Fast Estimated Calculation of Wideband Radar Angular Glint Using Single Frequency Method

YUNBO LI\textsuperscript{1}, (Member, IEEE), CHAO WANG\textsuperscript{2}, SHU-YUE DONG\textsuperscript{1}, JIA-LIN SHEN\textsuperscript{1}, AND HAI-PENG WANG\textsuperscript{1}\textsuperscript{a}

\textsuperscript{1}State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China
\textsuperscript{2}National Electromagnetic Scattering Laboratory, Beijing 100854, China

Corresponding author: Hai-Peng Wang (wanghaipeng4213@126.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61901113 and Grant 61801262, in part by the Southeast University—Nanjing Medical University (SEU-NJMU) Joint Fund under Grant 3204009351, in part by the Fundamental Research Funds for the Central Universities under Grant 2242020R20010, and in part by the Natural Science Foundation of the Jiangsu Higher Education Institutions of China under Grant 18KJB510039.

\textbf{ABSTRACT} In this paper, we proposed a fast and accurately calculated method to estimate the deviation of wideband angular glint based on single frequency or narrow band modeling method of the angular glint. By analyzing the three existing methods of modeling the target angular glint, we show that such methods are consistent when the geometrical optics approximation and linear polarized receiving antenna are assumed. Considering of the tracking system by wideband monopulse radar, the fast calculated method we present can estimate the angular glint in each resolution unit using modeling method of single frequency which is the center one of the whole bandwidth. The mathematical analysis of the unity between the wideband and narrowband modeling method is demonstrated, and the correctness of the new calculated method is well validated by high-frequency electromagnetic simulations based on the physical optics.

\textbf{INDEX TERMS} Angular glint, wideband monopulse radar, electromagnetic scattering, radar cross-section (RCS), fast estimated calculation.

\section{I. INTRODUCTION}

The angular glint of radar target is caused by the effect of multi-scattering centers in the extended target, and it can introduce the fixed error component in the measuring of the target’s angle and lead the departure from the radar target apparent center to the geometrical center. For the extended target, when the tracking radar gets closed to it, the target’s angular glint will be the main sources of error under the homing guidance.

Until now, there have been three methods in modeling the angular glint. Howard [1] initially explained the angular glint as the tilt of wave front resulting from the distortion of the target echo signal’s phase front. Linsay [2] extended the concept and calculated the glint value by the phase gradient method (PGM). Dunn and Howard interpreted the phenomenon of glint by the energy-flow tilt concept, and the deviation of angular glint was calculated by the Poynting vector method (PVM) [3]. The comparison of two above theories (PGM and PVM) of angle glint [4] under the polarization considerations was proposed. The comparison between the PGM and PVM methods under general considerations [5] was presented later, and made a further comparison between the two calculated methods [6]. Considering the receiving polarization of PGM and PVM, the formula to calculate the complex target was derived based on the rigorous electromagnetic scattering theory and presented the new modeling method of target angular glint under the angle tracking system by monopulse radar accordingly. Afterwards, the suppression of angular glint based on MIMO radar [7] was proposed due to the modeling methods above. The accelerated algorithm which is called adaptive cross approximation (ACA) [8] for calculating the performance of angular glint was presented. And by introducing the scattering models [9], [10], the angular error had been estimated and simulated. The deviation of angular glint could also be calculated in the near field [11], [12] based on the method of near-field iterative physical optics. The reduction or suppression [13]–[15] is also the important issue of radar angular glint. However, all of the calculated and analytical methods of angular glint were modeled based on narrow band radar.
For the wideband radar system, it has the ability of high-resolution range profile (HRRP) [16] which can divide the scattering centers of extended target into the range units according to the resolution ratio. And also the two-dimensional image of the target can be reconstructed due to the Range-Doppler (RD) technology [17] based on the Synthetic Aperture Radar (SAR) system, and also the threedimensional microwave image can be reconstructed based on the multi-view radar system [18]. The modeling method and the viewpoint of the target angular glint under the wideband system can also be extended due to appearance of HRRP, and the corresponding calculation for complex target which is composed multi-scattering centers had been presented [19].

