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Experimental Evaluation of 92–100 GHz Millimeter-Wave Radar Using Trihedral Corner Reflectors for Airport Runway Safety

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Abstract: This paper presents an experimental study on the use of triangular trihedral corner reflectors (TTCRs) for evaluating the performance of millimeter-wave radar systems operating in the 92–100 GHz frequency range. The experiment was conducted at Runway 2 of Kuala Lumpur International Airport under clear weather conditions using a Frequency Modulated Continuous Wave (FMCW) radar operating at 93.1 GHz. Three TTCRs of varying sizes were deployed as passive targets to investigate their Radar Cross Section (RCS) responses. The study examines the influence of radar incident angles, transverse slope, and reflector geometry on the backscattered signal strength. The experimental findings provide valuable insights into the reflectivity characteristics of TTCRs offering a practical reference for radar calibration and performance validation in airport runway environments.

Keywords: Airport Runway, FMCW Radar, Millimeter-Wave, Radar Cross Section, Trihedral Corner Reflector

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1. INTRODUCTION

Foreign Object Debris (FOD) remains a critical safety concern in modern airport operations with the potential to cause significant damage to aircraft and jeopardize the safety of ground personnel. FOD is defined as any object located in an inappropriate area of the airfield that may interfere with flight operations [1]. The global aviation industry incurs substantial economic losses due to FOD-related incidents, estimated at approximately USD 3-4 billion annually [2, 3].

To mitigate these risks, the International Civil Aviation Organization (ICAO) mandates routine runway inspections typically four times daily as outlined in Annex 14 [4]. However, manual inspection procedures are time-consuming, labour-intensive, and prone to human error, making them inefficient for continuous surveillance [5, 6]. These limitations have prompted increased interest in automated detection systems capable of operating in real time around the clock.

Millimetre-wave radar systems, particularly those employing Frequency-Modulated Continuous Wave (FMCW) technology, have been widely recognized for their suitability in FOD detection applications. These systems offer high spatial resolution, robust target detection, and resilience to adverse weather conditions [7-11]. Nevertheless, performance evaluation of such radar systems within actual airport environments remains a complex task due to environmental influences including ground structures and runway geometry.

Of particular relevance is the transverse slope of airport runways typically designed at 1.5% for a standard 60-meter width as recommended by ICAO. While necessary for effective drainage, this slope introduces angular variations that can affect radar signal incidence and backscatter behaviour. Accurate characterization of radar performance under such conditions is therefore essential for system calibration and reliability assessment.

Trihedral corner reflectors (TCRs), particularly in triangular configurations have long been established as reliable passive calibration targets for radar measurements. Their rigid structure, geometric stability, and high reflectivity especially when fabricated from conductive materials such as aluminium make them well-suited for high-frequency radar calibration [12]. The Radar Cross Section (RCS) of such reflectors plays a crucial role in quantifying the radar's backscattering response and overall detection capability.

This study presents an experimental characterization of a 92–100 GHz FMCW radar system using triangular trihedral corner reflectors (TTCRs) of three different sizes (0.1 m, 0.2 m, and 0.3 m) as calibration targets. The field measurements were conducted at Runway 2 of Kuala Lumpur International Airport (KLIA) under clear weather conditions to minimize signal attenuation. The experimental campaign aims to analyse the RCS response across varying reflector sizes and positions providing practical insight into the radar's detection behaviour in a real-world airfield environment.

The remainder of this paper is structured as follows: Section 2 details the experimental setup and methodology. Section 3 discusses the measurement results and analysis. Finally, Section 4 concludes the study with key findings and future recommendations.

2. EXPERIMENTAL SETUP

2.1 Specification of Radar System

The radar system employed in this experimental study is the ESF-R1LC/FT model developed by Kokusai Denki Electric Inc., Japan. This system is specifically designed for FOD detection applications in airport environments. It operates using a millimetre-wave Frequency-Modulated Continuous Wave radar technique with a central operating frequency of 93.1 GHz. The high-frequency operation enables enhanced resolution and sensitivity for detecting small objects on runway surfaces.

