Dynamic RCS Prediction of Rapidly Blooming Chaff Cloud and its Validation using Measurement on Scaled-down

Verandra Kumar, Ajit Kumar Singh, Prashant Vasistha* and Ravindra Kumar

Defence Laboratory, DRDO, Jodhpur, 342011, INDIA
**pvasistha@yahoo.com*

Abstract. In modern warfare scenario, chaff cloud consisting of millions of small individual microwave scatterers, is used as a passive electronic countermeasure to rapidly create a false target having Radar Cross Section (RCS) more than a real target. RCS prediction of chaff cloud by modeling and simulation is a complex phenomenon as each scatterer has different resonating length, oriented randomly and interact with each other in a complex form. Monostatic RCS measurement of the chaff cloud in the real scenario is also difficult as the target size is quite big and shape and size are changing with time. In the present paper, the dynamic RCS prediction of chaff cloud has been carried out by modeling and simulation using the in-house developed software in MATLAB. Various regular shapes like a plume, sphere, cylindrical and cubical have been presumed and interaction of each scatterer has been analytically evaluated based on screening effect. RCS response of chaff clouds of different shapes and sizes were predicted. To validate the predicted RCS values, miniaturized models of different shapes and sizes are prepared to simulate scale down dynamic chaff cloud blooming. Their monostatic RCS responses were measured in the anechoic chamber for 8-18 GHz. A good agreement is observed in measurement and predicted values.

Keywords: RCS, chaff, dipole, polarization

1. Introduction

Chaff cloud consisting of millions of small individual microwave dipoles resonating at specified frequencies suspended randomly in the space, is used to create a false target having RCS more than real target [1] to confuse or deceive hostile seekers. The chaff cloud shape and size are changing rapidly when ejected under the combined effect of the dispensing platform and the surrounding atmospheric conditions. As the RCS strongly depends upon shape, size and orientation of the individual dipoles, the rapid change in the cloud give rise to dynamic RCS behaviour. The dynamic RCS prediction and measurement of the chaff cloud is an important parameter for the effective functioning of chaff as a passive electronic countermeasure. The overall dynamic RCS response of chaff cloud depends upon a number of parameters of chaff material, radar polarization, kinetics of chaff cloud blooming, environmental conditions etc. Considering all these parameters, the prediction of dynamic RCS response of blooming chaff cloud is a complex phenomenon.

Several models have been proposed in the literature for the dipole behaviour in free space [1–8]. The efficiency of chaff cloud jamming, when deployed as corridor tactic, has been given in [2]. The scattering properties of individual chaff dipoles and their bi-static RCS behaviour has been discussed in [3] and [4]. The jamming effect of chaff to radar along with the introduction to RCS of chaff cloud reference has been described in [5]. Aerodynamics properties of chaff fiber and cloud along with the probability distribution of chaff fibers and RCS density within the chaff cloud have been elaborated in [6]. The chaff dipole by treating it as a wire scatterer has been analytically explained in [7]. Chaff interference based on polarization parameter measurement has been explained in [8]. The study of the spectral behaviour of chaff dipoles in terms of radar echoes is given in [9]–[11] explained the chaff cloud behaviour by considering the randomly distributed dipoles and evaluating the backscattering from it.

Theoretical discussions on the dynamic RCS behaviour of the chaff cloud based on screening effect have been provided in [12]. The dynamic RCS has been formulated for the chaff cloud distributed randomly in a spherical volume.

No reference is available in the literature for dynamic RCS prediction of realistic chaff cloud shapes and validation of predicted values by experimental measurement. In the present paper, an attempt has been made, using in-house developed software, to predict real-time dynamic RCS response of blooming chaff cloud by modeling various regular shapes like sphere, cylindrical, cubical and plume shape. Also, the predicted RCS values have been validated by preparing scale-down models of chaff cloud of different shapes and sizes and measurement of their RCS responses in the anechoic chamber in the frequency range of 8-18 GHz.

