

The analysis of impact factors in different application scenes of corner reflectors

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Abstract. The corner reflectors are a sort of electromagnetic structure equipment, with a number of important applications in different fields. The applications such as radar calibration and passive influence in military are summarized. Also, theoretical analysis and experimental simulation verification on practical production and application process are conducted. The machining edge length error, machining angle error and the extent of reflective surface deformation of the corner reflector and other errors that are easily introduced in the actual working environment are specifically listed and analyzed, which provides guidance on how to avoid and cope with such errors, both in the design of corner reflectors and in practical applications.

Keywords: Corner reflector, electromagnetic structure, radar calibration.

1. Introduction

Angle reflector is a kind of radar wave reflector which is made up of two or three mutually perpendicular metal surfaces according to different applications, and is widely used in synthetic aperture radar calibration and military passive interference.

Due to its simple structure and stable performance, the corner reflector can be used as a calibrator for scattering in radar calibration to obtain the actual target cross-sectional area represented by each pixel point in the radar image. And due to its good electromagnetic wave reflection characteristics, it is used in the military to interfere with enemy radar detection and guidance, reducing the probability of establishing effective tracking of vehicles, naval vessels and other targets by radar, thus providing protection.

Angle reflectors can be divided into two-surface angle reflectors and three-surface angle reflectors according to the number of reflecting surfaces; single-angle, four-quadrant and eight-quadrant angle reflectors according to the number of quadrants; triangular, circular, square and other angle reflectors according to the shape of the reflecting surface; and fixed, folded, permanent, hybrid and inflatable according to the form of structure [1]. Regardless of the shape or structure of the corner reflector, it is required that the reflective surfaces are perpendicular to each other.

In practical application, on the one hand, due to the limitation of processing accuracy, it is difficult to avoid introducing various processing errors, such as angular errors of corner reflector plates, which makes it non-orthogonal. On the other hand, the influence of the working environment can also lead to changes in the performance of the corner reflectors. For example, under the influence of wind, some inflatable corner reflectors will become irregular, unsmooth, or non-orthogonal.

This paper analyses some of the significant factors affecting the performance of corner reflectors that may occur in practical applications in response to these problems. Specifically, the analysis is conducted for the angle reflector processing edge length error, processing angle error, and the degree of reflective surface deformation to provide guidance for both the design and application of angle reflectors.

2. Comparative analysis of angular reflectors

To analyze the various influencing factors of the corner reflector, it is necessary to first have sufficient knowledge and understanding of the reflection characteristics of various corner reflectors themselves.

Radar cross section (RCS) is a physical quantity that characterizes the intensity of the echoes generated by the target under radar wave irradiation, and is an important metric in the application of corner reflectors, and is an important measure of the usefulness of corner reflectors.

The RCS of the two-surface corner reflector is greatly affected by the azimuth angle, and can only maintain a large RCS in a narrow range of incidence angles, which requires high accuracy in the installation process, and its structural stability is poor, so it is relatively little used.

The RCS of a three-surface corner reflector varies less with the angle of incidence than that of a two-surface corner reflector, which makes it more widely applied. As shown in Figure 1, there are three common types of triple-angle reflectors, including the reflecting surface consists of three right-angle sectors, squares, or isosceles triangles.

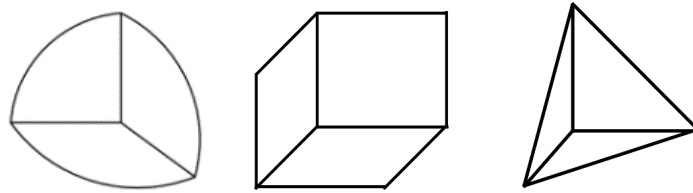


Figure 1. Three types of three-surface corner reflectors

The placement of the corner reflector plays an important role in the application of the corner reflector. In the actual process of using the corner reflector for calibration, the orientation of its placement is also an important influencing factor due to the difficulty of positioning the corner reflector precisely as required. The angle of incidence and pitch of the strongest reflection of the corner reflector, called the maximum RCS angle of incidence. Deviation from this maximum angle of incidence reduces the intensity of the reflected wave.

The RCS maximum value of the triangular three-surface corner reflector in the case of equal side length is less than that of the other two three-surface corner reflectors, but its RCS values are less attenuated with angular deviation from the maximum RCS angle of incidence, allowing smoother and more stable echoes to be obtained over a larger angular range, which means the highest tolerance to the angle of incidence, which is more suitable for practical applications, and therefore, its applications are more widespread [2].

