A chaff cloud modelisation

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Abstract
The objective of this paper is to present a Chaff cloud Radar Cross Section (RCS) model, able to characterize battle ship autoprotection systems under operational configurations.
This software, called SILEM, has been developed for French Ministry of Defence (DGA).
After reviewing the particularities of chaff clouds, this paper describes SILEM components to calculate decoy placement, chaff cloud evolution and dispersion, and radar scattering by dipoles.

Keywords: Chaff, decoy, dipole, Radar Cross Section, Power Spectral Density, electromagnetic scattering

1. Introduction

Chaff finds its main applications in electromagnetic countermeasures. Military are always worrying about radar objectives auto-protection. One 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. These dipoles, which consist of perfectly conducting aluminum-coated glass fibers, can generate quickly very strong RCS levels. 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. The RCS of a cloud in fact depends on many parameters like: technological characteristics of the dipoles, their aerodynamic behavior as well as atmospheric and initial dispersion conditions. Allowance must also be made for all poorly known phenomena liable to occur in the enormous chaff payloads dispensed in countermeasures.

Simplified theories [1-6] have been proposed to describe certain characteristics of chaff clouds. In [10], a mathematical model allowing the simulation of the main electromagnetic interactions capable of limiting the radar reflectivity of a set of dipoles distributed randomly within a volume of space is presented.
However, these approaches were not sufficient to perfectly describe the observed RCS of a realistic chaff cloud versus time. It is well known that such RCS are limited by different factors: technological imperfections, poor cloud dispersion and electromagnetic phenomena.

In order to address such situations LACROIX industry has carried out software, under CELAR specifications, called SILEM, able to simulate electromagnetic decoy RCS under battle naval configurations (cf. figure 1).

Figure 1: Example of chaff decoys fired from a frigate

2. Characteristics of chaff clouds

Chaff cloud characteristics, making them difficult to modelling, rely on high size volumes with inhomogeneous concentrations, changing versus time. It's also necessary to make a dynamic 3D-volume description, consuming therefore time simulation, to obtain good results on geometrical position and on scattering. 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 (impulse response) and tracking.
- Chaff clouds are also composed of various length dipoles in order to be effective against various frequency threats. Their RCS values must also be high enough to be attractive. So, it is necessary to know the scattering matrix of a dipole on a large spectral domain. In this work, we have chosen the analytical Van Vleck methods [8] to obtain it.
- Besides, chaff dipole motions induce RCS fluctuations, which can be analyzed by power spectral density (PSD) processing. Seeker to recognise chaff and distinguish decoy from real target can sometimes process these particular fluctuations, which are different for frigates.
- Also, the aerodynamic of dipoles gives them special orientations, which influence the polarimetric radar

signature of a cloud. We must add the sea environment, which contribute to modify the RCS of a cloud.

We must consider that the effective RCS observed 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 that it is necessary to use measurements performed in real conditions to determine correction coefficients.

3. Methodology of SILEM software

In order to proceed chaff cloud model, SILEM is composed of 4 main units concerning:

- The decoy placement unit, which determine placement point depending on threat arriving,
- The evolution and dispersion of chaff cloud into atmosphere, 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 cloud and the radar..

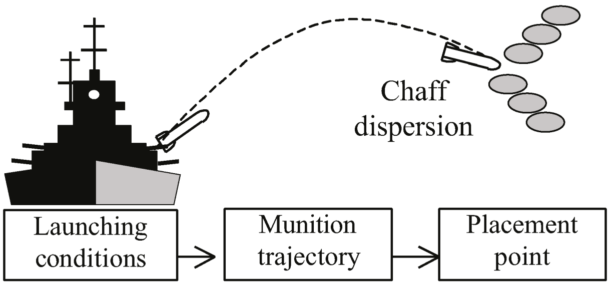
Taken into account all these particularities, SILEM is able to produce at each instant of the simulation, the following radar specifics on the chaff cloud:

- Its impulse response,
- Its RCS,
- Its harmonic response,
- 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-munitions. This step is based on fire tables exploitation.



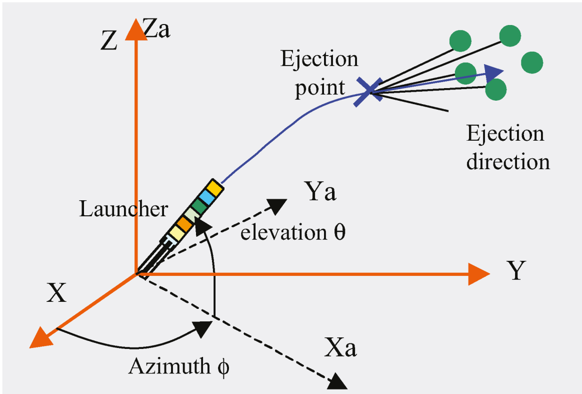
- Figure 2: Placement process -

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 ϕ and elevation θ angles, to verify this launching possibility.

