

Article

Design of Low Cross-Polarization Tri-Reflector CATR with Standard Quadric Surfaces Working in Terahertz

Zhi Li ¹ , Yuan Yao ^{1,*}, Tianyang Chen ¹, Junsheng Yu ¹ and Xiaodong Chen ²

¹ School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China; byliz@bupt.edu.cn (Z.L.); chentianyang@bupt.edu.cn (T.C.); jsyu@bupt.edu.cn (J.Y.)

² School of Electronic Engineering and Computer Science, Queen Mary, University of London, London E1 4NS, UK; xiaodong.chen@qmul.ac.uk

* Correspondence: yaoy@bupt.edu.cn

Abstract: In this paper, a tri-reflector compact antenna test range (CATR) consisting of a main parabolic reflector with a square aperture of 3 m in side length and two sub-reflectors of rotationally standard quadric surfaces working in terahertz is proposed. By using the equivalent paraboloid theory and cross-polarization elimination conditions and then combining with the appropriate shaped feed, the low cross-polarization and good quiet zone (QZ) performance of the system are achieved. The simulated results demonstrate that a cross-polarization isolation of >37 dB and a peak-to-peak amplitude (phase) ripple of <1.8 dB (13°) can be achieved on the principal cuts of the QZ at 100–500 GHz. At the same time, the QZ usage ratio of the CATR can reach 75%. The proposed tri-reflector CATR composed of standard quadric surfaces not only exhibits good quiet zone performance but also greatly reduces the manufacturing difficulty of the sub-reflectors and the construction cost of the system.



Citation: Li, Z.; Yao, Y.; Chen, T.; Yu, J.; Chen, X. Design of Low Cross-Polarization Tri-Reflector CATR with Standard Quadric Surfaces Working in Terahertz. *Electronics* **2021**, *10*, 1727. <https://doi.org/10.3390/electronics10141727>

Academic Editor: Paolo Baccarelli

Received: 8 June 2021

Accepted: 16 July 2021

Published: 18 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: tri-reflector; compact antenna test range; standard quadric surfaces; low cross-polarization

1. Introduction

With the wide application and development of millimeter-wave and terahertz technology in the field of antennas [1–4], the demand for accurate measurement of antenna radiation characteristics is becoming increasingly strong. The technique of compact antenna test range (CATR), which transforms the spherical wavefront to a plane wave aperture distribution, is a very promising solution for millimeter-wave and terahertz antenna measurement [5–12] due to its relatively stable electromagnetic environment and full-weather capability.

For millimeter-wave and terahertz applications, the commonly used single offset reflector CATR [13–15] has poor linear cross-polarization and low QZ usage. Although the dual-reflector CATR [16,17] can greatly improve the cross-polarization characteristics, the quiet zone (QZ) will be affected by the feed leakage. To overcome this disadvantage, it is necessary to build a larger sub-reflector [18], almost the same size as the main reflector, which will inevitably increase the construction cost. As for the current tri-reflector CATR, the cross-polarization and QZ performance have been greatly improved [19–21], but the two shaped sub-reflectors have high requirements for processing technology, long production cycle, and high cost. However, the cross-polarization cancellation tri-reflector antennas with rotationally quadric surfaces have been studied in [22], which provides a new idea for the large aperture and high-frequency tri-reflector CATR design of the mirror with standard quadric surfaces [23–26].

In this paper, a tri-reflector CATR with a parabolic main reflector and two rotationally standard quadratic surface reflectors is designed in 100–500 GHz bands. Of the two sub-reflectors, the one closer to the feed source is a rotationally ellipsoid mirror, and the other is a rotational hyperboloid mirror, which forms three confocal reflectors [27,28] with the

main reflector. Since the rays emitted from the feed have the same optical path after passing through the three confocal reflectors, a smaller phase ripple can be obtained in the QZ. Then, by using the equivalent paraboloid method and cross-polarization elimination conditions, the low cross-polarization characteristics of the QZ of the system can also be obtained. And finally, through the numerical simulation of the proposed tri-reflector CATR fed by the appropriate shaped feed source, the results show that the theoretical design of the tri-reflector CATR has achieved good QZ performance. The cross-polarization isolation is more than 37 dB, and the peak-to-peak amplitude (phase) ripple is less than 1.8 dB (13°) on the principal cuts at 100–500 GHz. At the same time, the QZ usage ratio has reached 75%.

2. Design of a Tri-Reflector CATR

2.1. Equivalent Paraboloid Method and Cross-Polarization Elimination Conditions

Figure 1a shows the Schematic diagram of a tri-reflector system. This system is composed of a feed at point F_0 , two sub-reflectors that are made of rotationally quadratic surfaces, and a parabolic main reflector. Of the two sub-reflectors, the one closer to the feed is sub-reflector one, and the other is sub-reflector two. Sub-reflector one is focused on F_0 and F_1 , sub-reflector two is focused on F_1 and F_2 , and the main reflector is focused on F_2 .