Figure 2 and Figure 3 show the RCS distribution of the triangular and square corner reflectors with respect to azimuth and pitch angles obtained from the FEKO software simulation, respectively. In the simulation model, the right-angle side length and square side length are 0.1m, and the operating frequency is 10GHz.

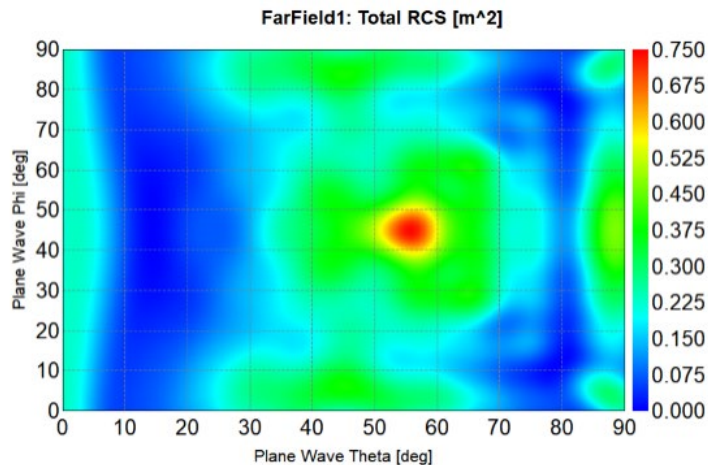


Figure 2. Single-station RCS of a triangular corner reflector

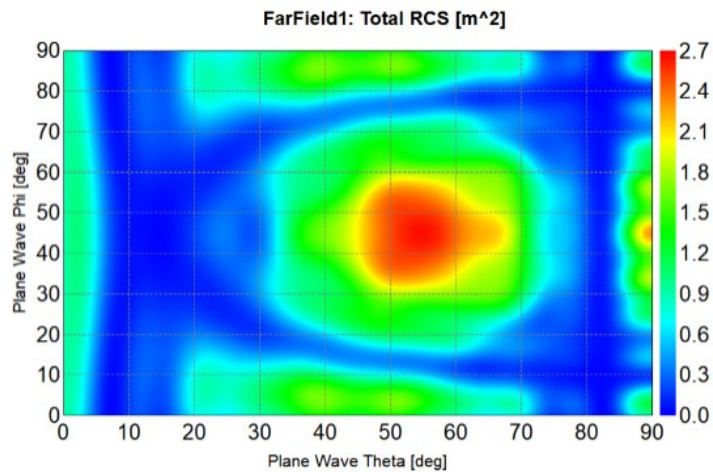


Figure 3. Single-station RCS of a square corner reflector

As shown in Figures 2 and 3, the triangular and square corner reflectors have some similarity in the RCS distribution. For a single triangular reflector, the RCS reaches its maximum value at azimuth $\varphi = 45^\circ$ and pitch $\theta = 55^\circ$ angles. For a single square reflector, the RCS reaches a maximum at azimuth $\varphi = 45^\circ$ and pitch $\theta = 56^\circ$ angles. If the incidence angle deviates from this maximum incidence angle, the RCS of the corner reflector will be attenuated to varying degrees.

Figures 4 and 5 show the relative RCS of the triangular and square corner reflectors, respectively, along the RCS maximum point with another angle change when the azimuth and pitch angles are fixed, and the angular range in which the RCS of the corner reflector decreases by 3 dB relative to its maximum is labeled.

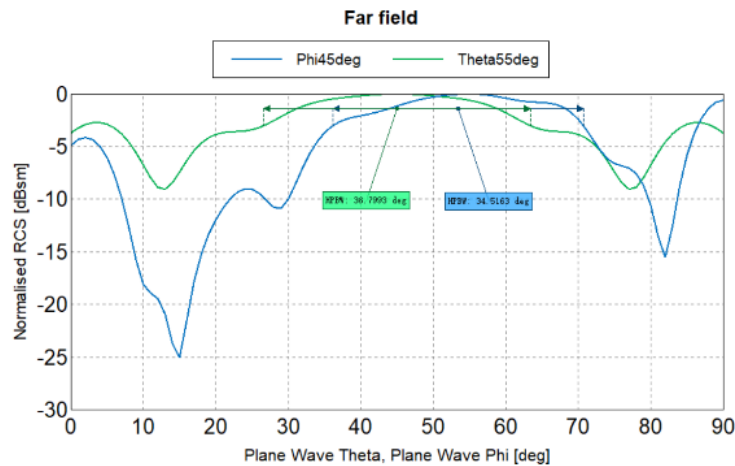


Figure 4. The relative RCS of the triangular corner reflector along the RCS maximum point at fixed azimuth and pitch angles