2. The backscattering of microwave with randomly distributed dipoles in the chaff cloud

The chaff cloud may expand in any irregular shape depending upon local environmental conditions and turbulence of aircraft. As any irregular shape can be constructed by integrating infinitesimal volume elements of regular shapes, backscattering based on screening effect from dipoles present in the infinitesimal volume elements has been analyzed and integrated to get the overall RCS response of whole chaff cloud.

2.1. *Backscattering model of spherical cloud*

The backscattering of spherical chaff cloud based on screening effect has been discussed in [12]. He analyzed the screening effect for the random distribution of dipoles in the spherical shaped cloud as shown in Figure 1. The incident power is given by P, reflected power P_1 and transmitted power as P_2.

DOI: http://dx.doi.org/10.32452/IJAMT.2018.170175

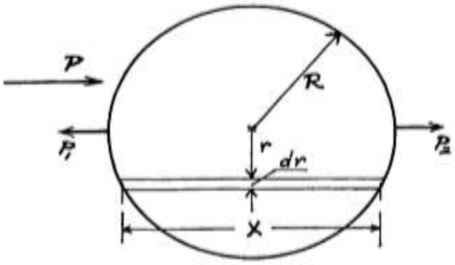

Fig. 1. Propagation of EM waves through spherical chaff cloud.

The RCS response is predicted based on the screening effect. The reduction in RCS of unit area is evaluated for the given depth. For a depth D, the reduction in the unit area of chaff cloud is given by [12]

$$S_d = 1 - \exp[- < \sigma_s > ND] \tag{1}$$

where S_D is the apparent radar cross section of a unit area of chaff extending to the depth of D units. <σs> is the average RCS of a randomized single dipole element. This equation will be used to get final RCS of chaff cloud formed.

The infinitesimal volume element is chosen having front area illuminated by the radar wave and having constant depth throughout the illuminated area. This infinitesimal volume has been integrated to generate whole chaff cloud shape. The final RCS response for spherical chaff cloud as a function of cloud radius is given by [12]

$$\boldsymbol{S_D} = \pi R^2 - \mathbf{2}\pi \left(\frac{1 - 2 < \boldsymbol{\sigma_s} > NR exp[-\mathbf{2} < \boldsymbol{\sigma_s} > NR] - \boldsymbol{exp}[-\mathbf{2} < \boldsymbol{\sigma_s} > NR]}{(2 < \boldsymbol{\sigma_s} > N)^2}\right) \tag{2}$$

where R is radius of sphere, $<\sigma_s>$ as described earlier and N is number of dipoles present per unit volume (uniform dipole distribution density).

Applying similar analogy as discussed in II.A, the backscattreing models for other shapes of chaff cloud have been analyzed.

2.2. *Backscattering model of cylindrical cloud*

Figure 2 shows the schematic of the propagation of electromagnetic waves through chaff filling a cylindrical volume. Similar power analogy has been taken as described for Figure 1, where the wave impinges on infinitesimal area dA= 2H dr at displacement r from the center longitudinal axis of the cylinder and propagates through the depth of *D=2r*

Its apparent RCS of infinitesimal area dS is given by

$$\mathrm{dRCS} = \int_0^R 2\mathrm{H}(1 - \mathrm{e}^{-\sigma_s \mathrm{N2r}})\mathrm{dr} \tag{3}$$

where R is the radius of the cylinder. Upon integrating the expression, the RCS of a cylindrical cloud comes out to be

$$\mathrm{RCS} = 2\mathrm{HR} + \frac{\mathrm{H}}{\mathrm{N}\sigma_s}(\mathrm{e}^{-\sigma_s \mathrm{N2R}} - 1) \tag{4}$$

where σ_s , N are defined as earlier, H is height and R is the radius of the cylinder.