In this paper, we mainly focus on the viewpoint from the electromagnetic scattering and target characteristic modeling. For the workflow of our work, firstly, based on the formulas of the three modeling methods to calculate the angular glint, the unity of three modeling methods is presented when the geometrical optics approximation is made and the receiving antenna is linearly polarized. Based on the tracking system by wideband monopulse radar, we propose a fast and accurately calculated method to estimate the angular glint in each resolution unit using modeling method of single frequency which is the center one of the whole bandwidth. Then the relationship or the unity between the wideband and narrowband modeling of the angular glint has been established. According to these conclusions, the wideband angular glint can be fast estimated using the three existing methods of narrowband modeling under their corresponding systems respectively. The correctness of this unity is validated by calculating the target of three metallic spheres using high frequency electromagnetic simulations [20], [21].

II. MODELING OF WIDEBAND OF ANGULAR GLINT

A. THE UNITY BASED ON THE NARROWBAND MODELING

The PGM is the method that calculates the angular glint using the gradient of phase function of the echo scattering field. Assuming that the phase function of the scattering field to be \( \Phi(r, \theta, \phi) \), the gradient of the phase function can be given by

\[
\nabla \Phi = \hat{r} \frac{\partial \Phi}{\partial r} + \hat{\theta} \frac{\partial \Phi}{\partial \theta} + \hat{\phi} \frac{1}{r \sin \theta} \frac{\partial \Phi}{\partial \phi}
\]

Then we can define the glint deviation caused by the phase front distortion of the target echo signal as

\[
e_{\phi} = r \Phi_{v}/\Phi_r, \quad v = \theta, \phi
\]

Based on the above definition and the derivation from rigorous theory of electromagnetic scattering, the formula of angular glint deviation by PGM is proposed. The formula of the angular glint deviation at the azimuthal direction (in this article, we only consider about the azimuthal direction) is given by [22]

\[
e_{\phi} = -\operatorname{Re} \left[ \frac{\int \hat{A}(r')A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'}{\int A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'} \right] + \frac{1}{k} \sin \delta_r \sin 2\theta_r \operatorname{Im} \left[ \frac{\int \hat{A}(r')A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'}{\int A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'} \right]
\]

in which \( A(r') \) can be expressed as \( Z_0(\hat{r}' \cdot \hat{p}_e + M(r') \cdot \hat{p}_m) \), where \( \hat{r}' \) is the position vector of the scattering unit, \( \hat{p}_e \) and \( \hat{p}_m \) are electric and magnetic polarization vectors of the receiving antenna, respectively. And at the point \( r, \hat{p}_e = \theta \cos \theta_R + \hat{\phi} \sin \theta_R \exp(j\delta_R), \hat{p}_m = \hat{r} \times \hat{p}_e, \) where \( \theta_R \) is the angle between \( \hat{p}_e \) and \( \hat{\phi} \), and \( \delta_R \) is the phase angle, at which the component of \( \hat{\phi} \) is beyond to the component of \( \hat{\theta} \). The signature of receiving effect to the radiant source, \( A(r') \), is defined as the receiving factor to the equivalent electric and magnetic currents of target surface, and \( \hat{A}(r', \theta, \phi) \) is defined as \( \hat{A}(r', \theta, \phi) = \partial A(r')/\partial \phi \).

PVM is the method that calculates the angular glint based on the concept of energy-flow tilt. The Poynting vector of the target echo is defined as

\[
S_{av}^4 = S_{av}^4 \hat{r} + S_{av}^4 \hat{\theta} + S_{av}^4 \hat{\phi}
\]

The formula of angular glint deviation by PVM is given by

\[
e_{\phi} = r S_{av}^4 / S_{arr} \quad v = \theta, \phi
\]

Due to the above definition and rigorous theory of electromagnetic scattering, the formula of angular glint deviation by PVM is obtained. The formula of the angular glint deviation at the azimuthal direction is derived as [22]

\[
e_{\phi} = -\operatorname{Re} \left[ \frac{\int \hat{A}(r')A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'}{\int A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'} \right] + \frac{1}{k} \sin \delta_r \sin 2\theta_r \operatorname{Im} \left[ \frac{\int \hat{A}(r')A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'}{\int A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'} \right]
\]

The definition of \( A(r') \), \( \hat{A}(r', \theta, \phi) \), \( \delta_r \) and \( \theta_R \) are the same as those in Eq. (3).