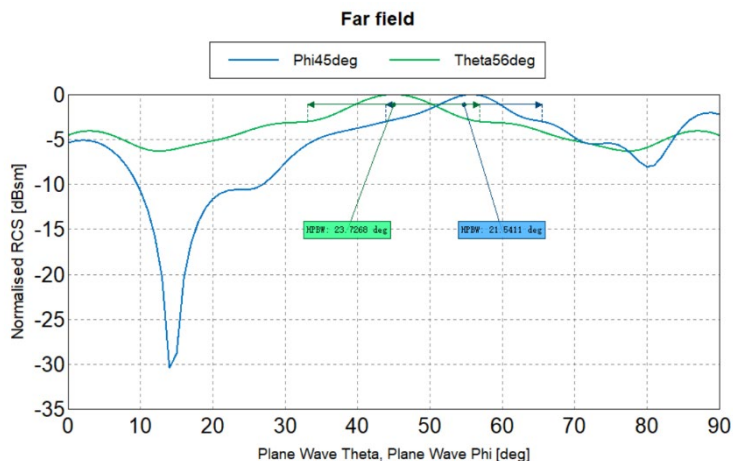


Figure 5. The relative RCS of the square corner reflector along the RCS maximum point at fixed azimuth and pitch angles

Table 1. Relative RCS of the two types of corner reflectors along the RCS maximum point at a fixed azimuth and pitch angle respectively in the angle range of the relative maximum reduction of 3dB

	triangular corner reflector/deg	square corner reflector/deg
Azimuth fixation	34.5163	21.5411
Pitch fixation	36.7993	23.7268

As shown in Figure 2-5, the relative degree of change in both azimuth and pitch angle of the triangular angle reflector RCS is smaller than that of the square angle reflector RCS, and the relative maximum reduction of 3 dB is larger. Therefore, it is more widely adopted.

3. Analysis of factors affecting the performance of angular reflectors

Corner reflectors in application require strict control of their RCS size. For example, a scatterer with a known RCS is required for radar calibration. If the RCS of the corner reflector as a scatterer is not confirmed, the calibration of the radar will be biased. If the RCS of the corner reflector as a target is too different from the RCS of the real target, it is impossible to cover the real target.

Due to the limitations of process accuracy and actual field conditions, errors are inevitably introduced during the fabrication and installation of corner reflectors. It is important to confirm the RCS of the corner reflector in the application process, so the following is an analysis of three important influencing factors, such as the edge length error, processing angle error and the extent of reflective surface deformation of the corner reflector. The study of these error factors can guide the process of reducing errors and better determining the RCS of the corner reflector.

Since triangular three-surface corner reflectors are more widely used in applications, the following analysis and simulation mainly use triangular three-surface corner reflectors.

3.1 Corner reflector processing edge length error

When machining the corner reflector, the error in the edge length of the corner reflector will also have an effect on the RCS value.

Let the side length of the triangular angle reflector be b and the operating wavelength be λ , then the maximum RCS be

$$\sigma_{\max} = 4.913 \frac{b^4}{\lambda^2} \tag{1}$$

Taking the same differentiation on both sides of the equal sign gives

$$\Delta\sigma_{\max} = 4 \times 4.193 \frac{b^4}{\lambda^2} \frac{\Delta b}{b} \quad (2)$$

$$\frac{\Delta\sigma_{\max}}{\sigma_{\max}} \sigma_{\max} = 4 \times 4.193 \frac{b^4}{\lambda^2} \frac{\Delta b}{b} \quad (3)$$

The relative error of RCS maximum value can be obtained as

$$\frac{\Delta\sigma_{\max}}{\sigma_{\max}} = 4 \frac{\Delta b}{b} \quad (4)$$

From Equation (4), the relative error of the RCS maximum value of the corner reflector is proportional to the ratio of the machining size error of the corner reflector to the side length within a specific machining error range. When the machining accuracy is determined, the RCS error is inversely proportional to the side length of the corner reflector, thus the larger the size of the corner reflector, the smaller the error in the RCS value.