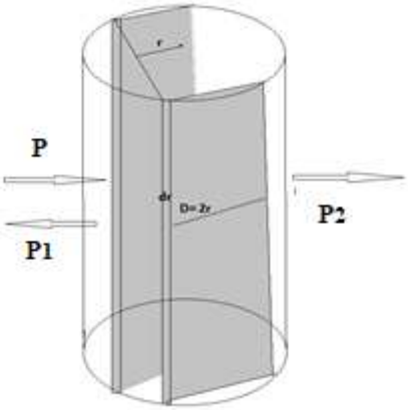

Fig. 2. Propagation of EM waves through cylindrical chaff cloud.

2.3. *Backscattering model of cubical cloud*

Figure 3 shows the schematic of the propagation of electromagnetic waves through chaff filling a cubical volume, where wave impinges on the infinitesimal area of ***dS=adr*** and propagates through the depth of cube size i.e. ***a***.

The apparent RCS of infinitesimal area dS is given by

$$\mathrm{dRCS} = \int_{-a/2}^{a/2} \mathrm{a}(1 - \mathrm{e}^{-\sigma_s \mathrm{Na}})\mathrm{dr} \tag{5}$$

Upon integrating the integral, the RCS comes out to be

$$RCS = a^2(1 - e^{-\sigma_s Na}) \tag{6}$$

2.4. *Backscattering model of plume shaped cloud*

Real-time chaff cloud is more near to a plume shape as it is formed under the combined effect of air turbulence caused by aircraft motion and ejection velocity. Figure 4 shows the schematic of the propagation of electromagnetic waves through chaff filling a plume volume.

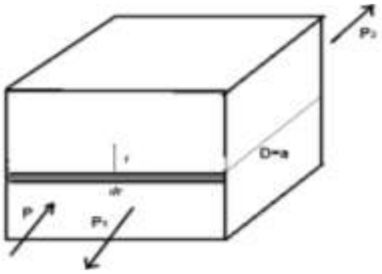

Fig. 3. Propagation of EM waves through cubical chaff cloud.

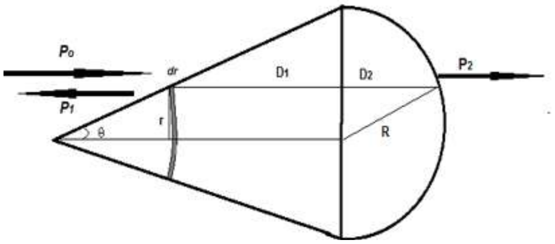

Fig. 4. Propagation of EM waves through plume-shaped chaff cloud.

DOI: http://dx.doi.org/10.32452/IJAMT.2018.170175

Here wave impinges on the infinitesimal area of dS=2πrdr and propagate through the depth of D given by

$$D=D1 + D2 \tag{7}$$

where $D_1 = H - r\cot(\theta)$ and $D_2 = \sqrt{R^2 - r^2}$

H is the height of cone and R is the radius of hemisphere mounted on the conical volume.

The expression for the RCS is given by

$$S=\pi R^2 + \frac{1-KR- e^{-KR}}{K^2}(K_1\, e^{KR}) \tag{8}$$

Where, $K =< \sigma s >\times N \times \cot\theta$

$$N = 3 \times \frac{Nt}{\pi(H+2R)(R^2)}$$

$$H = R \times \cot\theta$$

$$x = -s1 \times N \times (H + R)$$

$$k_1 = 2 \times \pi \times e^x$$

2.5. *Cross polar RCS dynamic response*

The dipoles are distributed randomly in the cloud, hence leads to significant co and cross-polar returns. Hence, the effect of cross polarization should also be taken into consideration while predicting the RCS of the chaff cloud.

The expression for the backscattered RCS of chaff dipole [8] is given in Eq. (9).

$$\sigma(\theta_i,\varphi_i,\theta_d,\varphi_d) = 4\frac{\lambda^2}{\pi} x \cos^2\phi_i\, cos^2\phi_d \frac{sin^2\theta_d}{sin^2\theta_i}\xi^2(\theta_i,\theta_d) \tag{9}$$

When $\theta_i = \theta_d$, then it is the expressions of the monostatic RCS. Φ_i and Φ_d are the angles depending upon the polarization condition on transmission and reception, and $\xi^2(\theta_i,\theta_d)$ is the directivity function of the dipole.