The decoy ejection direction at the placement point is read in the launching table. All sub-munitions can then be positioned relatively to this point.



- Figure 3: Decoy placement -

All sub-munitions will 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 a Gaussian spatial function which gives at any time chaff concentration. So, the concentration c_i in a cloud referenced 'i' can be given by the following expression:

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

where

(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 published in reference [8].

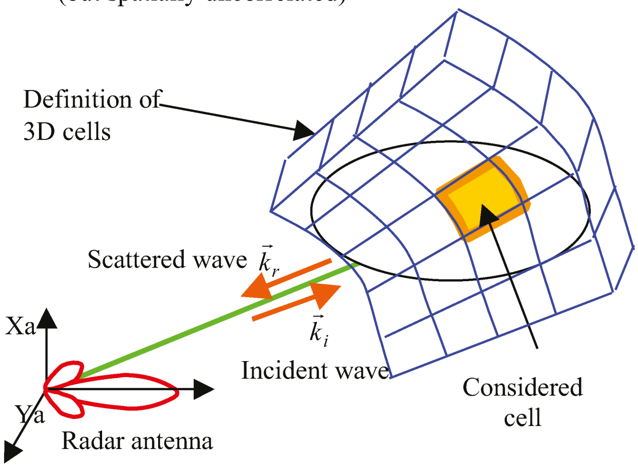
The positions of chaff cloud centres are also updated during simulation according to wind speed. The derivation of chaff clouds results in a small Doppler effect.

6. Dipoles scattering

As described above, chaff clouds are defined by a Gaussian spatial function. 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 dimensions
- to calculate radar impulse response which gives a depth discrimination
- to calculate fluctuations which are time correlated (but spatially uncorrelated)



- Figure 4: 3D cells definition -

Taking into account the concentration of dipoles, it is possible to calculate for each cell its contribution to the scattered field.

The huge numbers of dipoles that make up a chaff cloud justify perfectly the use of statistics as a tool of investigation. The ergodicity hypothesis makes it possible to combine the average time RCS and its statistical value. Owing to the incoherence of scattered fields and supposing that dipoles are uncoupled, we write:

$$<\sigma_{N\ dipoles}>= N.\bar{\sigma}_{dipole}$$

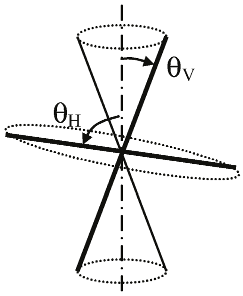
where <> represents statistical average.

This formula means that 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.

In atmosphere, the orientation of a dipole depends on the aerodynamic behaviour of the scatter as well as on the initial dispersion conditions and atmospheric turbulence. Vakin and Shustov [9] suggest that in a cloud, dipoles are distributed in two preferential groups of orientations, respectively horizontal and vertical positions. It's very difficult to know dipole orientations, so calculations often consider randomly orientated dipoles [10]. One method to estimate correctly orientation of dipoles is to use polarimetric RCS measurements in order to correct numerical results.

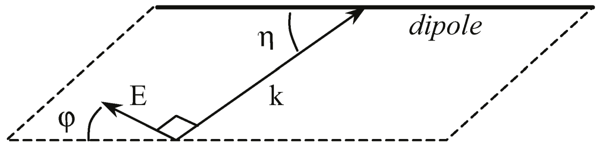
Therefore, SILEM software considers two preferential groups of orientation. Measurements in co-polarisation (HH, VV) and cross-polarisation (HV or VH) channels are used to determine the orientations of horizontal and vertical families, and also the proportion of dipoles for each family. Dipoles are considered randomly oriented in horizontal plane.



- Figure 5: The two main orientations of dipoles -

The scattered field for a dipole of length L and diameter d, can be calculated by Van Vleck methods (A or B) at frequency f [7].

The back scattering coefficient of a dipole in XY polarisation, $\sigma^{XY}(L,d,f,\eta,\varphi)$, is calculated by the Van Vleck A or B methods [7]. Angles (η,φ) represent the direction and the polarisation of the electric field in the incident plan.