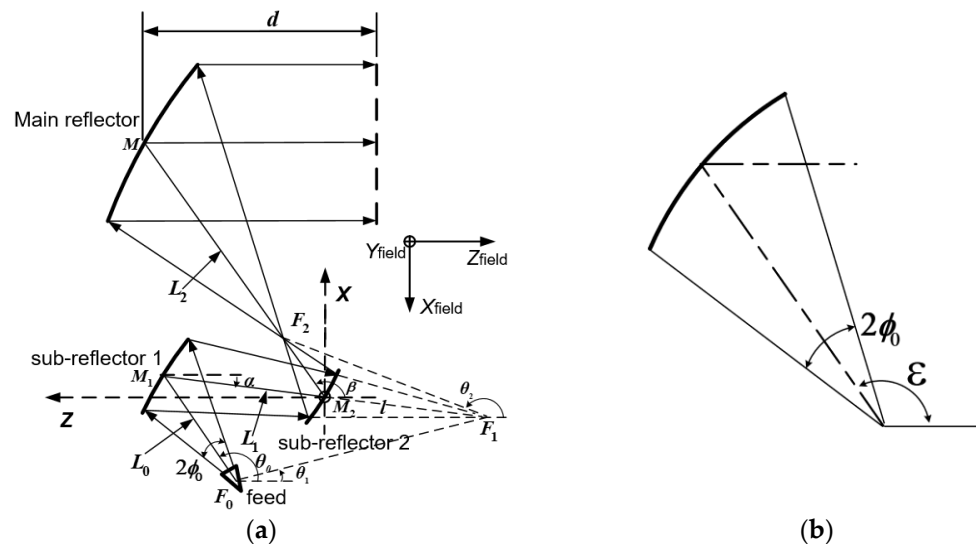


Figure 1. (a) Schematic diagram and design parameters of a tri-reflector system; (b) the equivalent paraboloid of a tri-reflector system.

In this system, the optical center of sub-reflector two is used as the origin of the global coordinate XYZ ; the z -axis is taken along the mirror axis, and the x -axis is taken along the vertical direction. M_1 , M_2 , and M are the points where the ray along the center axis of the feed from the point F_0 intersects with the sub-reflectors one and two and the main reflector. L_0 , L_1 , L_2 , and l are the lengths of the rays $|F_0M_1|$, $|M_1M_2|$, $|M_2M|$, and $|M_1F_1|$, respectively. The variable d represents the distance from the optical center of the main reflector to the QZ and the position of the minimum distance when the distance d gradually increases, and the QZ performance of the system is relatively stable and taken as the starting position of the QZ. The angle θ_0 is the offset angle of the feed, and $2\phi_0$ is the opening angle of the feed. It can be seen from Figure 1a that the two sub-reflectors and the main reflector together form a confocal reflector, and all the above reflectors together can be equivalent to a paraboloid reflector which will also become a rotationally symmetric paraboloid if the center axis of the feed coincides with the mirror axis of the paraboloid [29] and the structure becomes a system that eliminates cross-polarization. Figure 1b shows the equivalent single paraboloid system of the above tri-reflector system. And the equivalent paraboloid conversion relationship of the tri-reflector is shown in the following Equations (1) and (2):

$$\cos^2 \frac{\varepsilon}{2} = \frac{[\vec{e}_2 \{ \vec{e}_1 \cos(\frac{\theta_0}{2} - \theta_1 + \theta_2) - \cos(\frac{\theta_0}{2} - \theta_2) \} + \{ \vec{e}_1 \cos(\frac{\theta_0}{2} - \theta_1) - \cos(\frac{\theta_0}{2}) \}]^2}{(\vec{e}_2^2 + 2\vec{e}_2 \cos \theta_2 + 1)(\vec{e}_1^2 - 2\vec{e}_1 \cos \theta_1 + 1) + 4\vec{e}_1 \vec{e}_2 \sin \theta_2 \{ \vec{e}_2 \sin(\theta_2 - \theta_1) - \sin \theta_1 \}} \quad (1)$$

$$\vec{e}_i = P_i \delta_i \vec{e}_i \quad (i = 1, 2) \quad (2)$$

where ε is the angle between the axis of the feed and the axis of the equivalent paraboloid; e_i ($i = 1, 2$) is the eccentricity of the sub-reflector one or two; P_i is +1 for a rotationally hyperbolic surface and −1 for a rotationally elliptic surface; δ_i is +1 for a concave reflector and −1 for a convex reflector. As shown in Figure 1a, θ_0 , θ_1 , and θ_2 designate the angles between the axis of the paraboloid and vectors $\vec{F_0 M_1}$, $\vec{F_0 F_1}$ and $\vec{F_1 F_2}$ respectively.

In order to eliminate the cross-polarization of the system, it can be seen from Figure 1a that ε should be equal to 180° , that is $\cos \varepsilon/2 = 0$. Then, by substituting the designed variable parameters of the system in Figure 1a into Equations (1) and (2) and simplifying them, Equations (3)–(5) that satisfy the conditions of cross-polarization elimination can be obtained:

$$e_1^2 - 1 = -\frac{2lL_0\{1 - \cos(\theta_0 + \alpha)\}}{(l + L_0)^2} \quad (3)$$

$$e_2^2 - 1 = \frac{4 \sin(\frac{\alpha - \gamma}{2}) \sin(\frac{\beta - \gamma}{2}) \sin \frac{\alpha}{2} \sin \frac{\beta}{2}}{\sin^2(\frac{\alpha + \beta - \gamma}{2})} \quad (4)$$

$$\tan(\frac{\gamma - \alpha}{2}) = \frac{L_0}{l + L_0} \tan(\frac{\theta_0 - \alpha}{2}) \quad (5)$$

where α is the angle between the vector $\vec{M_1 M_2}$ and the z-axis; β is the angle between the vector $\vec{M_2 M}$ and the z-axis.

