Simulation of chaff cloud Radar Cross Section

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1. Introduction

Chaff finds its main applications in electromagnetic countermeasures. An auto-protection technique consists in spreading dipoles, also knows as "Chaff" in the proximity of the target to protect. A cloud of Chaff is a diffuse artificial target made up of half-wave resonant dipoles. In order to jam radar systems able to operate in a wide frequency band, since world war 2, use has been made of a technique consisting in dropping or firing from aircrafts, ships or land vehicles, cartridges containing large amounts of Chaff dipoles of varying lengths. Different Chaff dispensing methods allow its use for various types of mission: deception, distraction, seduction, confusion or screening. The study of electromagnetic scattering by a chaff cloud is so complex that no exact theory is currently available for well describing all the phenomena observed. Chaff RCS depends on many parameters like: technological characteristics of the dipoles, their packaging, and their aerodynamic behavior as well as atmospheric and initial dispersion conditions. Simplified theories [1-4] have been proposed to describe certain characteristics of chaff clouds. In [8] the main electromagnetic interactions limiting the radar reflectivity of dipoles distributed randomly within a volume of space are presented. However these approaches were not sufficient to perfectly describe the observed RCS of a realistic chaff cloud versus time. In order to address such situations LACROIX industry has carried out software, under French Ministry of Defence (DGA/CELAR specifications), called SILEM, able to characterize battle ship auto-protection systems under operational configurations.

2. Characteristics of chaff clouds

Chaff cloud characteristics rely on high size volumes with inhomogeneous concentrations, changing versus time. It's also necessary to make a dynamic 3D-volume description to obtain good results on geometrical position and on scattered fields. All the following effects have to be well simulated because they can considerably influence seeker-processing outputs:

- Geometrical position and cloud sizes have to be considered because they have a direct impact on seeker acquisition and tracking.
- Chaff clouds are also composed of various length dipoles in order to be effective against various frequency threats. So, it is necessary to know the scattering matrix of a dipole on a large spectral domain.
- Chaff dipole motions induce RCS fluctuations, which can be analyzed by power spectral density processing. To recognise chaff, seekers can process these particular fluctuations, which are different from frigates.
- Aerodynamic of dipoles gives them special orientations, which influence the polarimetric radar signatures of a cloud.
- Sea environment induces multi-paths that modify the RCS of a cloud.

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Also, we must consider that the effective RCS is always less than its theoretical value. It is mainly due to the packaging techniques that result in a phenomenon called birdnesting (when some dipoles cling together) and also to the shielding effect. Such difficulty justifies using measurements performed in real conditions to determine correction coefficients.

3. Methodology of SILEM software

SILEM is composed of 4 main units concerning:

- The decoy placement depending on threat arriving,
- The evolution and dispersion of chaff cloud, depending first on ejection initial conditions and then on weather conditions (atmosphere stability and wind force)
- The electromagnetic scattering of chaff clouds,
- The wave interaction with the sea surface, creating various multipaths between the chaff and the radar.

Taken into account all these particularities, SILEM is able to produce at each instant of the simulation: the chaff impulse response, its RCS, its harmonic response, and its power spectral density for all polarisation states (HH, VV, HV, VH).

4. Placement unit

According to user orderings (type of munitions, required placement position, ejection time...), the placement unit determines the munitions trajectory, the time necessary to reach the desired position, the apparition instants and positions of each sub-munition. This step is based on fire tables exploitation. A launching table has been defined, giving all reachable positions and time necessary to achieve them. Thus, it's possible to interrogate this table to determine the best position. It would be a compromise between the target range and the delay to produce an attractive echo. Such a choice must be defined by launching rules. When a placement point is determined, it's necessary to calculate launcher orientation that is given by azimuth and elevation angles, to verify this launching possibility. The decoy ejection direction at the placement point is read in the launching table. All sub-munitions are positioned relatively to this point and then evolve independently.

5. Chaff cloud evolution and dispersion

Sub-munitions are going through two successive evolution phases:

- First one, due to ejection booming, determines clouds growing under forced initial conditions,
- Second one is defined by chaff dispersion under weather conditions (atmosphere stability and wind force).