If $\Phi_i = \Phi_d$ then it is co-polar measurement and for cross polar measurement, $\Phi_i = \pm 90^0 - \Phi_d$. In random distribution, dipoles are having the random orientation, which makes Φ_i & Φ_d. random. This will provide the return in cross polar also. The averaged cross polar RCS of a single element is then given by

$$<\sigma_s>_{cross} = <\sigma_s>_{co}/3 \tag{10}$$

which implies that for the randomly distributed chaff cloud, the maximum achievable cross polar RCS will be one-third of the co-polar RCS.

3. Validation of predicted RCS response

3.1. *Preparation of scale down chaff cloud 3D models*

The scale down chaff cloud 3D models of plume, cubical, cylindrical and spherical shapes and of different sizes (30cm, 15cm, 7.5cm, and 3.75cm) were prepared (as shown in Figures 5 (a, b, c & d) by pasting 180 numbers of dipoles randomly at 2λ, λ, λ/2 and λ/4 inter dipole spacing on thermocol skeletons (low density foam) to simulate different initial stages of blooming chaff cloud.

3.2. *RCS measurements*

The co- and cross-polar RCS response of these models were measured in the the anechoic chamber of size 3m x 3m x 10m with quiet zone size of 30cm and frequency range 8–18 GHz using the Keysight Vector Network analyzer available at DLJ (as shown in Figure 6). The VNA, directional coupler along with the rack assembly, anechoic chamber and target stand is shown in Figure 6.

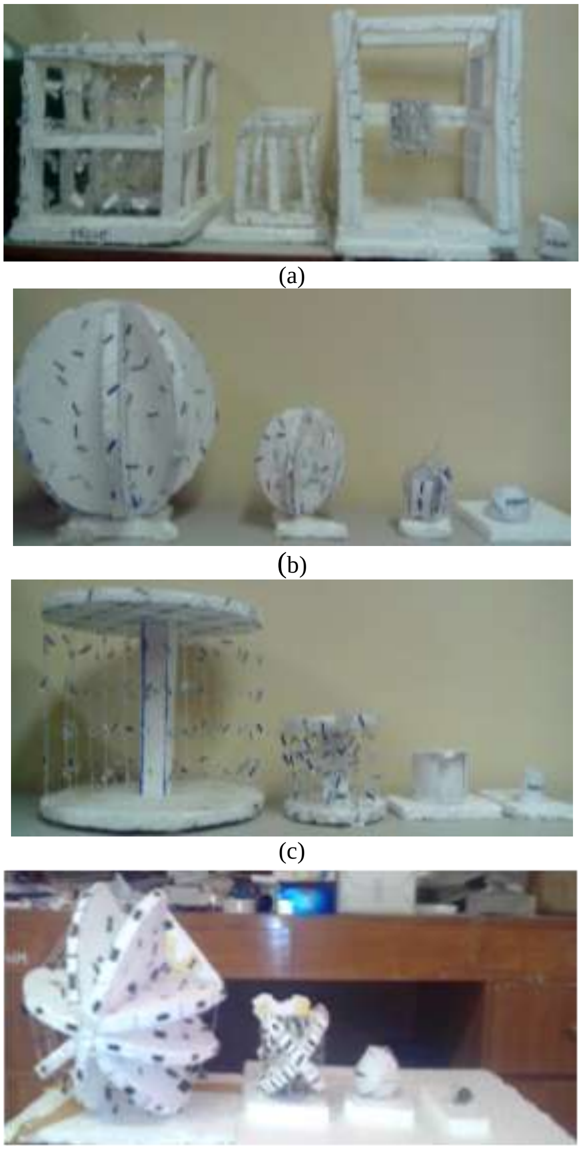
(a)
(b)
(c)
(d)

Fig. 5. 3D chaff cloud models: (a) Cubical shape (b) Spherical shape (c) Cylindrical shape (d) Plume shape.