According to the range of the eccentricity of the rotating quadric surface, we can determine the surface shape of the two sub-reflectors. Therefore, Equations (3)–(5) satisfying the conditions of cross-polarization elimination can be simplified to the following Equations (6)–(8):

$$P_1 = -\text{sign}(l) \quad (6)$$

$$P_2 = \text{sign}\{\alpha\beta(\beta - \alpha)(X_0 - \frac{l}{L_0})(\theta_0 - \alpha)\} \quad (7)$$

$$X_0 = \frac{\tan(\frac{\theta_0 - \alpha}{2})}{\tan(\frac{\beta - \alpha}{2})} - 1 \quad (8)$$

2.2. The Structure of Low Cross-Polarization Tri-Reflector CATR with Standard Quadric Surfaces

Figure 2 shows the geometric structure of the proposed tri-reflector CATR with standard quadric surfaces, in which sub-reflector one is an ellipsoid mirror and sub-reflector two is a hyperboloid mirror. According to the equivalent parabolic transformation theory in Section 2.1, three confocal reflectors in the system can be equivalent to a single parabolic reflector system. In order for the system to achieve low cross-polarization characteristics, the design should meet the cross-polarization elimination conditions derived in Section 2.1. Through the analysis and discussion of the shape of the two sub-reflectors and the relevant parameter variables in the system design, the value relationship between the relevant parameter variables under the condition of low cross-polarization can finally be obtained. Considering the compactness and practicability of the system structure in Figure 2, we can first take $\alpha < 0$, $\beta > 0$ and $\theta_0 > 0$, and then, according to Equations (6)–(8), the relationship between the relevant parameter variables can be derived as follows:

1. When sub-reflector one is an elliptic surface, that is: $P_1 < 0$, then $l > 0$ can be obtained;

2. When sub-reflector two is a hyperbolic surface, that is: $P_2 < 0$, and because $\alpha < 0$, $\beta > 0$, $\theta_0 > 0$, then $l/L_0 > \text{Max}(X_0, 0)$, and then $\theta_0 > \beta$, $l/L_0 > X_0$ or $0 < \theta_0 < \beta$ can also be obtained.

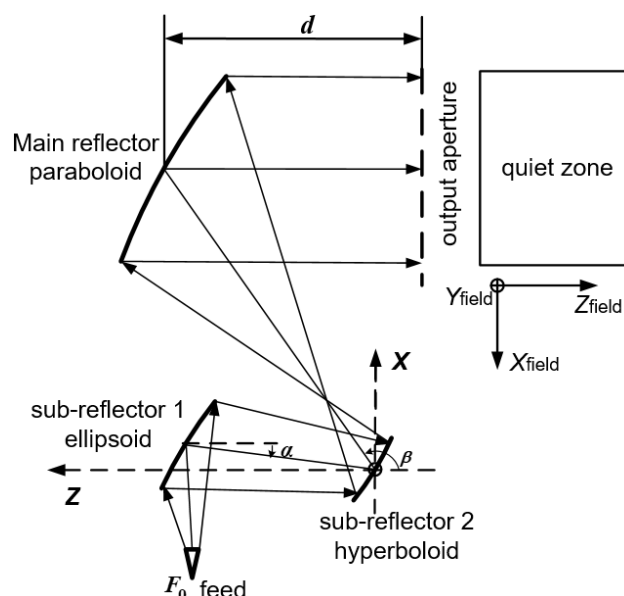


Figure 2. Geometry and design parameters of proposed tri-reflector compact antenna test range (CATR) with standard quadric surfaces.

Next, according to the design requirements, we can first assume the values of the known variables L_0 , L_1 , and θ_0 . Then, within the range of the relevant parameter variables derived above, we optimize the angle variables α and β and use the beam pattern analysis method in [22] to calculate the values of related parameters in the system, and finally, the value of the focal radius of each reflector and the values of the key variables L_2 and l can be obtained. The values of all the parameter variables obtained above should be within the value range that meets the conditions of cross-polarization elimination, and the specific values of these key parameter variables are shown in Table 1. In this design, in order to effectively reduce the influence of edge diffraction, the paraboloid main reflector uses a square aperture with a side length of 3 m, while the size of the two sub-reflectors of standard quadric surfaces is only about 0.25 m, which will greatly reduce the processing cycle and cost.

Table 1. The specific values of the optimized key parameter variables in the design of tri-reflector compact antenna test range (CATR).

Parameter	θ_0 (°)	α (°)	β (°)	L_0 (m)	L_1 (m)	L_2 (m)	l (m)	d (m)
value	90	−20.3	91.6	0.6	0.9	3.25	59.7	4.0

According to the parameter values obtained above, we can use the design method of the conic mirror surface in beam waveguides and quasi-optical networks to model the two sub-reflectors with standard quadric surfaces. To validate the proposed design strategy, the performance of the proposed tri-reflector CATR is simulated and numerically validated by the commercial software GRASP-10 with physical optics (PO) plus physical theory of diffraction (PTD) calculations. Figure 3 shows the GRASP model of the designed tri-reflector CATR.

