers in such a raid was very much reduced.

Since that date up today many parameters enter into the overall effectiveness of chaff, such as physical cross sectional area of chaff elements (diploes), losses in the elements, speed and extent to which clouds form, effects of winds and turbulence in dipole shape, fall speed and altitudes of the elements, weight, volume, clustering tendencies (birdnesting), and radar cross section.

The aim of this paper is to present a unified modelling approach which takes into account a number of the aforementioned parameters. Such model has been appositely designed in order to be directly exploitable in simulated tactical environments aimed at estimating chaff behaviours when illuminated either by radar or jamming systems. Moreover the model has been designed to be representative for both the naval and avionic chaff uses.

II. RELATED WORKS

The literature related to scattering from chaff and from chaff elements is voluminous and for the sake of room we will not give a comprehensive list of references. For a good listing of articles prior to about 1970, [24] is a good source. References [24], [21], [22], [23] can be considered a good bibliography on the subject up to 1983. We shall however cite a few references that are considered representative of the developments that have evolved and that relate most directly to the interests of this paper.

Several models have been proposed in literature for the chaff radar cross section (RCS) characterization representative either for the monostatic [2], [4], [5], [8], [9] or bistatic behaviour [1], [3], [6], [7], [10].

In [4] Xianli et al. propose a mathematical model of chaff jamming for RCS and RCS statistical feature. In [5] the authors introduce a chaff cloud model which exploits aerodynamic principles to determine the density and orientation distributions of fibers within a chaff cloud, the RCS of which can then be determined. In [9] YiNan et al. introduce the results of a studied done over non-coherent radar backscattering from chaff clouds. Two orthogonally polarimetric scattering cross sections are derived.

In [1], [3], [6], [7], [10] generic models for the bistatic characterization of the chaff RCS are introduced. In [3], Palermo et al. depict the results obtained from an application of the variational method of computing radar scattering cross sections to the bistatic scattering cross section for chaff dipoles. The paper is concerned with one aspect of the feasibility of using chaff for beyond line-of-sight communications. The bistatic cross section of a chaff cloud is calculated and compared with experimental results obtained from a chaff system operating over 50-mile range. In [10] the author assumes a chaff cloud can be treated as an ensamble of independent scatterers, where the average scattering cross section of a volume within such cloud can be determined by the ensamble average for a single dipole. In [6] Dedrick et al. present formulas and numerical results for the bistatic-radar scattering cross section of an atmosphere of randomly oriented conducting wires. The work is based on the Stokes parameter description of the general radiation field, so that the polarization of transmitter and receiver antenna arrays can be chosen in any desired combination. The wires in the atmosphere can be of arbitrary length, and the second order expressions due to Einarsson are used for the cross section of a single wire. Taking as reference the results presented by Dedrick at al. in [1] the authors determine explicit equations for the chaff bistatic cross section presented to a receiving antenna having arbitrary (elliptical) polarization, arbitrary location and viewing the chaff cloud in arbitrary direction when that cloud is being illuminated by a transmitter having an arbitrarily polarized (different elliptical) antenna.

Several papers exist which studies how chaff characteristics relate to time and kinematical properties, namely [12], [8], [2] [3]. In [8] Wickliff et al. assume the determination of the average cross section can be based upon a static cloud model, whereby a randomly time-varying cloud is replaced by an ensamble of M clouds, each “frozen” in time and viewed at 512 angles around a great circle with two orthogonal linear-to-linear polarizations to obtain its spatial average backscattering cross section. In [12] Estes at al. depict the results of a series of experiments which include the recording and analysis of echo signals from chaff as it was dispensed from an aircraft (chaff in this state is referred to as “new” chaff). Echo signals from chaff clouds observed several minutes after the dispensing aircraft has left the area (they call this “mature” chaff) are also analyzed. Both these kind of measurements are therefore compared with theorical data in order to asses the models’ representativeness. In [2] the measured radar cross section (RCS) trend with respect to time is depicted for both aluminium and aluminised-glass chaff payloads. The measurements have been performed by firing both chaff clouds from the same naval dispensing system, using the same chaff volume packed to normal packing density for each material. The same approach has been followed in [3] where the authors make a comparison between theoretical data and measured data concerning the RCS evolution of a blooming chaff with respect to time.

For the chaff PSD characteristic we have finally taken into account [11], [12]. In [11] the author introduces a stochastic model describing the spectral and polarization characteristic of radar echos from a chaff cloud consisting of a collection of rotating dipoles, which may have either completely random or preferred orientation. Estes et al. finally present in [12] the results obtained from experimental amplitude and phase measurements of radar echoes from chaff both in the wake of the dispensing aircraft (new chaff) and after the aircraft has left the area (mature chaff).

III. A Unified Model for Chaff Characterization

Starting from the results depicted by the research works described in the chapter above, we have defined a unified model which tries to be representative of the principal chaff characteristics with respect to the radar and jamming domains.