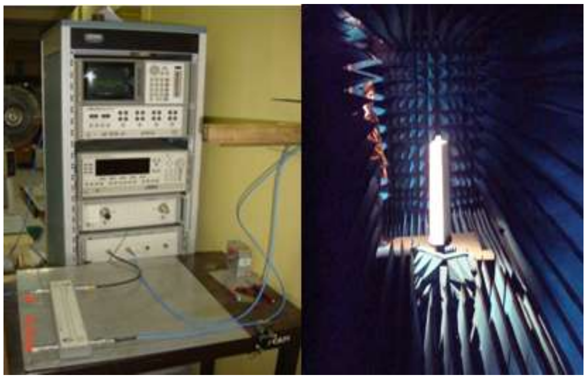
Fig. 6. VNA instrumentation and anechoic chamber for RCS measurements.

DOI: http://dx.doi.org/10.32452/IJAMT.2018.170175

The biggest size of the model was kept as 30 cm keeping in mind the constraint of quiet zone size (45cm cubical size @ 10 GHz) of the anechoic chamber. A total of 180 dipoles each having 15mm length were taken based on the 2 λ (6cm) spacing on biggest 30cm size chaff cloud. Broadband illumination horns (8 to 18 GHz with minimum gain 16dBi) were used to transmit and receive the radar wave with low side lobes. A target stand made of microwave transparent low-density foam is used for placement of the target. The pulse modulated CW measurements were performed. The standard sphere was taken as a calibration target. The background was measured and after performing background subtraction and normalizing with the calibration target response, absolute RCS measurement was carried out.

3.3. Results and discussions

The comparison of the measured and predicted RCS versus dimension of different shapes and sizes of chaff cloud models having 180 number of dipoles are shown in Figure 7-10.

3.3.1. Co-and cross- polar RCS measurement

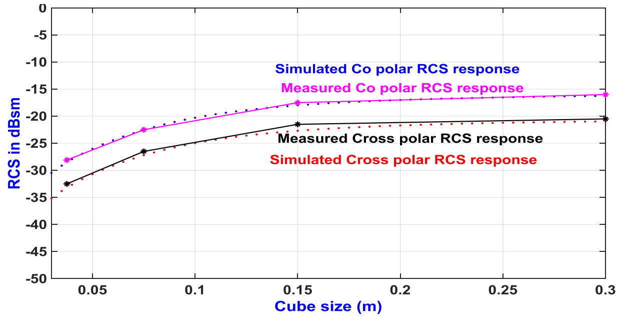

Fig. 7. Measured and predicted dynamic RCS response comparison of cubical chaff cloud.

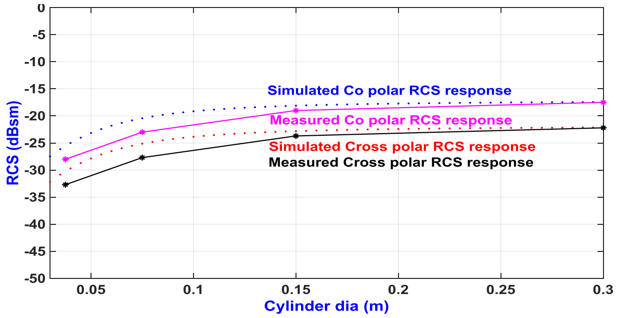

Fig. 8. Measured and simulated dynamic RCS response comparison of cylindrical chaff cloud.