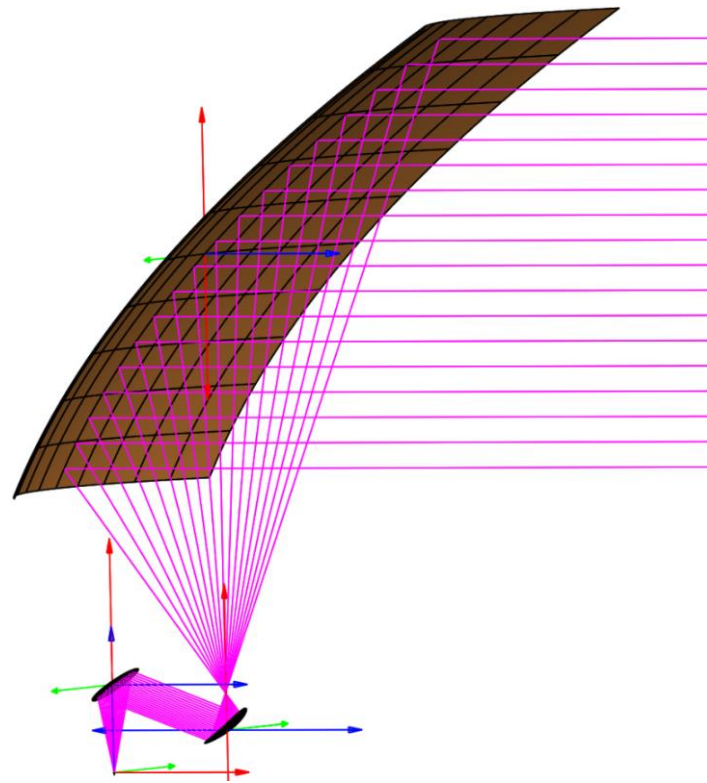


Figure 3. The simulated model of designed tri-reflector compact antenna test range (CATR) with standard quadric surfaces in GRASP-10 software.

3. Results and Discussion

In the process of numerical simulation, for the feed selection of the designed tri-reflector CATR system, we initially chose an ideal Gaussian feed [30] which is -21.6 dB at 18° . Since the system is composed of three confocal reflectors, the optical path of the rays emitted from the feed through sub-reflector one, sub-reflector two, and the main reflector is theoretically equal; therefore, theoretically speaking, the co-polar phase is evenly distributed in the QZ, as shown by the black solid line in Figure 4b; but, due to the influence of edge diffraction, the simulated co-polar phase has some small ripples on the principle cuts of the QZ. At the same time, without considering the transmission loss, according to the principle of energy conservation, the co-polar amplitude of the aperture field of the parabolic reflector is obtained by the reflection of the ray emitted by the ideal Gaussian feed with uneven energy distribution through the reflector surface will theoretically present distribution with the same taper as the feed, as shown by the black solid line in Figure 4a. Due to the influence of edge diffraction and the unevenness of the reflector surface, which ultimately leads to the simulated co-polar amplitude, there are some ripples on the principle cuts of the QZ.

Figure 4a shows the co-polar amplitude ripple under the illumination of an ideal Gaussian feed, and Figure 4b shows the co-polar phase ripple under the illumination of an ideal Gaussian feed. However, although the co-polar amplitude has a large ripple in the quiet zone, it can be seen from the numerical simulation results that the system still has high cross-polarization isolation, as shown in Figure 4c.

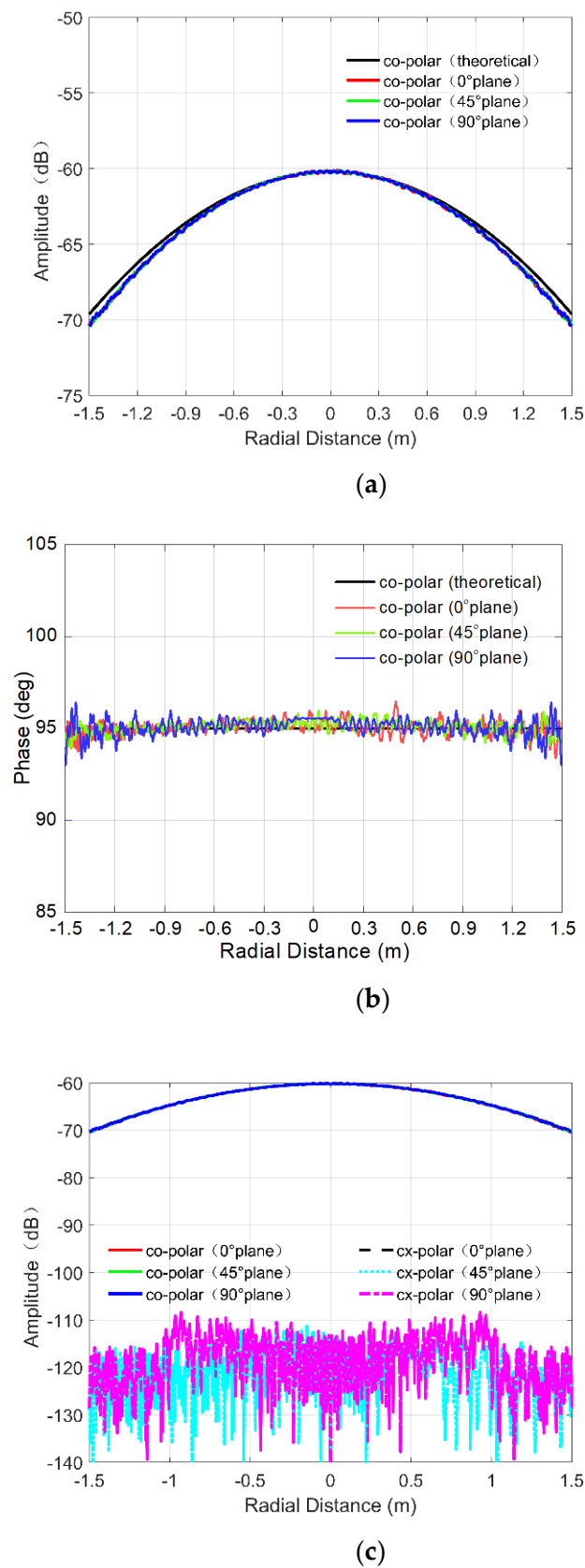


Figure 4. The simulated results of the designed tri-reflector compact antenna test range (CATR) with standard quadric surfaces when illuminated by an ideal Gaussian feed at 100 GHz. (a) Co-polar amplitude; (b) co-polar phase; (c) co- and cross-polar amplitude.