Observing the above derivation, we can find that the relative error of the maximum RCS of the corner reflector is independent of the coefficient of the relationship between its side length and the working wavelength, so Equation (4) is also applicable to the square corner reflector and the sector-shaped corner reflector.

3.2 Corner reflector processing angle error

The physical process is that the incident electromagnetic wave is reflected several times between multiple orthogonal metal surfaces of the corner reflector, and finally the reflected wave is in the opposite direction of the incident wave. The above reflection characteristics are based on the three metal plates of the corner reflector being strictly orthogonal to each other. If there is an angular error between the reflector plates of the corner reflector, so that the corner reflector cannot meet the condition of strict orthogonality of each reflecting surface, then its reflected wave will be more obvious changes.

Simulation studies were conducted for corner reflectors with different degrees of angular errors, and FEKO software was used to model the case of angular errors in the processing of corner reflectors, and only single-quadrant corner reflectors with a single reflector were considered for processing errors.

As shown in Figure 6, the right-angle side of the triangular plate corner reflector is 0.2m, the material is an ideal conductor, and the operating frequency is 10GHz. Ignoring the thickness of the metal plate, the simulation calculation is performed separately for the case of different processing angle errors occurring in a single reflector plate

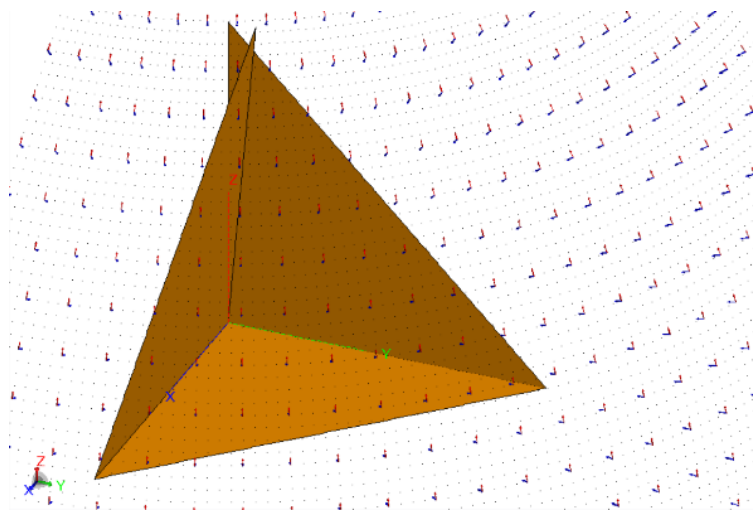


Figure 6. Corner reflector machining angle error model

The single-station RCS cases of the corner reflector without angular deviation and with 1° , 2° , 3° and 5° deviations of individual reflector plates are shown in Figures 7-11, respectively.

