Electromagnetic analysis for complex satellite targets using time-frequency representations

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Abstract. An analytical method for electromagnetic scattering characteristics of complex satellite targets by using multilevel fast multipole algorithm (MLFMA) and short-time fourier transformation (STFT) is proposed in this paper. By constructing different electromagnetic models of satellite target with multi-scale structures and coatings, the aspect and polarization characteristics of radar cross section (RCS) and time-frequency representation (TFR) are studied. To validate the influence of the multi-scale structure and coating, the full-polarization RCS at specific angles, RCS statistical characteristics and TFR correlation are simulated and compared. It is concluded that the multi-scale structures and coating materials should be sufficiently considered to calculate the accurate scattering characteristics.

1. Introduction
Space target detecting systems include space-based and ground-based systems. The ground-based system is currently the major detection means of space target detection which has many advantages by using of large-diameter antenna and high transmit power. In comparison to other space observation sensors, such as optical telescopes or radio detection means, ground-based radar has the advantages of all-weather, fast response, and large coverage airspace.

The radar cross section (RCS) of a space target is a physical quantity that characterizes the ability of a radar target to scatter electromagnetic waves. It contains rich target information and is an important parameter for radar detection of space targets. How to obtain accurate RCS of space targets such as satellites is of great significance to the study of space targets.

Compared with actual measurement, electromagnetic simulation has low cost and short research period, and it has been widely used in characteristics analysis and design for various military targets. Currently, there existed three representative numerical methods for electromagnetic simulation [1-3]: finite difference time domain (FDTD), finite element method (FEM) based on differential equation, and method of moments (MoM) based on integral equation. The scattering field calculation mainly adopts the MoM which has high calculation precision. To deal with the challenge to computer storage and CPU resources posed by high computational complexity of MoM, especially in large-scale scattering problem, a series of fast algorithms are proposed for saving memory and accelerating the iteration of equations. The multilevel fast multipole algorithm (MLFMA) is one of the most attractive integral equation fast algorithms [4–5] of whose advantages are high precision and efficiency, and it is widely used in electromagnetic scattering analysis of various complex targets, including satellite targets [6]. Thus, MLFMA is used to obtain RCS of space target

For most radars, the scattering of space targets is generally in optical region, and the total scattering field can be described by the synthesis of a series of local scattering fields. These local scattering
sources are usually called equivalent scattering centers, referred to as scattering centers. In the analysis of the target scattering characteristics in optical zone, the Doppler frequency of each scattering center varies with time. Time-frequency representation (TFR) can be used to separate the scattering centers in the time domain and obtain corresponding relationship between them and their time-frequency signature, which further provides support for geometric feature and motion feature extraction and target recognition. There are linear and nonlinear TFR methods. Typical methods include short-time Fourier transform (STFT) and continuous wavelet transform for linear, Wigner-Ville distribution and Cohen class distribution for nonlinear [7]. The STFT algorithm is simple and facilitates the understanding of image features, so the following theoretical analysis uses this algorithm.

In this article, aiming at typical satellite targets, complex electromagnetic models are constructed, including multi-scale structures and coatings. The multi-scale structures include various antennas and other micro-scale structures, and coatings include thermal insulation and solar silicon plate coatings. Through calculation and comparison of electromagnetic signature of RCS and TFRs, the effect of different structures is studied. The influence of characteristics provides an effective basis for the construction of the electromagnetic characteristics database of satellite targets.

2. Electromagnetic Modeling and Numerical Method

The target modeling is the basis for electromagnetic characteristics calculation, and the accuracy and efficiency of the target RCS are directly affected by the modeling method. In this paper, accurate and usable models for satellite target are built and meshed by the combined use of CATIA and FEKO software.

In order to analyze the effects of multi-scale structures and coatings on the scattering characteristics for satellite targets, three typical models are established. The geometric structure is shown in figure 1, which built together with small structures such as antennas and thrusters on the satellite surface, as well as different coating materials on the satellite body and solar panels. The model A consists of satellite body and solar array, and model B is model A loaded small structures, model C is model B coated multi-material.

![Electromagnetic models for different Targets](image)

Figure 1. Electromagnetic models for different Targets.(a)Model A(b)Model B(c)Model C.