Therefore, in order to reduce the amplitude ripple in the quiet zone of the tri-reflector CATR and make the system achieve better QZ performance, according to the research and analysis of the electric field distribution in the focal region of the tri-reflector CATR [31] and the aperture field distribution of a parabolic reflector [32], here we use the $\cos^{-4}(\theta)$ function form with the radiation pattern truncated in the beam width $[-14^\circ, -12^\circ]$ and $[12^\circ, 14^\circ]$ interval as the feed pattern, which can compensate the aperture field of the parabolic reflector and obtain the pseudo-plane wave in the output aperture region. When the transmission loss is not considered, the co-polar amplitude of the aperture field obtained by the reflection of the parabolic reflector is a constant in theory, and at the same time, the optical paths of all rays transmitted from the feed to the aperture surface of the QZ are equal, so the QZ field theoretically has an even co-polar amplitude and phase distribution, as shown by the black solid line in Figures 5–7. Next, by substituting the discrete data of the designed feed into GRASP for numerical simulation, we can finally see that the amplitude ripple in the QZ of the designed tri-reflector CATR system has been greatly improved, and the aperture field of the tri-reflector CATR system is close to a uniform distribution within the range of the QZ. At the same time, since the geometric configuration of the tri-reflector CATR with standard curved surfaces is adopted, the low cross-polarization of the system is also obtained. Figures 5–7 demonstrate the simulated results of QZ performance on the principal cuts, which are summarized in Table 2.

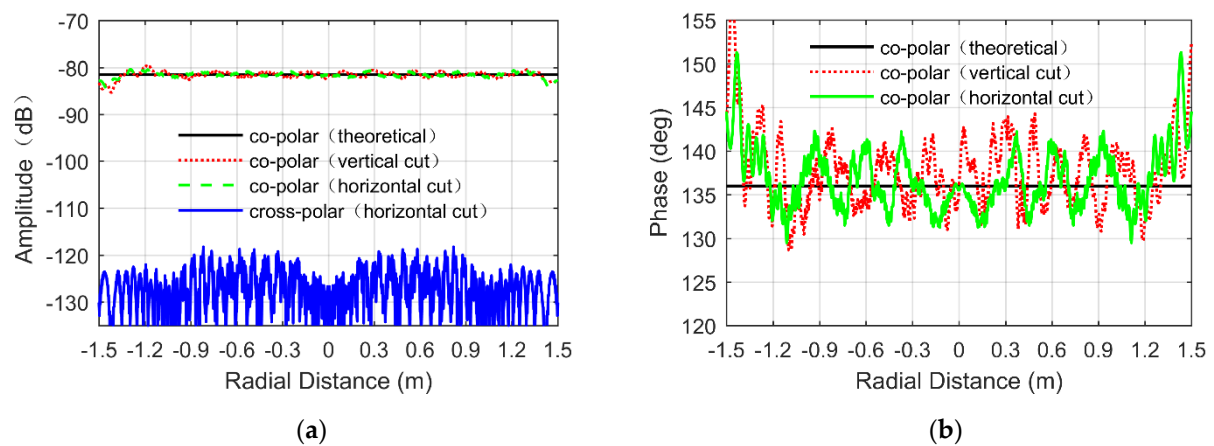


Figure 5. PO + PTD one-dimensional simulated results of the designed tri-reflector CATR with standard quadric surfaces when illuminated by a shaped feed at 100 GHz. (a) Co- and cross-polar amplitude; (b) co-polar phase.

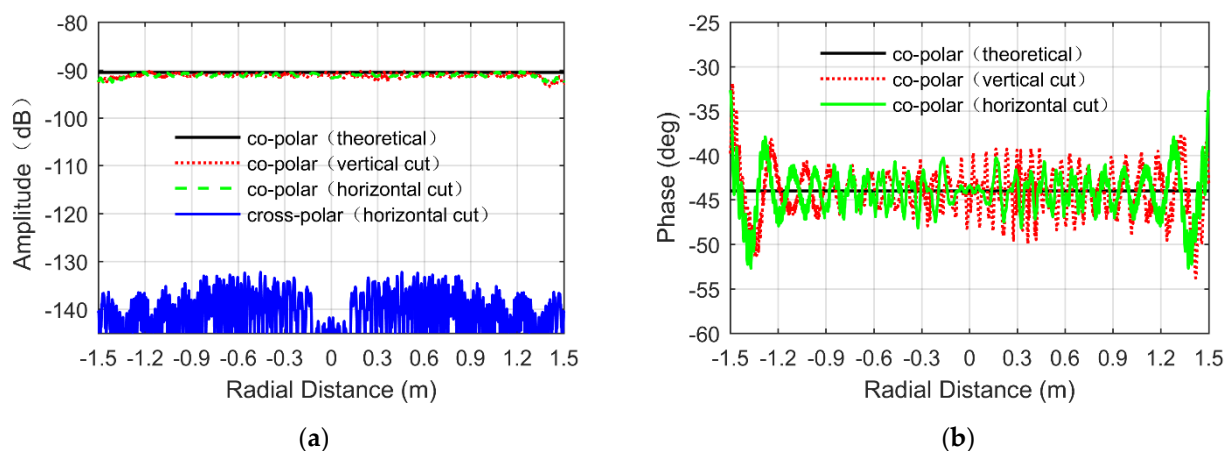


Figure 6. PO + PTD one-dimensional simulated results of the designed tri-reflector CATR with standard quadric surfaces when illuminated by a shaped feed at 300 GHz. (a) Co- and cross-polar amplitude; (b) co-polar phase.

