ANALYSIS OF CHAFF CLOUD RCS APPLYING FUZZY CALCULUS

A. D. Macedo F.
DSAM - Brazilian Navy Weapon Systems Directorate
Rua 1º de Março 118 - 20º andar - Centro
Rio de Janeiro -RJ, Brasil, CEP: 20010-000

ABSTRACT

This work provides an insight to the application of fuzzy theory to evaluate chaff cloud RCS, $\hat{\sigma}$. First, it describes a model for $\hat{\sigma}$, and then some of the parameters are taken as fuzzy. It also indicates how the efectiveness of a chaff system against specific threaths can be assessed by means of a Belief function. Futhermore, before the conclusions, it comments a technique to evaluate $\hat{\sigma}$ when only fixed frequency radars are available.

1. INTRODUCTION

It is well known that sea-skimming missiles are the most critical challenge to a Naval Force [1]. The defense against such weapons is difficult and expensive. Among the defensive measures, chaff is probably the oldest, yet still effective. Besides, comparing to other countermeasures, chaff is quite inexpensive. It is used since 1937, when the british discovered that a radar would detect a strip of wire $\lambda/2$ long, suspended from a baloon, at ranges up to 30Km. Chaff can be made of aluminum strips, zinc coated fiberglass, cooper wire, and aluminum coated fiberglass, which is the most popular material. Chaff clouds act as decoy targets or can saturate an area to confuse radar systems. Therefore, to defend surface ships, chaff clouds must present a Radar Cross Section, $\hat{\sigma}$, at least around 10^4 m^2.

However, the nature of the chaff cloud makes it hard to quantify crisp parametres, while fuzzy numbers [2] describe more realistically the uncertainties of the equivalent radar cross section, blooming and collapsing time. The aim of this work is to introduce the fuzzy techniques to describe the chaff cloud RCS and effectiveness.

2. RADAR CROSS SECTION OF CHAFF CLOUDS

The RCS of an object is defined as :

$$\sigma_c = \left[\frac{\text{Power returned to radar receiver / unit solid angle}}{\text{Incident power density} / \ 4\pi} \right] \tag{1}$$

A simple dipole reflector is a straight element of conductive material which behaves as an antenna when illuminated by an incident RF wave. In theory, the shortest length of such antenna would be $\lambda/2$. Nevertheless, in real dipoles, depending on their physical properties, the velocity of propagation is less then c. Furthermore, since the current induced along the length of the chaff dipole is proportional to the projection of the electrical field along its axis, the response depends on the signal polarisation.

The chaff dipole RCS near the ressonance region is considered, as [3]:

$$\sigma_d = .153\lambda^2 = .014/f^2 \tag{2}$$

As frequency drifts away from the resonant point, the RCS will decrease, with smaller peaks at multiples of $\lambda/2$. Nonetheless, in practice, the skirt around 2λ is the upper limit of the chaff response, since beyond this point it is insignificant and usually outside the bands of interest. Fig 1 shows a typical chaff dipole response. Note that the curve shapness depend on the aspect ratio AR= l/d, (length/diameter) [4].

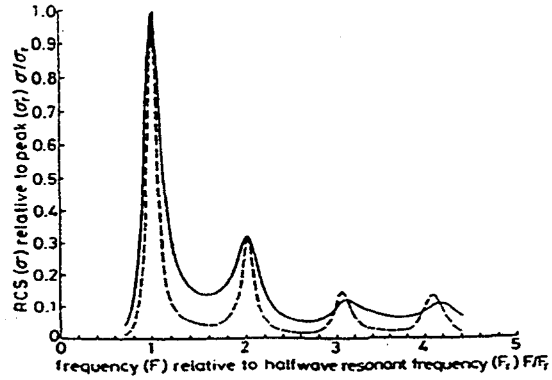


Fig1 - Normalised response of chaff dipoles with A=200 and 2000

Concerning the behaviour of chaff clouds, effectiveness factors η_f, η_e and η_{pol} are used to describe its deviations [5] such as: a)"birdnesting", that is, depending on the dispensing and packing techniques, sets of chaff dipoles can cling togheter providing a less effective response; b)dipoles within two wavelengths from each other don't behave like isolated dipoles because there is energy coupling among adjacent dipoles; c)dipoles near to the radar can shield the far side ones from the full energy; and d)as vertical attitude dipoles fall faster, the chaff cloud RCS significsantly depends on the radar signal polarisation.