- Figure 6: Scattered field by a dipole -

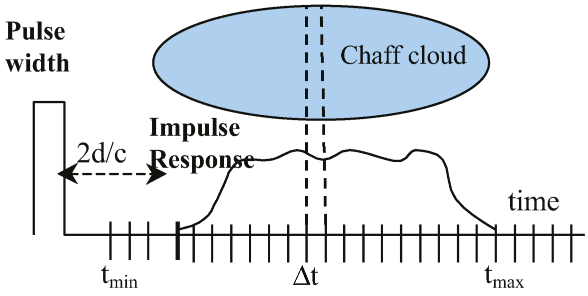
Calculations are made for various azimuth angles to consider randomly oriented chaff in horizontal plane and to determine average RCS values. According to Vakin and Shustov hypothesis, 2 populations of dipole orientations are considered: one near of horizontal and the other near of vertical. For each population, the average RCS is calculated by the following formula:

$$\bar{\sigma}^{XY}(f)=\frac{1}{2\pi}\int_0^{2\pi}\sigma^{XY}(L,d,f,\eta,\varphi)\times d\nu$$

where ν represents the dipole orientation in horizontal plane.

For each cell, average RCS values are stored. Fluctuations are spatially uncorrelated but time correlated. They are calculated via Auto Regressive Model to respect Power Spectral Density. For each cell, fluctuation values are stored for the next iteration.

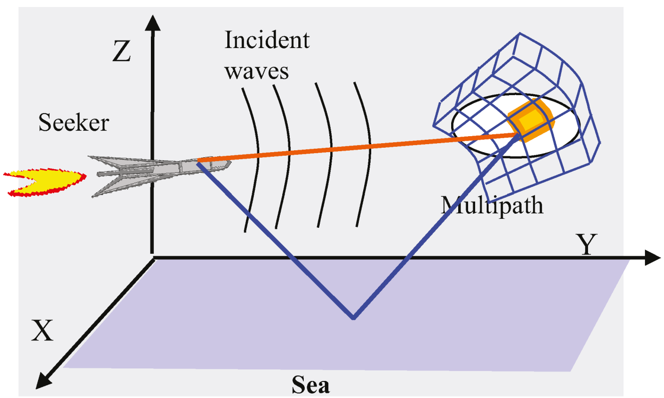
All theses considerations enable to calculate radar impulse response for all polarisation states.



- Figure 7: Impulse response of a chaff cloud -

7. Multipath considerations

The low altitude of chaff clouds above the sea surface justifies taking into account multipaths that contribute significantly to scattered field in simulations.
For instance, for a localized target above perfectly conducting surface, a gain of 12 dB (direct path + 3 indirect paths) could be obtained. For a large target such as chaff clouds, this value can be slightly revised but in all cases, it remains as an important contribution.
In SILEM software, multipaths have been considered for each cell.



- Figure 8 : Multipath contribution -

Fresnel laws give reflection coefficients:

$$Polar\ HH:\ \rho_{mer}\exp(j\phi_{mer}) = \frac{\sin\psi - (\varepsilon_r - \cos^2\psi)^{\frac{1}{2}}}{\sin\psi + (\varepsilon_r - \cos^2\psi)^{\frac{1}{2}}}$$

$$Polar\ VV:\ \rho_{mer}\exp(j\phi_{mer}) = \frac{\varepsilon_r\sin\psi - (\varepsilon_r - \cos^2\psi)^{\frac{1}{2}}}{\varepsilon_r\sin\psi + (\varepsilon_r - \cos^2\psi)^{\frac{1}{2}}}$$

To take into account sea state and especially waves heights, a diffusion coefficient is used:

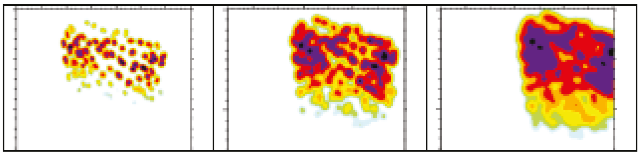
$$\rho_{surface} = \exp\left(-2(2\pi.\sigma_h.\sin\psi/\lambda)^2\right)$$

where σ_h is the standard deviation of waves height.

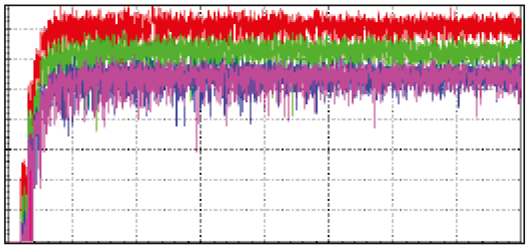
Therefore, sea state has an important impact on RCS, particularly for grazing angles where reflection coefficient is near –1 and for calm sea.

8. Results

Some results of dispersion and scattering by chaff clouds are presented below:



- Figure 9: Spatial representation versus time -



- Figure 10: RCS versus time for all polarisation states -

9. Conclusion

This paper presents a chaff clouds simulation developed by LACROIX/CESTA for French Ministry of Defence (DGA). It shows how SILEM software has overcome difficulties of modelling chaff clouds to reproduce as well as possible a realistic scattered signal 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.

10. References

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