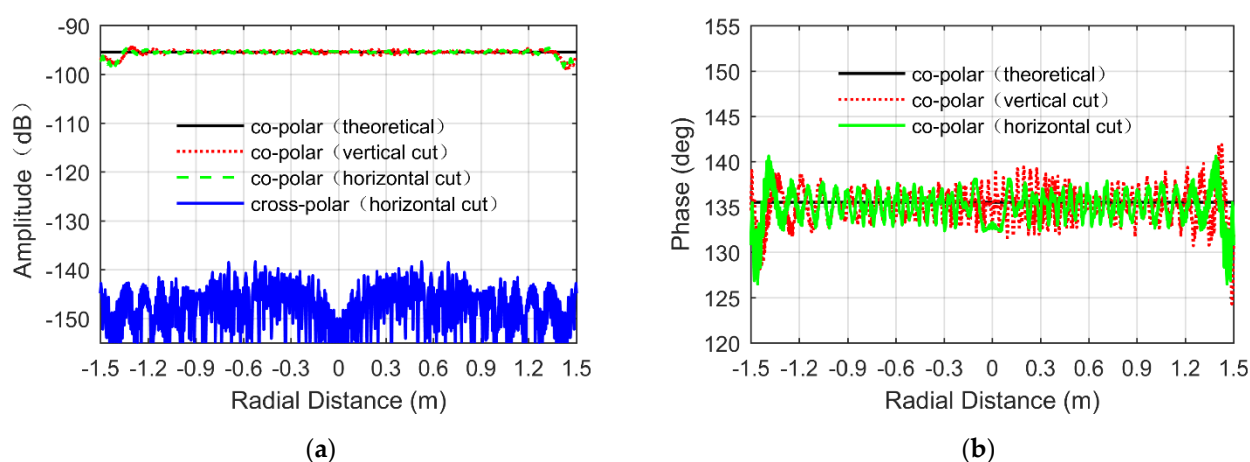


Figure 7. PO + PTD one-dimensional simulated results of the designed tri-reflector CATR with standard quadric surfaces when illuminated by a shaped feed at 500 GHz. (a) Co- and cross-polar amplitude; (b) co-polar phase.

Table 2. Quiet zone performance of the designed tri-reflector compact antenna test range (CATR) on principal cuts (quiet zone diameter 2.25 m).

Frequency (GHz)	Co-Polar Amplitude Ripple (dB)	Co-Polar Phase Ripple (°)	Cross-Polar Isolation (dB)
100	1.75	12.84	37.12
200	1.61	10.88	39.87
300	1.54	9.55	40.36
400	1.34	9.06	41.64
500	1.16	7.42	42.18

From the simulated results above, it can be seen that the peak-to-peak amplitude (phase) ripples are all within 1.8 dB (13°), and the cross-polarization isolations are all >37 dB on the principal cuts of the QZ. Because of the edge diffraction effect of the reflector surface, the co-polar amplitude and phase have a certain range of ripples at low frequencies, but as the simulation frequency increases, the edge diffraction effect gradually decreases, so the ripple gradually decreases, and the QZ performance is also gradually improved. At the same time, due to the application of the cross-polarization cancellation condition, the simulated cross-polarization component on the horizontal cut of the QZ is also suppressed to a certain extent, which made the proposed tri-reflector CATR system with standard quadric surfaces achieving a low cross-polarization. Table 2 shows the QZ performance of the designed tri-reflector CATR on principal cuts.

Finally, Table 3 lists the major performance between the proposed and the already reported CATR systems. Although the CATR system in [13–15] has no sub-reflectors, its structure is simple, the QZ usage ratio and cross-polarization isolation in [17,18] have been improved, and the size of the sub-reflectors in [20] is smaller, the proposed tri-reflector CATR system composed of two rotationally standard quadratic surface sub-reflectors has higher QZ usage ratio and cross-polarization isolation compared with the CATR in [13–15], and has a smaller size of sub-reflectors compared with the CATR in [17,18], and has higher cross-polarization isolation and simpler sub-reflectors processing technology compared with the CATR in [20]. At the same time, the proposed tri-reflector CATR system also has a higher operating frequency upper limit compared with all CATR systems mentioned in the above literature.

Table 3. Comparison between the reported compact antenna test range (CATR) systems and the proposed tri-reflector CATR system.