If $\eta_f \approx 1$, the cloud RCS, $\hat{\sigma}$, is N times the single dipole RCS, σ_{dip}, where N is the number of chaff dipoles in the payload. However, η_f may range from roughly .8, for I-band dipoles, to .4, for D-band dipoles. Usually, $0.4 < \eta_f < .5$, and is typically a fuzzy number. Factor η_e model the effectiveness of the dispersion technique applied. For pyrotechnically ejected chaff, due to damage caused by the ejection forces and heat, $\eta_e \approx .8$, while for mechanically ejected chaff $\eta_e \approx 1$. Finally, η_{pol}, takes into account the signal polarization. As soon as chaff is deployed it is subject to a great deal of turbulence, when any orientation for each individual dipole is equally likely. However, as time passes, the dipoles orientation tend to stabilize under the influence of gravity and aerodynamic characteristics. Dipoles with horizontal attitude descends more slowly than dipoles with vertical attitude. Thus, the lower portion of the chaff cloud becomes predominantly V-pol, while the whole cloud is mainly H-pol. Here, it will be considered that $\eta_{pol} \approx .6$ for H-pol, .4 for V-pol and .5 for circularlly polarized waves.

Moreover, after blooming, not all of the chaff dipoles contained in the payload will be inside the radar's resolution cell, as in Fig 2. The larger the resolution cell, the larger will be the measured cloud RCS. The volume taken by such cell depends on the radar pulse width (τ), the slant range to the point in space in which the cell is centered (R) and the horizontal (θ) and vertical (ϕ) beawidths, and is given by [6]:

$$a = k_1 \tau \tag{5.a}$$
$$b = k_2 R \theta \tag{5.b}$$
$$c = k_2 R \phi \tag{5.c}$$

Where $k_1 \cong 500$ ft/μs and $k_2 \cong 106$ ft/° NM. Here τ is in μs, and R is in NM, while both θ and ϕ are in degrees. Here a, b and c are also given in ft.

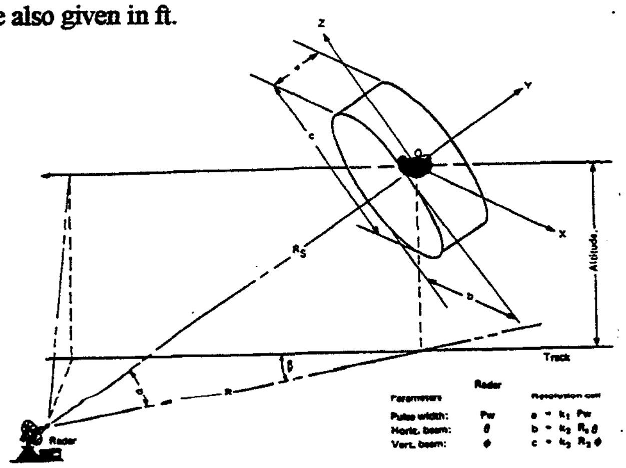


Fig 2 - Radar resolution cell

It is important to distinguish the clouds produced through the two basic blooming techniques. In pyrothecnical ejection systems, the cloud is approximatelly spherical, while the plume cloud, produced by mechanical ejection techniques, resebles a "croissant" shaped cigar. The first ones are more evenly dispersed and allows a short blooming time with equal screening effect in all directions. In the other hand, the plume type cloud usually has one very long dimension. Therefore, such clouds presents a far worse screening effect in one direction than in the other. Besides, plume clouds are more likely to unfold beyond the radar resolution cell being more inefficient. Furthermore, the signal attenuation in a chaff cloud makes a chaff element located inside the cloud to receive less energy then an isolated element at the same location. Thus, if L is the chaff clouds dimension in the sense of the radar propagation, then according to [6], the simplified expression of the chaff cloud RCS is:

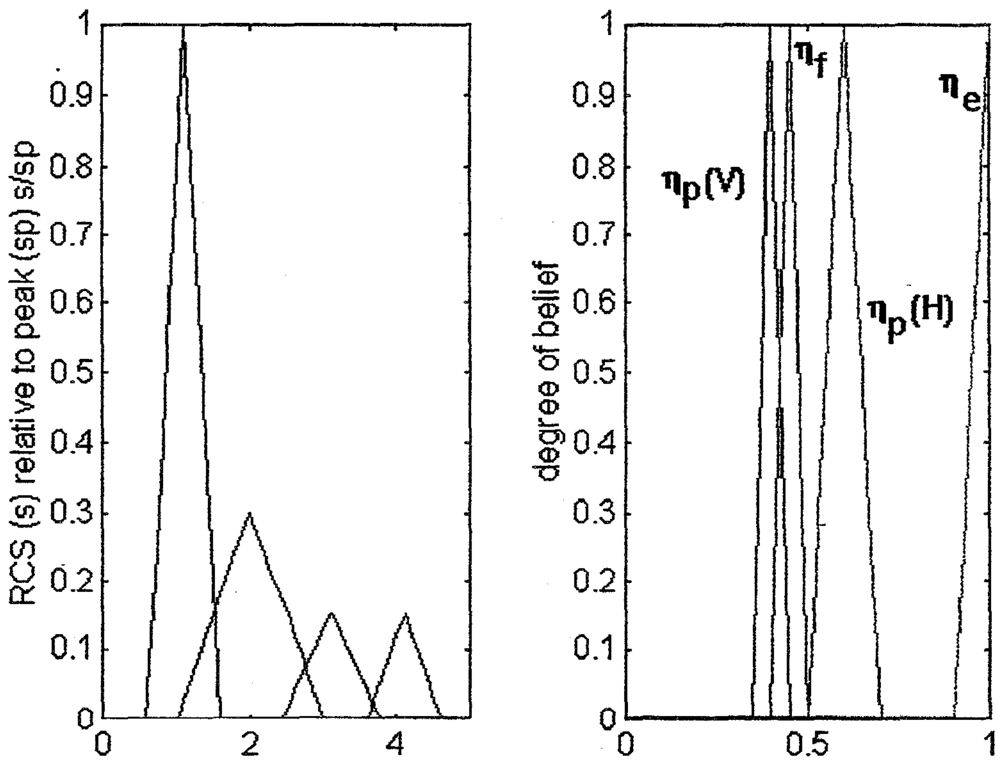
$$\hat{\sigma} = \boldsymbol{MIN}(A_{\theta\phi}, A_c)[1-\exp(-\eta_f\, \eta_e\, \eta_p\, N\, \sigma_d\, L)] \qquad (6)$$