The model is aimed at providing radar cross section and power spectral density curves describing the way a modelled chaff behave with respect to an emitter which is actually illuminating it. In this model a chaff can be described by means of a set characteristics depicted in table I, while the characteristics of the emitter (either a radar or a jamming system) can be defined by means of table II. Environmental concerns are then taken into account by means of a proper model of the wind vector, the current chaff height, the angles between the chaff and the emitter, etc. (table III). However even though the first two models depict chaff and emitter properties which are not time dependent, the environmental model consists of data which can strictly depend on the scenario evolution.

TABLE I
Chaff Model

Chaff characteristics	
Name	**Semantics**
N	The number of dipoles contained by the chaff
τ_{IF}	Chaff’s fall starting instant
τ_{EF}	Chaff’s fall ending instant
τ_C	Constant related to the chaff’s blooming time
V_i	Chaff initial velocity

TABLE IIII
Emitter Model

Emitter characteristics	
Name	**Semantics**
λ	The emitted wave length
φ	Half power antenna elevation beamwidth
θ	Half power antenna azimuth beamwidth
ψ	Antenna’s elevation angle
α_T	Angle between the z-axes and the polarization of the electric field incident at the chaff

TABLE IIII
Environment Model

characteristics	
Name	**Semantics**
V_o	Wind medium radial velocity
δ	Azimuth angle relative to the wind direction at the beam center (boresight).
R	Slant range between the chaff and the emitter
h	Current chaff height
α_R	Angle between the z-axes and the polarization of the electric field incident at the riceiver
β	Angle between the emitter and the receiver

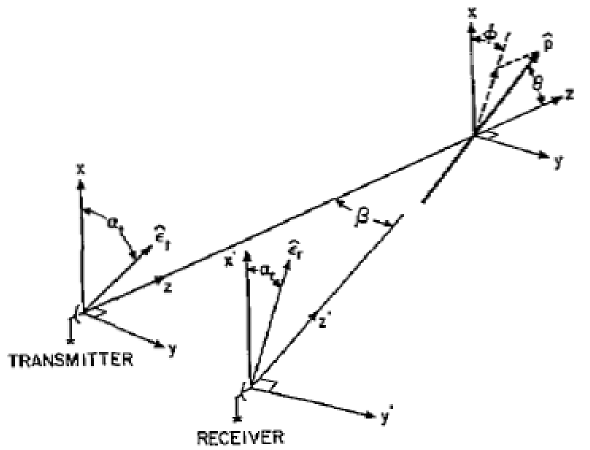

Fig. 1 Scenario's geometry

Fig.1 depicts a graphical representation of the scenario's geometry represented by Table III.

A. RCS model

Starting from the modelling elements defined in the section above our RCS model calculates the value of the chaff average radar cross section exploiting the related model presented in [13] (Fig 2.a). At the same time the statistical distribution of the backscattering cross section is determined through a cumulative probability function introduced in [17] (Fig 2.b). These data are then related to the chaff temporal evolution according to a model of the blooming behaviour defined by the function depicted in Fig 2.d.

The obtained data are then properly weighted in order to obtain a representative RCS value with respect to a receiving angle different from the transmitting one (Fig. 1) according to the bistatic model introduced in [10] (Fig 2.c). Fig 3 depicts the trend of the blooming time function (Fig 2.d) with respect to a specific scenario while Fig 4 depicts the trend of the resulting chaff RCS behaviour. This has been done under the assumption of uncorrelated returns (i.e. agile radars).

a) $RCS_0 = 0.18\lambda^2 N$

b) $P(\sigma) = 1 - e^{(-\sigma / RCS_0)}$

c) $f = \frac{1}{3}(1 + 2(\cos\alpha_T \cos\alpha_R + \cos\beta \sin\alpha_T \sin\alpha_R)^2)$

d) $$B(t) = \begin{cases} 1 - e^{(-t/\tau_C)} & t \le \tau \\ 1 & \tau < t \le \tau_{IF} \\ \frac{1}{2} - \frac{1}{\pi} arctg(t - \tau_{IF} - \Delta) & \tau_{IF} < t \le \tau_{EF} \end{cases}$$

Fig. 2 : chaff RCS model

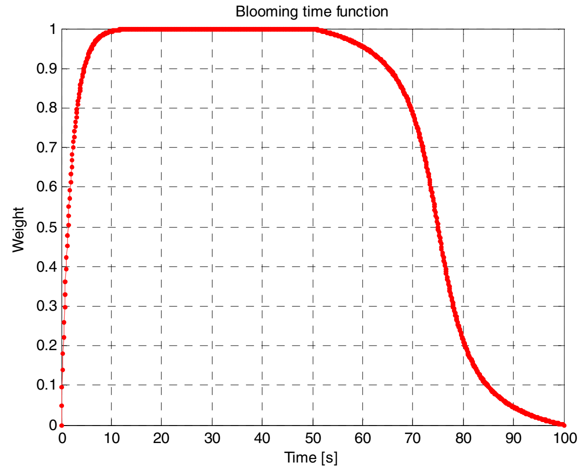

Fig. 3 Blooming trend for λ =0.03m, N=100000, τ_C =2 s, τ_{IF} =50 s, τ_{EF} =100 s, $\alpha_T = 0^\circ$, $\alpha_R = 90^\circ$, β $= 30^\circ$.