Ref.	Upper Frequency Limit (GHz)	QZ Usage (%)	QZ Diameter (m)	Size of Sub-Reflectors (m)	Cross-Polar Isolation (dB)
[13]	100	30	0.9		20
[15]	110	50	0.6		25
[17]	200	66	5	5.6	30
[18]	200	75	6	6.1	30
[20]	325	70	0.7	0.3 and 0.32	30
Proposed	500	75	2.25	0.27 and 0.25	37

4. Conclusions

In this paper, a tri-reflector CATR consisting of a parabolic main reflector and two sub-reflectors of rotationally standard quadric surfaces has been theoretically implemented and simulated at 100–500 GHz. By using the equivalent paraboloid method and cross-polarization elimination conditions, the proposed tri-reflector CATR achieves lower cross-polarization performance. At the same time, a shaped feed based on the aperture field distribution theory of the reflector is used to illuminate the CATR system, which greatly reduces the amplitude ripple of the QZ. The simulated results showing that the cross-polarization isolation is >37 dB on the principal cuts of the QZ, with a peak-to-peak amplitude (phase) ripple within 1.8 dB (13°), and the QZ usage ratio of the CATR has also reached 75%, which all show a better QZ performance. Since the QZ diameter of the proposed tri-reflector CATR system with a 3 m large aperture can reach 2.25 m, it can be used for the measurements in the large-aperture, high-performance antennas, and satellite payloads in millimeter-wave and terahertz band, which has the value and significance of engineering applications.

Author Contributions: Conceptualization, Z.L. and Y.Y.; methodology, Z.L. and Y.Y.; software, Z.L.; validation, Z.L., Y.Y., T.C., J.Y., and X.C.; formal analysis, Z.L.; investigation, Z.L.; resources, Z.L., Y.Y., T.C., J.Y., and X.C.; data curation, Z.L.; writing—original draft preparation, Z.L.; writing—review and editing, Y.Y., J.Y., and X.C.; visualization, Z.L.; supervision, Y.Y.; project administration, Y.Y.; funding acquisition, Y.Y. and J.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Fundamental Research Funds for the Central Universities.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Doyle, D.; Pilbratt, G.; Tauber, J. The Herschel and Planck Space Telescopes. *Proc. IEEE* **2009**, *97*, 1403–1411. [\[CrossRef\]](#)
- Rolo, L.F.; Paquay, M.H.; Daddato, R.J.; Parian, J.A.; Doyle, D.; De Maagt, P. Terahertz Antenna Technology and Verification: Herschel and Planck—A Review. *IEEE Trans. Microw. Theory Tech.* **2010**, *58*, 2046–2063. [\[CrossRef\]](#)
- Cooper, K.B.; Dengler, R.J.; Llombart, N.; Bryllert, T.; Chattopadhyay, G.; Schlecht, E.; Gill, J.; Lee, C.; Skalare, A.; Mehdi, I.; et al. Penetrating 3-D Imaging at 4- and 25-m Range Using a Submillimeter-Wave Radar. *IEEE Trans. Microw. Theory Tech.* **2008**, *56*, 2771–2778. [\[CrossRef\]](#)
- Harmon, S.A.; Cheville, R.A. Part-per-million gas detection from long-baseline THz spectroscopy. *Appl. Phys. Lett.* **2004**, *85*, 2128. [\[CrossRef\]](#)
- Tuovinen, J. Method for testing reflector antennas at THz frequencies. *IEEE Antennas Propag. Mag.* **1993**, *35*, 7–13. [\[CrossRef\]](#)
- Newell, A. Error analysis techniques for planar near-field measurements. *IEEE Trans. Antennas Propag.* **1988**, *36*, 754–768. [\[CrossRef\]](#)
- Jorgensen, R.; Padovan, G.; De Maagt, P.; Lamarre, D.; Costes, L. A 5-frequency millimeter wave antenna for a spaceborne limb sounding instrument. *IEEE Trans. Antennas Propag.* **2001**, *49*, 703–714. [\[CrossRef\]](#)
- Pistorius, C.; Clerici, G.; Burnside, W. A dual chamber Gregorian subreflector system for compact range applications. *IEEE Trans. Antennas Propag.* **1989**, *37*, 305–313. [\[CrossRef\]](#)
- Menzel, W.; Hunder, B. Compact range for millimetre-wave frequencies using a dielectric lens. *Electron. Lett.* **1984**, *20*, 768. [\[CrossRef\]](#)
- Säily, J.; Ala-Laurinaho, J.; Häkli, J.; Tuovinen, J.; Lehto, A.; Räisänen, A. Test results of 310 GHz hologram compact antenna test range. *Electron. Lett.* **2000**, *36*, 111. [\[CrossRef\]](#)