Based on the theory of angle tracking by narrowband monopulse radar, the modeling formula of angular glint has been presented [6]

\[
e_{\phi} = -\operatorname{Re} \left[ \frac{\int \hat{A}(r')A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'}{\int A(r')e^{jk\hat{r}' \cdot \hat{r}} \, dv'} \right]
\]

in which the denominator characterizes the received sum channel RCS, and the numerator characterizes the received azimuthal differential channel RCS. We note that the glint
deviation is the comprehensive results of the projection at azimuthal direction from the position vector of the target scattering centers weighted by RCS of target scattering centers.

In above discussions, the general formulas of three modeling methods for angular glints are given. When the geometrical optics approximation \((k \to \infty)\) is assumed, we notice that the second term on the right-hand side of Eq. (3) will be zero, and hence Eq. (3) will be equivalent to Eq. (7). When the receiving antenna is linearly polarized \((\delta_r = 0)\), the second term on the right-hand side of Eq. (6) will be zero, and hence Eq. (6) is equivalent to Eq. (7). Based on the above analyses, we conclude that the three modeling methods result in equivalent angular glint under the geometrical optics approximation and linearly-polarized receiving antenna. This conclusion extends the concept presented in [6]. And this result is the foundation for establishing the unity of modeling methods between narrowband and wideband angular glint.

**B. THE METHOD OF WIDEBAND ANGULAR GLINT MODELING**

In the wideband amplitude-comparison monopulse radar, the sum-differential converter makes the echo signals plus and minus at the receiving antenna. The high-frequency sum and differential signals from the converter are added to the sum and differential receiving branches separately. In this course, the high-frequency signals should be changed to the low-frequency signals and be amplified to the level we need. After using the pulse compression to the sum and differential receiving-branch signals separately and phase detection to the waveform after compression, the echo waveform data of IQ channels are obtained. The process of pulse compression can generate radar high-resolution range profile (HRRP).

After generating the high-resolution range based on the limited bandwidth, the scattering centers of the target will be distributed in the units of high-resolution range discretely. However, the angle measurement error in the units of range will be caused by the interference effect of multi-scattering centers in the same range units. We can define HRRP of the will be caused by the interference effect of multi-scattering centers in the same range units. We can define HRRP of the targets. From Eq. (11), the wideband angular glint is negative relevant to the angular glint [24], hence the weaker signal generally corresponds to the bigger angular glint, which will cause big tracking error in the wideband radar system. Therefore, we can set a threshold in detecting that if the signal of sum channel range unit is lower than the threshold, the measuring unit should be abandoned to avoid generating the big angle measurement error.

**C. SIMULATION BY HIGH-FREQUENCY CALCULATED METHOD**

The wideband angular glints of two metallic sphere targets are calculated by the physical optics (PO) method [20]. We calculate the angular glint based on the simulated RCSs of the targets. From Eq. (11), the wideband angular glints are relevant to both RCSs of sum and differential channels. To obtain RCSs, the surface of the metallic target should be
meshed into triangles by CAD technology and the position vector \( \mathbf{r}' \) of the triangular geometrical center point can be obtained at the same time. The sum channel RCS can be calculated directly by PO; and the differential channel RCS will be calculated after weighting \( \mathbf{r}' \cdot \hat{\phi} \) to the scattering field of each triangle element.

The geometrical view of the two metallic spheres is shown in Fig. 2, in which the radius of spheres are 0.04 m and 0.06 m, respectively. The coordinate of the two spheres are \((2, -2, 0)\) and \((-2, 2, 0)\) respectively, and the unit is m. We define the incident wave propagate along the \(-\hat{x}\) axis. In this case, there is no shelter among the two spheres. The frequency range is from 35 GHz to 36 GHz with the bandwidth of 1 GHz. The frequency step is 0.01GHz. According to the formula of radar range resolution \( \delta_r = c/2B \), in which \( B \) stands for the radar bandwidth, we can obtain the resolution range to be 0.15m. Hence it is easy to distinguish the two spheres completely under this range resolution.

Considering of the monostatic receiving, the calculated results of HRRPs in the sum and differential channels are given in Fig. 3. Then we can obtain the deviation of the wideband angular glint relevant to the range applying Eq. (11), and the corresponding results are shown in Fig. 4.