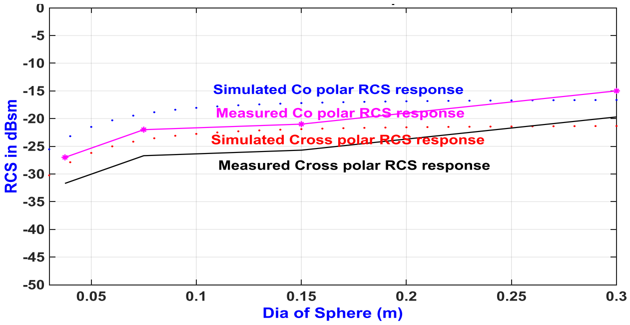

Fig. 9. Measured and simulated dynamic RCS response comparison of spherical chaff cloud.

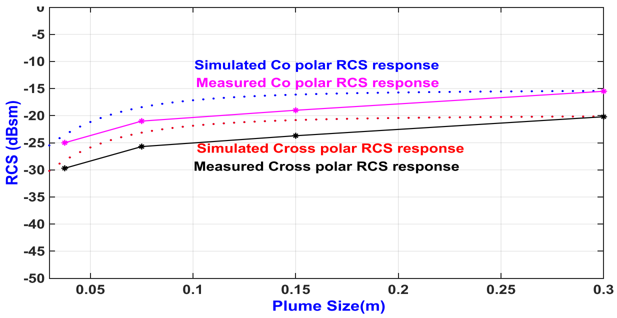

Fig.10. Measured and simulated dynamic RCS response comparison of plume shape chaff cloud.

As evident from Figures 7-10, the RCS response of chaff cloud initially increases with increase in the chaff cloud size simulating initial stages of chaff cloud blooming and gets saturated afterward when the inter dipole spacing becomes greater than 2λ. Initially, when chaff dipoles are very near, scattering by outermost dipoles is significant as inner dipoles are screened by the outer dipoles. As chaff cloud start expanding, the separation between the diploes increases thereby reducing mutual coupling and screening effect, thus increasing the RCS response. After 2λ separation, all fibers scatters independently without any mutual coupling and screening effect and hence the final RCS get saturated. The RCS response will remain constant till all the fibers will be in radar viewing cell.

The cross-polar RCS response is significant due to randomized chaff dipoles and is an added advantage in the functioning of the chaff cloud as an ECM against modern radar seeker with dual polarized capabilities. It is evident that it is one-fourth of the co-polar return for a uniformly distributed and randomly oriented chaff cloud.

Co- and Cross-polar RCS response on simulated chaff cloud models of different shapes and sizes were measured and were found in close agreement with predicted values. Thus the prediction methodology can be utilized to predict dynamic RCS of real-time chaff cloud blooming.

3.4. Real-time dynamic RCS prediction of chaff cloud

The predicted RCS data (dBsm) of the chaff cloud of different shapes and sizes (at different inter-element spacing) are summarized in Table1.

Table 1: Predicted RCS data (in dBsm) of chaff cloud of different shapes and sizes (at different inter element spacing)

Inter dipole spacing → Cloud shape↓	λ/4	λ/2	λ	2λ
Cubical cloud	-28.1	-22.5	-17.5	-16.0
Cylindrical cloud	-27.2	-21.5	-17.5	-16.1
Spherical cloud	-23.5	-18.5	-16.5	-15.3
Plume shaped cloud	-24.5	-19.5	-17.5	-15.5

It is observed from the table that:

1) After 2 λ spacing, all the shapes show almost similar RCS ($0.17N\ \lambda^2$) values of the order of -15dBsm, as there is no mutual coupling and screening effect at this stage.
2) The screening effect increases with reduction in inter dipole spacing being of the order of -25dBsm at λ /4 for all the shapes. Thus screening and mutual coupling

effect reduce the RCS significantly in the initial stages of chaff cloud blooming which is very important from the chaff functionality point of view.

3) When the dipoles are near, cloud shape effect on RCS values is more pronounced and with an increase in inter dipole spacing, the RCS values become less dependent on chaff cloud shape.
4) The maximum RCS is achieved earlier in spherical and plumed shaped chaff cloud (more near to real-time chaff cloud) as the more number of dipoles are situated on the outer surface in radar line of sight.