The geometric parameters are set as follows: the side length of satellite body is 0.56m, the width and total length of solar panels on both sides are the same as 2m and 8m when satellite deploys the solar array.
The initial satellite structure materials are mainly composed of metal materials. Due to the development of satellite technology, composite materials are gradually adopted. The type of coating materials is generally determined by the parameter dielectric constant and loss. The coating materials and EM parameters are set as follow: the satellite body is coated with a layer of insulating material polyimide and the two sides of solar panel are coated with carbon fiber composite materials. The coated material on the side facing the sun which installed with solar array is silicon wafer, and the other side is carbon fiber. For composite materials, carbon fiber conforms to the same properties as ideal metal. Among them, the dielectric constant and the loss of polyimide and silicon wafer are (3.8, 0.004), (11.9, 0), respectively.

The STFT used of the micro-Doppler signature in this paper is [8]:

$$\text{STFT}(\xi, f) = \int E^s(\xi') w(\xi' - \xi) \exp(-j2\pi f \xi') d\xi'$$

Where $E^s$ indicates the back-scattering echo of the target, which can obtained by MLFMA, $w(\cdot)$ is the smoothing window function, $f$ is the incident electromagnetic wave frequency and $\xi$ is the angle of the target coordinate origin relative to the radar sight.

3. Electromagnetic Scattering Analysis

3.1. Signature of RCS

As mentioned in Section II, three electromagnetic models of satellite target are shown in figure 1. The antennas and satellite body are located towards the -z direction, the solar array is axially along the ±x direction and the normal direction is 45° off +z direction. In order to study the polarization and aspect characteristics of different models, the monostatic RCS is calculated by MLFMA and given for comparison depending on the designed azimuth angles and observed polarization.

EM parameters are set as follow: the incident wave is a plane wave, the incident frequency is 1 GHz, and the incident angles are $\phi = 0^\circ$ and $\theta = -180^\circ \sim 180^\circ$ with the step of 1° in $xoz$-plane. The co-polarization RCS is shown as figure 2, where VV polarization in (a) means that the incident wave has electric field vector in $\theta$ direction and the scattered wave for electric field vector also in $\theta$ direction is calculated, and HH polarization in (b) means that the incident and scattered electric field vector both in $\phi$ direction. The cross-polarization RCS is shown as figure 3, where VH polarization in (a) means that the incident electric field vector is in $\theta$ direction and the scattered electric field vector in $\phi$ direction is calculated, and HV polarization in (b) means that the incident electric field vector in $\phi$ direction and scattered electric field vector in $\theta$ direction.

![Figure 2](image-url)  
(a) Co-polarization RCS of three targets in xoz-plane. (a) VV. (b) HH.
From figure 2, it can be seen that the co-polarization RCS difference between Model A and other models exceeds 10dB or even greater within about 50° angles interval around $\theta = 0^\circ$. The appearance of other scattering phenomena other than specular reflection of upper surface on satellite body can be considered to be responsible for the differences. From figure 3, it is obvious that two more peaks appear in the cross-polarization RCS of Model C within $\theta = \pm(45^\circ - 90^\circ)$ than that of Model A.

The root mean square error (RMSE) for RCS results between these three models are illustrated in table 1. All the RMSE values are greater than 5dB for every two sets of data, which shows that the RCS of satellite target is greatly affected by the multi-scale structures and coatings.

### Table 1. RMSE of RCS results between models

| Polarization | Model A & B | Model B & C | Model A & C |
|--------------|-------------|-------------|-------------|
| VV           | 6.3492      | 5.8882      | 7.5845      |
| HH           | 7.4630      | 5.4393      | 8.5582      |
| VH           | 7.7009      | 6.1014      | 8.5476      |
| HV           | 7.5118      | 6.0841      | 8.3521      |

#### 3.2. Signature of TFR

In this section, the TFRs of the scattered waves from the three targets are simulated and analyzed, which are under different observation azimuths and different polarizations. The radar signals used in the TFR analysis are assumed to be the backscattered waves of the target illuminated by a singular frequency plane wave, and the carrier frequency has been moved to zero after demodulation. The signatures shown in TFR represent the Doppler frequencies and scattering amplitudes of scattering centers. Doppler frequencies are closely related with the locations of scattering centers.