Where σ_d is the response of a single chaff dipole.

This expression contains many values which are typically fuzzy: η_f, η_e η_{pol}, and L. Such statement agrees with the common sense opinion that $\hat{\sigma}$ must be also fuzzy. The next item provides an insigth to chaff cloud RCS analysis through fuzzy theory.

3. CHAFF CLOUDS RADAR CROSS SECTION FUZZY PARAMETERS

First, it is necessary to model the chaff dipole frequency response. This response can be seen as the composition of four triangles as shown in Fig 3a). Furthermore, the three effectiveness factors are also modeled as triangles as in Fig 3b). These factors are estimated computing the data measured from several chaff launchings in different conditions. Wind speed and direction, humidity and rocket settings impose important constraints to these values. A more accurate model would use gaussian curves instead of triangles.



a) frequency (f) relative to resonant frequency (fr) f/fr

b) efectiveness parameters values

Fig 3 - Chaff cloud fuzzy parameters

A more complicated guess is to define the chaff cloud size and shape. A pyrothecnical ejection system produces a rather spherical cloud, but its diameter depends on the strength given to the ejection itself, on the chaff payload weigth, and on the altitude where the chaff is deployed. For naval purposes, the chaff cloud is usually deployed so near to the sea surface, that the difference between the air density from where the cloud blooms to the sea surface is negligible. This size and shape may only be possible to model impirically after a great number of launchings in different meteorological conditions. The plume type cloud can be a bit more easy to model as it is usually larger than the radar resolution cell. Thus, if L is considered to be the chaff cloud depth length at its maximum, while effective number of dipoles in the cell is assumed to be around $(V_{cell}/V_{cloud})N$. Thus, expression (6) can be evaluated as.

$$\hat{\sigma} = \boldsymbol{MAX}\,[\boldsymbol{MIN}\,(A_{\theta\phi}, A_{\chi})[1\text{-}\exp(-\exp(\mathcal{OWA}[\,\eta_f, \eta_e, \eta_p])\,N\,\sigma_d\,L)]] \qquad (7)$$

Where the $\mathcal{OWA}$ means a "ordered weigthed average" operator [7].

Therefore, the application of fuzzy theory produces a simple method to evaluate chaff system effectiveness and also to prospect the improvements obtained in different tactical situations. It can also be defined a Belief function, $\mathcal{Bel}_{cloud}(\hat{\sigma}, f_t, [m]$ and $[c])$, to estimates the defense effectiveness of the chaff system. Here, f_t is the threath frequency and [m] and [c] are the set of meteorological and cinematic conditions of the ship and the missile. One must note that, as the enemy data are in principle unknown, they are also fuzzy numbers, or fuzzy measures [8].

Moreover, when no wideband instrumental radar [9] is available to measure the chaff cloud RCS, fuzzy theory can also be useful. If there are at least 2 fixed low frequency radars and the chaff payload is set for a single frequency, then two fuzzy points are known in the curve response. These fuzzy points must fall in a curve similar to the one in Fig 3a). Thus the straigth lines joining the peaks from these responses and the one passing by their mean values, limits the uncertainty around the chaff response curve. The projection of these lines can be made up to the point corresponding to the chaff payload central frequency f obtaining RCS values a_1 and a_2. The belief function defining the maximum RCS is:

$$Bel_{cloud} = \mathcal{OWA}(a_1, a_2) \qquad (8)$$

A multi-frequency payload is estimated coposing the individual responses.

4. CONCLUSIONS

This work introduced the use of fuzzy numbers to chaff clouds RCS analysis. The advantage of such approach is that it takes into account the uncertainties that are intrinsical to this problem. It also provides a good method to infer the effectiveness of the chaff launching system against specific threaths. Unfortunately, as most of the data and studies being conducted in this area are classified they were omited here. However, this work exposes an entirely novel approach which is being considered by soe in the Brazilian Navy.

5. REFERENCES

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