It is clear from above discussions that, screening and mutual coupling effects significantly reduce the actual RCS response of chaff cloud in the initial stages of chaff cloud blooming. This can critically affect the functionality of the chaff cloud during its engagement with a hostile missile. This fact should be taken into account while designing the chaff payloads for different platform.

The shape of real-time chaff cloud is more near to plume shape as it is created under the influence of chaff ejection velocity and aircraft turbulence created by aircraft movement. The actual chaff cloud contains millions of dipoles. The prediction model has been utilized for predicting dynamic RCS response of chaff cloud with 10,00,000 elements each having 1.5cm length, distributed in plume-shaped cloud. The dynamic RCS is evaluated at 10 GHz and shown in Figure 11. It is observed that the RCS increases exponentially during initial expansion. This expansion depends upon the ejection mechanism. The initial engagement within 200ms is very crucial for the safety of aircraft. In 200ms the cloud expands approximately up-to 10m of radius as per the ejection velocity of 35 m/s in presence of atmospheric drag. The dynamic RCS behaviour up-to plume radius of 10m is shown in Figure 12.

From figure 12, it is observed that the initial RCS response varies from nil to 115 m^2 within 10m of cloud expansion which is the cloud size during initial engagement of chaff cloud with missile within initial 200msec. This RCS value is approximately 25% less than the designed theoretical RCS of chaff payload. This reduction will be more significant if we take into account the cross polarization consideration. This fact should be kept in mind while designing the chaff payload and its deployment. Hence, the initial rapid RCS response of chaff cloud is very crucial for the effective functioning of the chaff cloud.

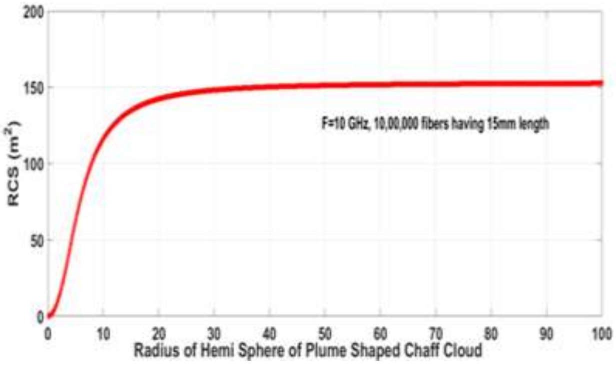

Fig. 11. Predicted dynamic RCS of plume shape chaff cloud at 10 GHz with 100000 dipoles each having 1.5cm length.

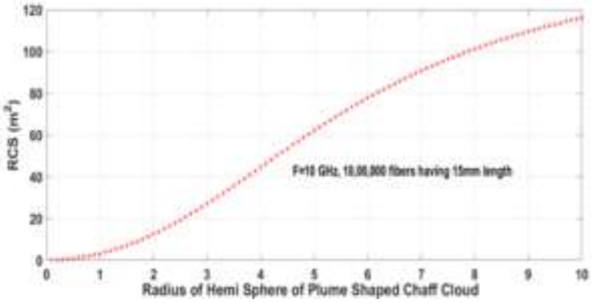

Fig. 12. Predicted dynamic RCS vs radius (up to 10m) of plume shape chaff cloud at 10 GHz with 100000 dipoles each having 1.5 cm length.

4. Conclusion

The chaff cloud functionality is determined by its capability to generate sufficient RCS rapidly before its engagement with hostile missiles. The method of calculating maximum RCS based on formula RCS=0.17 N λ^2 provides RCS of mature chaff cloud. However, screening and internal mutual coupling of dipoles significantly reduce RCS response (more than 10 dBsm) of chaff cloud in its early stages of blooming (up to 500msec). Thus, it must be taken into consideration while designing the chaff payload as this the crucial period when chaff cloud interacts with hostile radar seeker. The effect has been analyzed using the in-house developed code for calculating screening effect in an infinitesimal volume element and then integrating it for different chaff cloud shapes. The predicted values have been verified by preparing 3D scaled-down models of different shapes and RCS measurement in the anechoic chamber. Close agreement in the measurement and predicted RCS values is observed. The model is being used to predict dynamic RCS response of real-time chaff cloud having millions of dipoles.