![FIGURE 2. The geometrical view of the two metallic spheres.](image)

![FIGURE 3. (a) HRRP results of the sum channel. (b) HRRP results of the differential channel.](image)

angle error will also be generated by angular glint effect due to calculation based on the such range unit. For this case, we present a fast estimated method for calculating wideband angular glint based on the resolution unit with multiple scattering elements only depending on the narrow band method, and thus the unity between the modeling methods of wideband and narrowband angular glints will be established. Here we will discuss the unity of the two methods in the high-frequency electromagnetic domain. Under the system of step-frequency radar, the frequency sweeping RCSs of receiving sum channel of scattering centers which are located in the \( m \)th range unit can be given as

\[
X_{um}(f_i) = \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(-i \frac{2\pi f_i |r_k|}{c})] (12)
\]

and

\[
X_{um}(f_i)
= \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(-i \frac{2\pi f_i |r_k|}{c})] \exp(-i \frac{2\pi f_i r_m}{c})
= \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(-i \frac{2\pi (f_i + f_0) |r_k|}{c})] \exp(-i \frac{2\pi f_i r_m}{c})
= \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(-i \frac{2\pi f_i |r_k|}{c})] \exp(-i \frac{2\pi f_i f_0}{c}) \exp(-i \frac{2\pi f_i \Delta f}{c})
\]

where \( r_m \) is the center of the \( m \)th range unit, \( m_n \) is the quantity of the scattering center in the \( m \)th range unit, \( r_k \) is the \((k+1)\)th scattering center in the \( m \)th range unit, \( A_k \sqrt{\sigma_k} \) is the complex amplitude of the \((k+1)\)th scattering center of the target and it is assumed that the value is not varied with the changing of frequency. The \( f_i \) is the \( i \)th frequency point, and \( \Delta f_i \) is the frequency difference of \( f_i \) and \( f_0 \) (the center frequency of the bandwidth).

![FIGURE 4. The wideband angular glint deviation of two metallic spheres.](image)
Applying the algorithm of HRRP(IDFT) to $X_{um}(f_i)$, the range profile at position $r_m$ is given as

$$A_{um}(r_m) = \frac{1}{N} \sum_{i=0}^{N-1} [X_{um}(f_i) \cdot \exp(\frac{j2\pi f_i r_m}{c})]$$

$$= \frac{1}{N} \sum_{i=0}^{N-1} \left[ \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c}) \cdot \exp(\frac{-j2\pi f_0 r_m}{c})] \cdot \exp(\frac{j2\pi f_i r_m}{c}) \right]$$

$$= \frac{1}{N} \sum_{i=0}^{N-1} \left[ \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c}) \cdot \exp(\frac{-j2\pi f_0 r_m}{c})] \cdot \exp(\frac{j2\pi f_i r_m}{c}) \right]$$

$$= \frac{1}{N} \sum_{i=0}^{N-1} \left[ \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c}) \cdot \exp(\frac{-j2\pi f_0 r_m}{c})] \cdot \exp(\frac{j2\pi f_i r_m}{c}) \right]$$

We can mark the last term of Eq. (14) as

$$W = \frac{1}{N} \sum_{i=0}^{N-1} \exp(-j2\pi f_i \Delta r_k / c)$$

which can be considered as the weighting value due to the corresponding $k$th subitem in the whole summation. And according to the former definition, we have $\Delta f_i \leq B/2$ and $\Delta r_k \leq c/4B$, where $B$ represents the bandwidth. When the $\Delta r_k$ is equal to zero, the value of $W$ in Eq. (15) will be one. And if the $\Delta r_k$ is equal to biggest value which is $c/4B$, the value of $W$ will be 0.8811, 0.8965 and 0.8984 when $N$ is 11, 51 and 101 respectively. Generally, the number of $N$ will be large and Eq. (15) is monotonic function. Thus, the value of $W$ could be from 0.88 to 1 and for the Eq. (14), it will be approximatively given as

$$A_{um}(r_m) \approx \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c})]$$

Similarly, the result of HRRP for the differential channel is given as

$$A^\Delta_{um}(r_m) \approx \sum_{k=0}^{m_n} [A_k^\Delta \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c})]$$