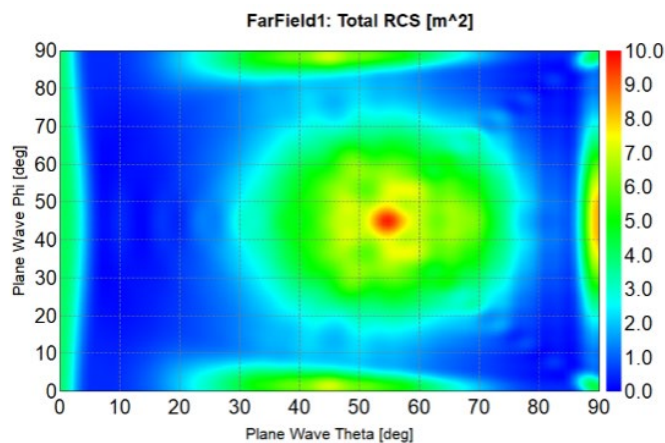


Figure 7. Corner reflector single-station RCS without angular error

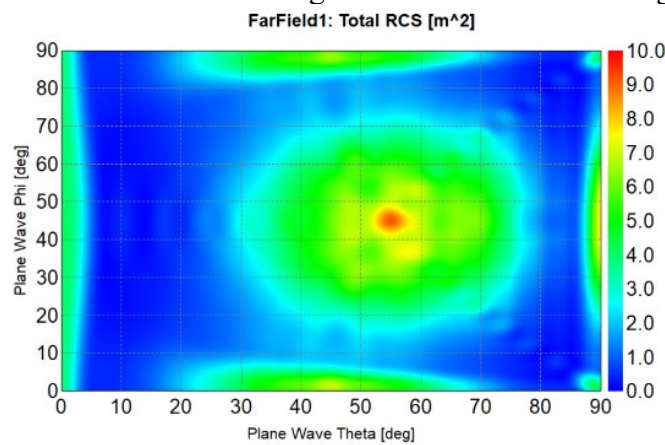


Figure 8. Single-station RCS of angle deviation of 1° for corner reflector

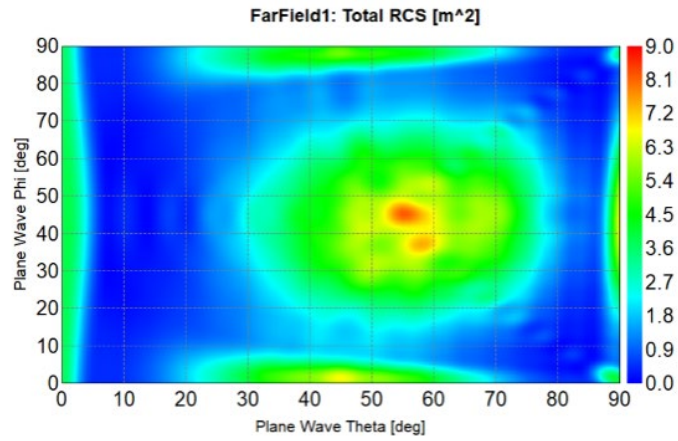


Figure 9. Single-station RCS of angle deviation of 2° for corner reflector

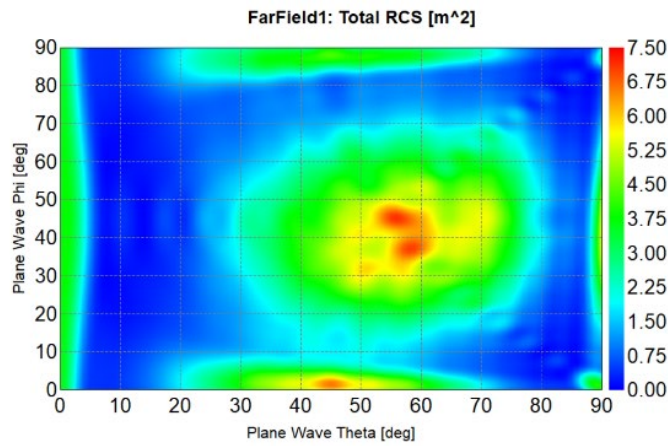


Figure 10. Single-station RCS of angle deviation of 3° for corner reflector

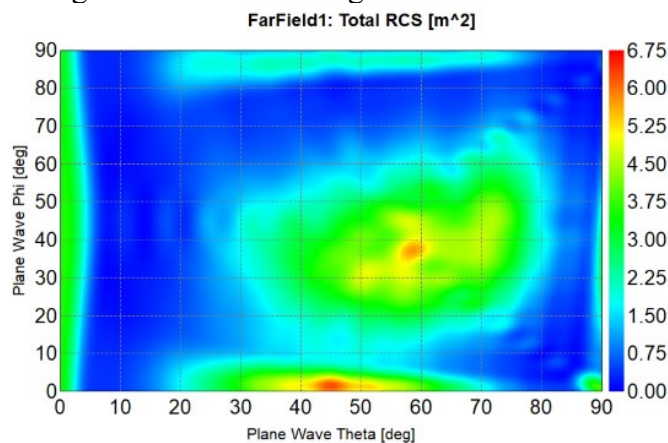


Figure 11. Single-station RCS of angle deviation of 5° for corner reflector

Table 2. Single-station RCS maximum values and corresponding angles of angular reflectors of different degrees of angular deviation

Angle deviation	0°	1°	2°	3°	5°
Maximum RCS/m ²	9.8	9.3	8.2	7.2	5.8
Azimuth/°	45	45	45	43	37
Pitch/°	55	55	56	57	59

As shown in Figure 7-11, the incidence angle of the RCS maximum for a single station of the corner reflector remains basically stable when the angle deviation is relatively small. And when the angle deviation is larger, the RCS maximum value shows a significant decrease. And as the angle error increases, the RCS maximum value shows an accelerating trend of decreasing. It means that when the metal plate in the angle reflector does not meet the strict orthogonality, the reflected electromagnetic waves cannot all return along the original path, and the energy is "scattered". Therefore, when the angle deviation is large, the RCS of the corner reflector will appear two or even more extreme values.