References

[1]. B. Butters, Chaff, *IEE Proc.*, vo1.129, pt. F, no. 3, pp. 197-201, 1982.

[2]. Mingshan L.V.and W. Longtao, Research on the efficiency of the chaff jamming corridor, *IEEE Conference on Information Science and Control*, pp. 1673-1676, 2017.

[3]. P. Peebies, Bistatic radar cross section of chaff', *IEEE Transactions on Aerospace and Electronic System*, vol. AES-20, No.2 University of Florida, pp. 128-140, March 1984.

[4]. Palermo, C. and L. Bauer, Bistatic scattering cross section of chaff dipoles with application to communication, *Proceedings of the IEEE*, vol. 53, no. 8, pp. 1119-1121, Aug.1965.

[5]. Xianli, W. and Q. Teng, Chaff jamming effect to radar and math model building, *CIE International Conference on Radar*, Shanghai, China, Oct 2006.

[6]. S. Marcus, Dynamics and radar cross section density of chaff cloud, *IEEE Transaction on Aerospace and Electronic System* vol. 40, no.1, Rafael Israel, pp. 93-102, January 2004.

[7]. K. Dedrick, A. Hessing, and G. Johnson, Bistatic radar scattering by randomly oriented wires, *IEEE Transactions on Antennas and Propagation*, vol. AP-26, no.3, pp 420-426, May 1978.

[8]. Cui G. and L. Shi, Identification of chaff interference based on polarization parameter measurement, *IEEE Conference on Electronic Measurement and Instruments*, Yangzhou, China, pp. 392-396, Oct 2017.

[9]. W. Estes and C. Pinson, Spectral characteristics of radar echoes from aircraft dispensed chaff, *IEEE Transactions on*

Aerospace and Electronic Systems, vol. AES-21, no. 7, pp 8-20, Jan. 1985.

[10]. R. Wickliff and R. Garbacz, The average backscattering cross sections from randomized resonant dipoles, *IEEE Transactions on Antenna and Propagation*, vol. 23, no. 3, pp. 503-505, 1974.

[11]. Y. Guo and H. Uberall, Bistatic radar scattering by a chaff cloud, *IEEE Transactions on Antenna and Propagation*, vol. 40, no. 7, pp. 837 – 841, July 1992.

[12]. S. Kownacki, Screening (shielding) effect of chaff cloud, *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-3, no. 4, pp. 731-734 Feb. 1967,.

Biography of the authors

Verandra Kumar did his B Tech from MNIT, Jaipur in ECE during 2005-09. He joined DRDO in 2009 at DL, Jodhpur and currently working as Scientist C. His area of work includes RCS measurement and simulation of targets for stealth application as well as Dynamic RCS modeling, simulation, and measurements of decoys currently being used by IAF and IN.

Ajit Kumar Singh joined DRDO in 2013 at DL, Jodhpur. He has the experience of 06 years in the area of design and development of software to simulate the parameters of electronic countermeasure and analysis of various chaff decoys used by IAF and IN.

Prashant Vasistha did his Ph.D. from Department of Electronics Engineering, IIT BHU. He joined DRDO in 1998 at DL, Jodhpur. He has been working in the area of radar cross section (RCS) studies and RCS measurement technologies for combat systems. He has an experience of 18 years in the area of radar camouflage and electronic counter measure decoys.

Ravindra Kumar did his BE from IIT Roorkee in 1983 and M Tech from IIT Mumbai in 1987. He joined DRDO in 1983 at DL, Jodhpur. He has an R&D experience of 35 years in the area of desert warfare scenraio management, Phase change materials, water purifications systems and design, development and testing of electronic countermeasures.

DOI: http://dx.doi.org/10.32452/IJAMT.2018.170175