Then, the wideband angular glint by using Eq. (11) is given by

$$e(r_m) = \text{Re} \left[ \frac{HRRP(X^\Delta_{um}(f_i))}{HRRP(X_{um}(f_i))} \right]$$

$$\approx \text{Re} \left[ \sum_{k=0}^{m_n} [A_k^\Delta \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c})] / \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c})] \right]$$

in which $e(r_m)$ represent the deviation of angular glint at center position $r_m$ of the $m$th range unit. Then we use Eq. (7) to calculate the deviation of angular glint of multi-scattering centers in the $m$th range unit at the center frequency using narrowband method. The result is given by

$$f(0) = \text{Re} \left[ \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c})] / \sum_{k=0}^{m_n} [A_k \sqrt{\sigma_k} \exp(\frac{-j2\pi f_0 \Delta r_k}{c})] \right]$$

Comparing with Eq. (18) and Eq. (19), it is easy to find that they are identical. It means that in the full wave or the high-frequency simulation, the calculation of wideband angular glint can be replaced by the single frequency simulation which has the much less calculated time especially for the extremely complex target and without the IFFT operation, the proposed fast calculated method has low mathematical complexity compared with the wideband method. And also the unity between the wideband and narrow modeling method has been established. Thus, the wideband angular glint can be fast calculated using the three existing narrowband modeling methods which are PGM, PVM and the monopulse tracking system respectively according to the corresponding applications and circumstance.

B. THE VERIFYING USING HIGH FREQUENCY ELECTROMAGNETIC SIMULATION

To verify the unity of wideband and narrow and angular glint modeling, the angular glint deviations of three metallic spheres are calculated using the PO method.

The frequency sweep is from 35GHz to 35.2GHz with the sweep step is 0.001GHz. Because the bandwidth is 200MHz, the range resolution will be 0.75m. To illustrate the unity clearly, the three spheres are still in one range unit no matter what the azimuth (from 0 to 60 degrees) is. The geometrical view is shown in Fig. 5, and the simulated result is shown in Fig. 6. We can clearly notice that the wideband algorithm...
IV. DISCUSSION

The foundation of this unity will help the researchers to estimate the angular glint of wideband rapidly from the narrowband calculation, which avoids consuming much time without performing the frequency sweep in the simulation and measurement. The unity will play a tremendous advantage in investigating the feature of multiple targets in the different range unit.

Considering of the angular glints of multiple targets or scattering centers shown in Fig. 7, we can find that the targets 1 to 6 are distributed in three range units separately. To calculate the angular glint of whole target shown in Fig. 7 at the center position of each range unit, we can only consider the angular glint caused by multi-scattering centers due to the wideband modeling method. And for each range unit which have the multi-scattering centers, according to the proposed unity of wideband and narrowband angular glint modeling, we can only calculate the angular glint of the multi-scattering centers in the range unit using single frequency (the center frequency in the whole bandwidth) modeling method without the simulation under frequency sweep.

V. CONCLUSION

We presented the estimated algorithm for fast and accurately simulating the wideband angular glint based on single frequency modeling method. The three main methods for modeling the target angular glint had been unified under the assumption of geometrical optics approximation and the linear polarized receiving. According to our mathematical derivation, the calculation of wideband angular glint can be replaced by the single frequency simulation which has the much less calculated time especially for the extremely complex target. Not only the former three modeling method under narrowband had been unified, but also the unity of the wideband and narrowband have been established. The estimated algorithm for fast calculating the wideband angular glint can also provide a great tool to investigate the suppression of angular glint efficiently.