Under the standard conditions, the maximum RCS of the corner reflector occurs at the azimuth and pitch angles. And with the increase of the angular error of the corner reflector, the coordinate position where the maximum RCS point appears will be changed because the orthogonality of the corner reflector is disrupted. Compared to the standard case, the maximum RCS incidence angle of the corner reflector will be closer to the reflector plate where the angular deviation occurs in azimuth, while the pitch angle will enlarge.

At the same time, it can be observed that the angular error of the corner reflector makes the RCS at its edge become relatively larger. This trend has a relatively small range and its RCS absolute value is basically stable, which is due to the fact that the reflected electromagnetic wave energy of the non-ideal corner reflector is distributed in a larger angular range, resulting in a larger relative value of RCS at the edges, but this phenomenon has little effect in practical applications.

3.3 The extent of reflective surface deformation of the corner reflector

Reflective surface deformation refers to the reflective surface of the corner reflector deformation so as to make it not a flat surface, such as the inflatable corner reflector often used in the sea battlefield environment by the sea wind and other influences into the surface. Another example is the deformation that occurs during processing and after installation by external forces. When the corner reflector reflective surface deformation, will also change the orthogonality of the corner reflector three reflective plate, so that its RCS produced a large change.

The degree of deformation is an important factor affecting the performance of the corner reflector [3].

Since the surface of flexible materials is prone to bending and wrinkling that have a great impact on its RCS, extra attention should be paid to the part of the flexible surface during the production process.

The ratio of the degree of deformation of the reflector surface to the operating wavelength of the corner reflector will increase at a certain degree of deformation and increasing frequency. The same degree of deformation has a greater effect on the RCS of the corner reflector at shorter wavelengths, and the RCS reduction will be more significant [4].

At a fixed degree of deformation, the ratio of the deformation of the reflector surface to the operating wavelength of the corner reflector will increase as the frequency increases, and the same degree of deformation will have a greater effect on the RCS of the corner reflector at shorter wavelengths, making the RCS reduction more significant [5].

The degree of deformation has a large impact on the corner reflector, so every effort should be made to avoid large reflective surface deformation during design, fabrication and application.

In this paper, the effect of corner reflector deformation on RCS is modeled using FEKO software for different degrees of deformation, and only the case of deflection deformation of a single reflector plate is considered.

As shown in Figure 12, the right angle side of the triangular plate corner reflector is chosen to be 0.2m long, the material is an ideal conductor, the operating frequency is 10GHz, and the thickness of the metal plate is neglected. The deformation occurs in the reflector plate in the XOZ plane, and the simulations are carried out separately for the cases where the midpoint of the beveled edge of the reflector plate projects outward at different distances.

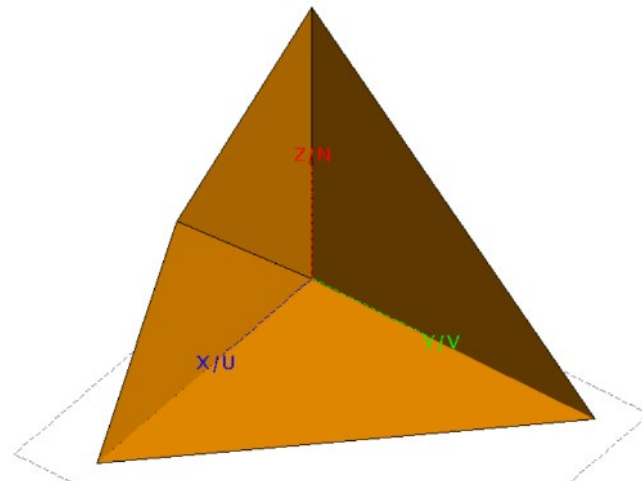


Figure 12. The extent of reflective surface deformation of the corner reflector model

The situation when no deformation is present is the same as in Figure 9.