For these two phases, sub-munitions are defined by Gaussian spatial functions that give at any time chaff concentration. So, the concentration c_i in a cloud referenced 'i' can be given by the following expression:

$$c_i(x,y,z) = \frac{m_i}{(2\pi)^{3/2}\sigma_X\sigma_Y\sigma_Z} e^{\left[-\frac{(x-x_C)^2}{2\sigma_X^2}-\frac{(y-y_C)^2}{2\sigma_Y^2}-\frac{(z-z_C)^2}{2\sigma_Z^2}\right]} \qquad (1)$$

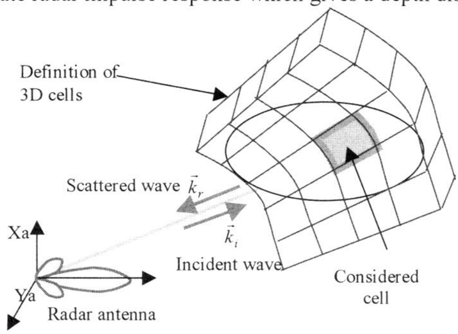
with:

(x_c, y_c, z_c) : chaff cloud centre.

$(\sigma_x, \sigma_y, \sigma_z)$: standard deviations along x, y and z coordinates.
m_i : masse of dipoles contained in sub-munition 'i'
Standard deviations $(\sigma_x, \sigma_y, \sigma_z)$ change versus time according to the two phases. Under weather conditions, the standard deviations are calculated from Pasquill coefficients [6]. The positions of chaff cloud centres are also updated during simulation according to wind speed. The displacement of chaff cloud centre results in a small Doppler effect.

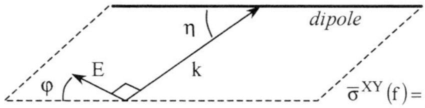
6. Chaff scattering

Before scattering calculation, clouds are divided into 3D cells. Each cell is referenced geometrically from the radar position and gives its dipole concentration. Such a 3D space dividing is necessary to take into account antenna diagram, which can not be considered constant on all cloud volume and to calculate radar impulse response which gives a depth discrimination.



- Figure 1: 3D cells definition -

The huge numbers of dipoles that make up a chaff cloud justify perfectly the use of statistics as a tool of investigation. Owing to the incoherence of scattered fields and supposing that dipoles are uncoupled, the average RCS of a cloud of N dipoles is equal as a first approximation to N times the average RCS of a dipole. To calculate scattering from one dipole, it's necessary to have a good knowledge of dipole mean orientation. The orientation of a dipole depends on its aerodynamic behaviour as well as on the initial dispersion conditions and atmospheric turbulence. It's very difficult to know dipole orientations, so calculations often consider randomly orientated dipoles [8]. Vakin and Shustov [7] suggest that in a cloud, dipoles are distributed in two preferential groups of orientations, respectively horizontal and vertical positions. Therefore, SILEM software considers two preferential groups of orientation. To estimate the orientations of horizontal and vertical families, and also the proportion of dipoles for each family, measurements in co-polarisation (HH, VV) and cross-polarisation (HV or VH) channels are used. Dipoles are considered randomly oriented in horizontal plane. The back scattering coefficient of a dipole of length L and diameter d at frequency f in XY polarisation (2) is calculated by the Van Vleck A or B methods [5] where angles (η, φ) represent the direction and the polarisation of the electric field in the incident plan. Calculations are made for various azimuth angles to consider randomly oriented chaff in horizontal plane. For each population of dipole orientations, the average RCS is calculated by the formula (3) where ν represents the dipole orientation in horizontal plane.



$$\sigma^{XY}\left(L, d, f, \eta, \varphi\right) \qquad (2)$$

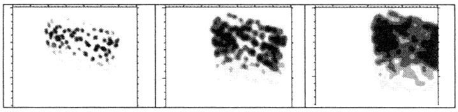
$$\overline{\sigma}^{XY}(f) = \frac{1}{2\pi}\int_0^{2\pi} \sigma^{XY}\left(L, d, f, \eta(\nu), \varphi(\nu)\right) \cdot d\nu \qquad (3)$$

- Figure 2: Scattered field by a dipole -

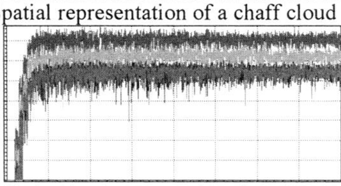
For each cell, average RCS values are stored. Fluctuations are calculated via an Auto Regressive model to respect spectral density. For each cell, fluctuation values are stored for the next iteration.

7. Results

Some results of dispersion and scattering by chaff clouds will be given under realistic naval conditions. Figures 3 and 4 show such examples.



- Figure 3: Spatial representation of a chaff cloud versus time -



- Figure 4: Chaff cloud RCS versus time for all polarisation states -

8. Conclusion

A chaff cloud simulation developed by LACROIX/CESTA for French Ministry of Defence (DGA) is presented. It shows how authors have overcome the difficulties of modelling chaff clouds to reproduce realistic scattered signals in all polarisation states, taking into account chaff fluctuations and multipaths on sea surface. Such a modelling can now be used to evaluate the performance of seekers jamming.

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