REFERENCES

[1] D. D. Howard, “Radar target angular scintillation in tracking and guidance system based on echo signal phase front distortion,” in Proc. NEC, vol. 15, 1959, pp. 840–849.
[2] J. E. Lindsay, “Angular glint and the moving, rotating, complex radar target,” IEEE Trans. Aerosp. Electron. Syst., vol. AES-14, no. 2, pp. 164–173, Mar.1968.
[3] J. H. Dunn and D. D. Howard, “Radar target amplitude, angle, and Doppler scintillation from analysis of the echo signal propagating in space,” IEEE Trans. Microw. Theory Techn., vol. 16, no. 9, pp. 715–728, Sep. 1968.
[4] P. J. Kajenski, “Comparison of two theories of angle glint: Polarization considerations,” IEEE Trans. Aerosp. Electron. Syst., vol. 42, no. 1, pp. 206–210, Jan. 2006.
[5] W. Chao, Y. Hongcheng, and H. Peikang, “Comparison between two concepts of angular glint: General considerations,” J. Syst. Eng. Electron., vol. 19, no. 4, pp. 635–642, Aug. 2008.
[6] H. C. Yin and P. R. Huang, “Further comparison between two concepts of radar target angular glint,” IEEE Trans. Aerosp. Electron. Syst., vol. 44, no. 1, pp. 372–380, Jan. 2008.
[7] H. Lin, J.-X. Ge, and J. Wang, “Simulation of suppression technology of angular glint based on MIMO radar,” in Proc. Asia-Pacific Microwave Conf. (APMC), Nov. 2018, pp. 905–907.
[8] M. Sui and X. Xu, “Angular glint calculation and analysis of radar targets via adaptive cross approximation algorithm,” J. Syst. Eng. Electron., vol. 25, no. 3, pp. 411–421, Jun. 2014.
[9] K.-Y. Guo, G.-L. Xiao, Y. Zhai, and X.-Q. Sheng, “Angular glint error simulation using attributed scattering center models,” IEEE Access, vol. 6, pp. 35194–35205, 2018.
[10] J. Wu, K. Guo, B. Wu, and X. Sheng, “Estimation of vector miss distance for complex objects based on scattering center model,” Sci. China Inf. Sci., vol. 64, no. 4, Apr. 2021, Art. no. 149301.
[11] M. Sui and X. Xu, “NFPO based technique for near-field angular glint calculation of radar targets,” in Proc. Int. Conf. Electromagn. Adv. Appl., Sep. 2010, pp. 851–854.
[12] H. Zhang, L. Guo, Z. Liang, and X. Wang, “Bi-static angular glint calculation on complex targets in near-regions via multilevel fast multipole algorithm,” in Proc. Prog. Electromagn. Res. Symp. (PIERS), Aug. 2016, pp. 470–473.
[13] S. Bai and C. Xu, “A method to improve the accuracy of angle for automotive radar,” in Proc. IEEE Int. Conf. Signal, Inf. Data Process. (ICSIDP), Dec. 2019, pp. 1–5.

[14] X. Wang, Z. Xu, X. Wang, J. Zhang, and H. Qiu, “Research on filtering method of monopulse radar angular glint suppression,” in Proc. IEEE 3rd Adv. Inf. Technol., Electron. Autom. Control Conf. (IAEAC), Oct. 2018, pp. 668–671.

[15] C. Wang, X. Feng, W. Zhang, and X. Zhou, “Research on pulse compression radar angular glint modelling and suppression,” J. Eng., vol. 2019, no. 21, pp. 7658–7661, Nov. 2019.

[16] R. A. Mitchell and R. Dewall, “Overview of high range resolution radar target identification,” Autom. Target Recognit. Working Group, Monterey, CA, USA, Tech. Rep., 1994.

[17] J. Walker, “Range-Doppler imaging of rotating objects,” IEEE Trans. Aerosp. Electron. Syst., vols. AES–16, no. 1, pp. 23–52, Jan. 1980.

[18] Y. Zhou, L. Zhang, C. Xing, P. Xie, and Y. Cao, “Target three-dimensional reconstruction from the multi-view radar image sequence,” IEEE Access, vol. 7, pp. 36722–36735, 2019.

[19] M. Sui and X. Xu, “Angular glint of complex targets for high range resolution radar,” in Proc. Int. Conf. Electromagn. Adv. Appl., Sep. 2012, pp. 895–898.

[20] R. F. Harrington, Time-Harmonic Electromagnetic Fields. New York, NY, USA: McGraw-Hill, vol. 1961, p. 127.

[21] R. Bhalla and H. Ling, “Three-dimensional scattering center extraction using the shooting and bouncing ray technique,” IEEE Trans. Antennas Propag., vol. 44, no. 11, pp. 1445–1453, Nov. 1996.

[22] C. Wang, H. C. Yin, X. B. Feng, and P. Huang, “Computation of angular glint for complex targets: Polarization consideration,” Syst. Eng. Electron., vol. 30, no. 7, pp. 1195–1199, 2008.

[23] C. Wang, “High frequency electromagnetic scattering modeling and its application,” (in Chinese), Ph.D. dissertation, Dept. Elect. Eng., Commun. Univ. China, Beijing, China, 2009.

[24] R. J. Sims and E. R. Graf, “The reduction of radar glint by diversity techniques,” IEEE Trans. Antennas Propag., vol. 19, no. 4, pp. 462–468, Jul. 1971.