Figures 15-19 show the single-station RCS of the corner reflector with 0.005m, 0.01m and 0.02m outwardly convex and 0.005m and 0.01m inwardly concave at the midpoint of the beveled edge of the corner reflector, respectively.

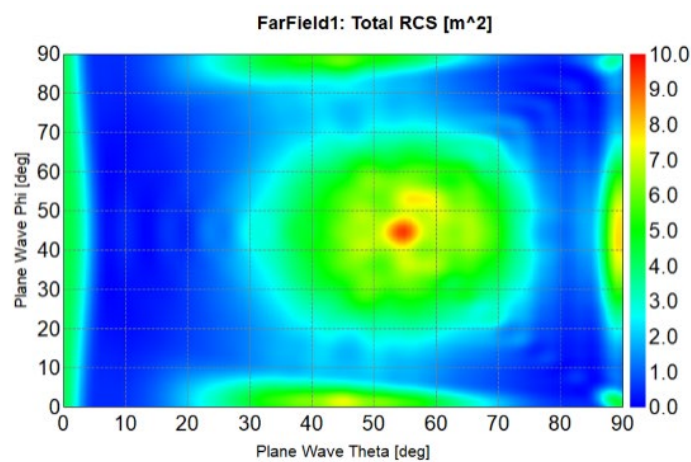


Figure 13. Single-station RCS of angular reflector with 0.005m outwardly convex

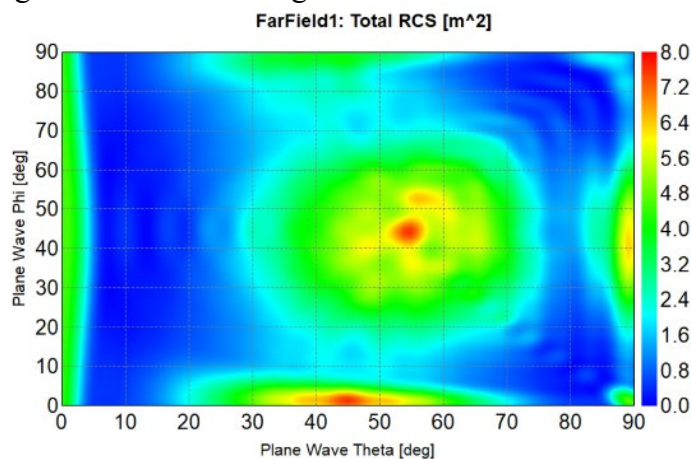


Figure 14. Single-station RCS of angular reflector with 0.01m outwardly convex

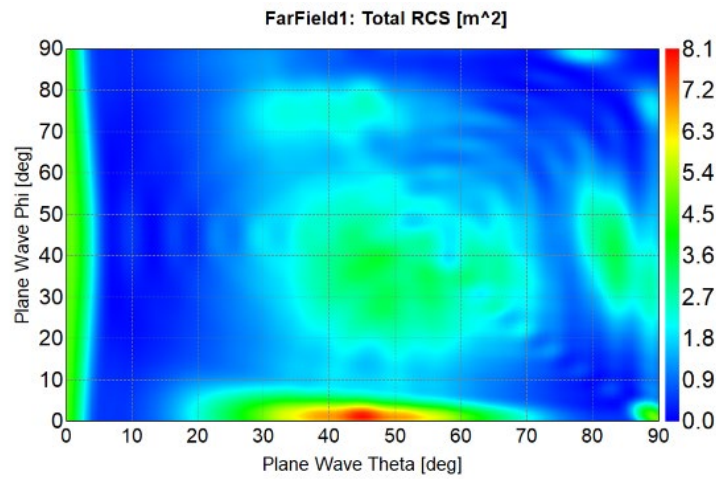


Figure 15. Single-station RCS of angular reflector with 0.02m outwardly convex

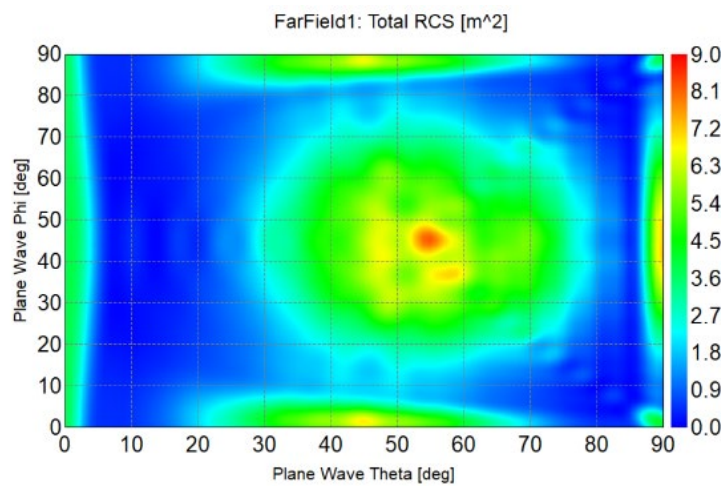


Figure 16. Single-station RCS of angular reflector with 0.005m inwardly concave

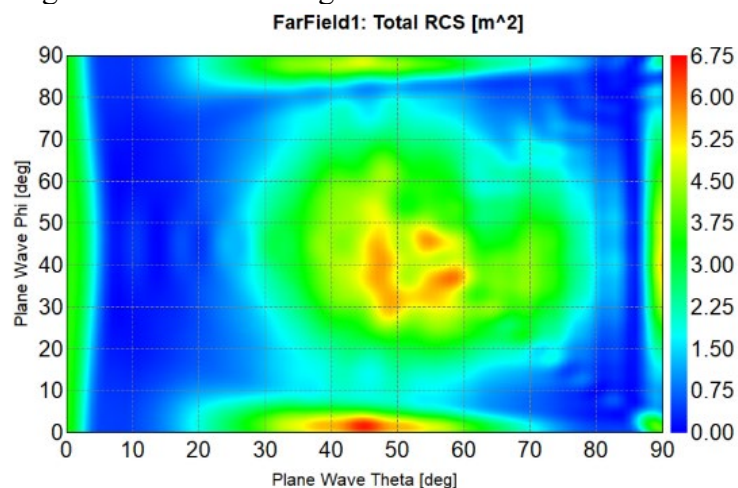


Figure 17. Single-station RCS of angular reflector with 0.01m inwardly concave

Table 3. Single-station RCS maximum values and corresponding angles of angular reflectors of different degrees of angular deviation

The extent of deformation/m	0	0.005	0.01	0.02	-0.005	-0.01
Maximum RCS/m ²	9.8	9.4	7.6	3.7	8.8	6.7

Azimuth/ $^{\circ}$	45	45	43	36	45	38
Pitch/ $^{\circ}$	55	55	54	48	55	58

As shown in Figures 13-17, the effect of the extent of deformation of the corner reflector on the RCS is somewhat similar in results to the effect of angular error on the RCS of the corner reflector.

The maximum RCS of the corner reflector decreases with the increase of the deformation of the reflector plate. When the extent of deformation is small, the RCS of the corner reflector has less influence, while when the extent of deformation is large, the maximum RCS of the corner reflector decreases significantly, and with the increase of the deformation shows an accelerating trend. As the reflector plate in the corner reflector does not meet the strict orthogonality, the