The results of TFRs of Model A, Model B and Model C using STFT in $xoz-plane$ are compared in figure 4-5. It is shown in figure 4 (a) that located scattering centers are distributed induced by reflected waves, are shown as individual bright blocks flashed at discrete angles, which agree exactly with the angles in figure 4 (b) and (c). Comparing the TFRs of the same model under different polarization between figure 4 and figure 5, it is noteworthy that the influence of solar array on the TFR under H polarization is more obvious, which divided into multiple scattering centers around $\theta = 90^\circ, 135^\circ$.

Through the comparison of TFRs azimuth and polarization difference between three models, the influence of multi-scale structures and coatings on the amplitude and position of the scattering centers at certain angles is confirmed. The correlation coefficients (Corr-Coeffs) between the extracted
Doppler frequencies between different models under vertically and horizontally polarization in \textit{xoz-plane} are given in table 2.

![Figure 4. TFRs processed by STFT of different Targets in \textit{xoz-plane} at VV. (a)Model A (b)Model B (c)Model C](Image)

![Figure 5. TFRs processed by STFT of different Targets in \textit{xoz-plane} at HH. (a)Model A (b)Model B (c)Model C](Image)

From table 2, it can be seen that the Corr-Coefs in \textit{xoz-plane} are among 78\%-91\% for co-polarization and less than 78\% for cross-polarization. Through the comparison of TFRs in VV and HH case, the differences for VV are 3\%-5\% larger than that for HH. Furthermore, the differences between Model B and Model C are about 5\% larger than that between Model A and Model B, which indicates that the coatings has greater influence over the scattering characteristics in \textit{xoz-plane}.

The results of TFRs of Model A, Model B and Model C using STFT in \textit{yoz-plane} are compared in figure 6-7. The corresponding Corr-Coefs are also given in table 2.

![Figure 6. TFRs processed by STFT of different Targets in \textit{yoz-plane} at VV. (a)Model A (b)Model B (c)Model C](Image)

![Figure 7. TFRs processed by STFT of different Targets in \textit{yoz-plane} at HH. (a)Model A (b)Model B (c)Model C](Image)
Table 2. Corr-Coefs(%) of TFR results between models

| Polarization | xoz-plane | yoz-plane |
|--------------|-----------|-----------|
|              | Model A& B | Model B& C | Model A& C | Model A& B | Model B& C | Model A& C |
| VV           | 85.11      | 81.27      | 78.08      | 80.10      | 97.66      | 79.82      |
| HH           | 90.66      | 84.43      | 81.42      | 79.74      | 97.80      | 79.19      |
| VH           | 71.95      | 77.27      | 64.86      | 30.56      | 87.43      | 30.08      |
| HV           | 73.90      | 77.75      | 65.20      | 37.94      | 89.68      | 39.58      |

Through the comparison of TFR results in figure 6-7 (b) and (c), it is shown that the Doppler frequency curve of Model B shares a similar form with that of Model C, for the curved generating lines are the same in light and shadow areas. Similarly, it can be seen that the Corr-Coefs between Model B and Model C are higher than 97% for co-polarization and higher than 87% for cross-polarization.

4. Conclusion

Aiming at the electromagnetic scattering problem of complex satellite targets, the aspect and polarization characteristics of RCS and TFR are analyzed in this paper. In order to study the effects of multi-scale structures and coatings on their scattering characteristics, CATIA and FEKO software are used to jointly carry out accurate modeling and triangular element meshing for satellite targets, and MLFMA is used to accomplish RCS calculation for the established satellite models. The simulation analysis results show that the RCS differences at certain angles are greater than 10 dB, and the RMSE of all polarization is greater than 5dB. Moreover, the correlation coefficients of other TFR in the two observation planes are less than 90% except for the case about coating in the yoz-plane, which confirm that the influence of the multi-scale structures and coatings on the echo characteristics should be sufficiently considered. The research in this paper provides a theoretical basis for the accurate analysis of satellite target scattering characteristics.

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