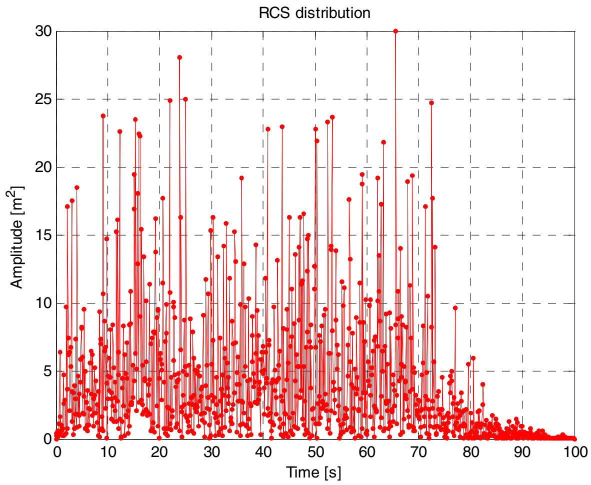

Fig. 4 RCS trend for λ =0.03m, N=100000, τ_C =2 s, τ_{IF} =50 s, τ_{EF} =100 s, $\alpha_T = 0^\circ$, $\alpha_R = 90^\circ$, β $= 30^\circ$.

B. PSD model

If the radar is not agile from pulse to pulse the returns are correlated thus a PSD has to be introduced. The PSD model we propose has been mainly derived from the related models introduced in [13] and [12]. The model consists in a first estimation of the standard deviation due to the wind shear which is the change in wind velocity with altitude (Fig. 5.a). Wind shear can be the greatest factor contributing to the Doppler spectrum spread of precipitation echoes in a long-range, ground based radar. Then the standard deviation due to the beam broadening is estimated which affect the spectrum component because of the distribution of radial velocity components of a tangential wind blowing across a radar beam of nonzero width (Fig 5.b) . The contribution to the spectrum deviation due to the wind turbulence and chaff fall velocity is finally calculated [13] (Fig 5.c and 5.d). Starting from this data (Fig 5.e) the PSD distribution is finally calculated by means of the model defined in [12] (Fig 5.f). In Fig 6 the trend of the modelled chaff PSD is depicted with respect to a given scenario data.

a) $\sigma_{SHEAR} = 0.42kR\varphi$

b) $\sigma_{BEAM} = 0.42V_0\theta\sin\delta$

c) $\sigma_{TURB} = \begin{cases} 1 & 0.3 \le h \le 3.6 \\ 0.7 & h > 3.6 \end{cases}$

d) $\sigma_{FALL} = \sin\psi$

e) $\sigma^2 = \sigma_{SHEAR}{}^2 + \sigma_{BEAM}{}^2 + \sigma_{TURB}{}^2 + \sigma_{FALL}{}^2$

f) $S(f) = S_0 \exp\left\{-\left[(f - f_0)\lambda / \sqrt{8}\sigma\right]^2\right\}$

Fig. 5 : chaff PSD model

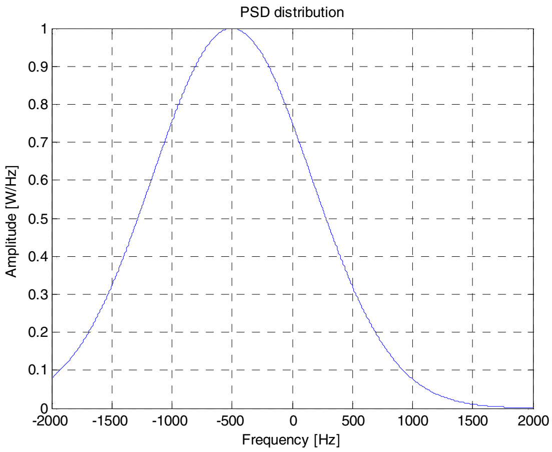

Fig. 6: PSD trend for R=8 Km, $\varphi = 45^{\circ}$, $\theta = 2.25^{\circ}$, V_O =8 m/s, $\delta = 1^{\circ}$, h=0.5 Km, $\psi = 22.5^{\circ}$, λ =0.03 m.

IV. Conclusions and Future Works

Aimed at reproducing the chaff behaviour with respect to its relevant parameters, we have defined a unified behavioural model for chaff which takes into account all its fundamental characteristics including the kinematical properties, the statistical properties and the non-stationary behaviours. While the available literature in this research topic typically consists of modelling proposals for single chaff characteristic we have tried to define an approach which exploits the proposed models in a comprehensive way so that the whole chaff characteristics are taken into account. Such model is also aimed at being representative for both naval as well as avionic situations. The depicted results represent a first step of an ongoing work. Future improvements will consists of: a validation of the defined model with data obtained from real measurements; a better characterization of the chaff model (i.e., number of dipoles for each dipole's length, etc.) ; a characterization of the RCS behaviour which takes into account the way the chaff behaves at different frequencies (i.e. depending on the number of dipoles at the related length); a porting of the developed model from the Matlab environment [18] to integrated and distributed simulation environments [19], [20].

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