reflected electromagnetic wave can not return along the original path, and the energy "scattered" situation, the same makes the maximum RCS point appeared in the coordinate position change and produce two or more RCS extreme value. Especially when the convexity is 0.02m, as shown in Figure 15, there is no obvious maximum point.

Comparing the effects of equal degrees of convex and concave deformation on the maximum RCS of the corner reflector, it is found that the concave deformation has a stronger effect on the reduction of the maximum RCS of the corner reflector for equal degrees of deformation. The reason for this is that the concavity reduces the projected area of the corner reflector in the direction of electromagnetic wave incidence, which results in a greater reduction of the RCS.

The degree of reflective surface deformation has a high impact on the RCS attenuation of the corner reflector when the deviation is large. The maximum RCS value in this case is less than half of the maximum RCS value in the standard case, and the maximum RCS azimuth and pitch angles also have large deviations from the standard case, so it can be considered that the corner reflector is not functioning properly in this case.

4. Conclusion

Corner reflectors have an important role in many fields because of their good electromagnetic return characteristics. Because of its outstanding RCS stability, the triangular surface corner reflector can be used in many scenes where the direction of the incoming wave is uncertain or has a wide range of variation. All kinds of practical factors of the corner reflector will have an impact on its application effect, so it is necessary to control its error within the acceptable range as much as possible in both processing and application.

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