11. Lonnqvist, A.; Koskinen, T.; Hakli, J.; Saily, J.; Ala-Laurinaho, J.; Mallat, J.; Viikari, V.; Tuovinen, J.; Raisanen, A. Hologram-based compact range for submillimeter-wave antenna testing. *IEEE Trans. Antennas Propag.* **2005**, *53*, 3151–3159. [\[CrossRef\]](#)
12. Zhigang, L.; Dong, C. Research on improving CATR system design in test area. In Proceedings of the 2020 IEEE MTT-S International Wireless Symposium (IWS), Shanghai, China, 20–23 September 2020; pp. 1–3.
13. Parini, C.G.; Olver, A.D.; M, P.; Prior, C.J. The design, construction and use of a millimetrewave compact antenna test range. In Proceedings of the 1989 Sixth International Conference on Antennas and Propagation, ICAP 89 (Conf. Publ. No.301), Coventry, UK, 4–7 April 1989.
14. Shields, M. The compact RCS/antenna range at MIT Lincoln Laboratory. In Proceedings of the 2009 European Conference on Antennas and Propagation, Berlin, Germany, 23–27 March 2009; pp. 939–943.
15. Le Coq, L.; Fuchs, B.; Kozan, T.; Burgos, S.; Iversen, P.O. IETR millimeter-wave Compact Antenna Test Range implementation and validation. In Proceedings of the 2015 9th European Conference on Antennas Propagation, Lisbon, Portugal, 13–17 April 2015.
16. Smith, S.L.; Archer, J.W.; Timms, G.P.; Smart, K.W.; Barker, S.J.; Hay, S.G.; Granet, C. A Millimeter-Wave Antenna Amplitude and Phase Measurement System. *IEEE Trans. Antennas Propag.* **2012**, *60*, 1744–1757. [\[CrossRef\]](#)
17. Hartmann, J.; Fasold, D. Analysis and Performance Verification of Advanced Compensated Compact Ranges. In Proceedings of the 1999 29th European Microwave Conference, Munich, Germany, 5–7 October 1999. [\[CrossRef\]](#)
18. Schmidt, C.H.; Steiner, H.J.; Klett, S.; Garcia, H.; Forma, G. Quiet Zone Extension of an existing Compensated Compact Range 75/60. In Proceedings of the 2015 9th European Conference on Antennas Propagation, Lisbon, Portugal, 13–17 April 2015; pp. 12–16.
19. Lu, Z.; Chen, X.; Yao, Y.; Liu, X.; Yang, C.; Wang, H.; Yu, J. Modeling and simulation of a tri-reflector CATR system at 300GHz. In Proceedings of the IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Suzhou, China, 1–3 July 2015. [\[CrossRef\]](#)
20. Chen, X.; Liu, X.; Yu, J.; Yao, Y.; Yang, C.; Wang, H.; Liu, H.; Lu, Z.; Wylde, R. A tri-reflector compact antenna test range operating in the THz range. In Proceedings of the 2015 9th European Conference on Antennas Propagation, Lisbon, Portugal, 13–17 April 2015; pp. 3–5.
21. Yang, C.; Yu, J.; Yao, Y.; Liu, X.; Chen, X. Numerical synthesis of tri-reflector CATR with high cross-polarisation isolation. *Electron. Lett.* **2016**, *52*, 1286–1288. [\[CrossRef\]](#)
22. Furuno, T.; Urasaki, S.; Katagi, T.; Furuno, T.; Urasaki, S.; Katagi, T. Tri-reflector antennas eliminating cross-polarized component based on beam-mode analysis. *Electron. Commun. Jpn. (Part I Commun.)* **1996**, *79*, 55–64. [\[CrossRef\]](#)
23. Granet, C. Designing classical Dragonian offset dual-reflector antennas from combinations of prescribed geometric parameters. *IEEE Antennas Propag. Mag.* **2001**, *43*, 100–107. [\[CrossRef\]](#)
24. Mizugutch, Y.; Akagawa, M.; Yokoi, H. Offset dual reflector antenna. In Proceedings of the 1976 Antennas and Propagation Society International Symposium, Amherst, MA, USA, 11–15 October 1976; Volume 14, pp. 2–5.
25. Barkeshli, K.; Mazlumi, F.; Azadegan, R. The synthesis of offset dual reflector antennas by genetic algorithms. In Proceedings of the IEEE Antennas and Propagation Society International Symposium (IEEE Cat. No.02CH37313), San Antonio, TX, USA, 16–21 June 2002; Volume 1, pp. 670–673.
26. Brown, K.; Lee, Y.-H.; Prata, A. A systematic design procedure for classical offset dual reflector antennas with optimal electrical performance. In Proceedings of the IEEE Antennas and Propagation Society International Symposium, Ann Arbor, MI, USA, 28 June–2 July 1993. [\[CrossRef\]](#)
27. Rusch, W.V.; Prata, A.L.U.I.Z.; Rahmat-Samii, Y.; Shore, R.A. Derivation and application of the equivalent paraboloid for classical offset Cassegrain and Gregorian antennas. *IEEE Trans. Antennas Propag.* **1990**, *38*, 1141–1149. [\[CrossRef\]](#)
28. Dragone, C. Offset Multireflector Antennas with Perfect Pattern Symmetry and Polarization Discrimination. *Bell Syst. Tech. J.* **1978**, *57*, 2663–2684. [\[CrossRef\]](#)
29. Urasaki, S.; Makino, S.; Katagi, T. Tri-reflector antennas with no cross-polarized component. *Electron. Commun. Jpn. (Part I Commun.)* **1985**, *68*, 85–92. [\[CrossRef\]](#)
30. Yao, Y.; Cao, Y.; Liu, Y.; Yu, J.; Chen, X. Design and implementation of THz ultra Gaussian corrugated feed horn. In Proceedings of the 2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS), Beijing, China, 16–23 August 2014; pp. 1–4.
31. Yang, C.; Yu, J.; Yao, Y.; Liu, X.; Chen, X. Novel Corrugated Matched Feed for Cross-Polar Cancellation in Tri-Reflector Compact Range. *IEEE Antennas Wirel. Propag. Lett.* **2014**, *13*, 1003–1006. [\[CrossRef\]](#)
32. Wang, J.; Yao, Y.; Liu, X.; Qi, L.; Chen, Z.; Yu, J.; Chen, X. Enhancing reflector aperture usage efficiency using a coaxial cavity antenna: Application to compact antenna test range. In Proceedings of the 2017 10th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies (UCMMT), Liverpool, UK, 11–13 September 2017; pp. 1–3. [\[CrossRef\]](#)