The technical specifications of the radar system are summarized in Table 1. The system is installed on a fixed Radar Antenna Unit (RAU) and is configured to scan the runway environment continuously. Its millimetre-wave capability offers strong resistance to environmental interference such as rain, dust, and fog making it suitable for continuous surveillance under varying atmospheric conditions.

Table 1. Specification of FOD detection system.

No.	Parameters	Values
1.	Center frequency	93.1
2.	Signal Type	FMCW
3.	Channel bandwidth (GHz)	580
4.	Antenna type	Cassegrain
5.	Tx/Rx Antenna Gain (dB)	41.7
6.	Antenna height (m)	4-8
7.	Antenna rotation speed (rpm)	15
8.	Detection distance (m)	200-500

2.2 Measurement Procedure

The experimental characterization of radar backscatter was conducted at Runway 2 of KLIA, focusing on the detection performance of a millimetre-wave radar system using TTCRs as FOD targets. The experiment utilized the FMCW radar unit mounted on Radar Antenna Unit 2-3 (RAU 2-3), which operates at a central frequency of 93.1 GHz.

The RAU 2-3 tower is situated approximately 187 meters from the runway centreline, a location selected to account for existing ground structures and the transverse slope of the runway. For this study, the TTCRs were aligned orthogonally (90°) relative to the RAU 2-3 tower to ensure consistent radar illumination. Nine identical TTCRs were arranged in a 3×3 grid with 10-meter spacing between each unit. The positions were labelled P1 through P9 and measured individually. Positions P1 to P3 were placed closest to the RAU tower, P4 to P6 aligned along the runway centreline and P7 to P9 were placed on the far side of the runway opposite the RAU. The central reference point in the grid P5 was used as the alignment benchmark.

Each measurement began with the TTCR oriented at 0° directly facing the radar source. The radar system then performed a full 360° azimuthal scan to capture backscatter data. Subsequently, the reflector was manually rotated through twelve discrete angles from 30° to 330°, in 30° increments to capture angular-dependent RCS variations as depicted in Figure 2. This measurement sequence was repeated for three TTCR sizes: 0.1 m, 0.2 m, and 0.3 m to evaluate size-dependent reflectivity characteristics.

An overview of the experimental site including the RAU 2-3 location and TTCR placement positions is shown in Figure 1 using satellite imagery for contextual reference.

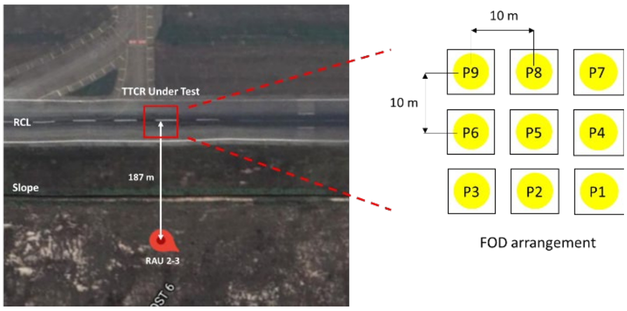

Figure 1. Satellite map view of the experimental site of RAU 2-3 and the positioning layout of the TTCR for all measurement points.

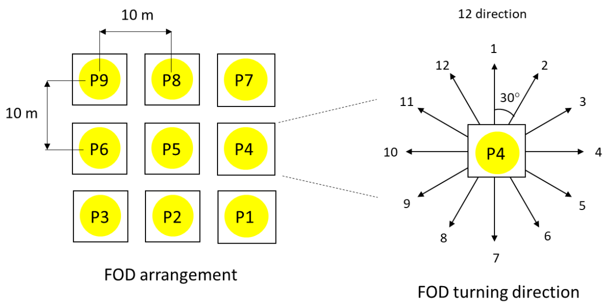

Figure 2. FOD arrangement and twelve turning points.

The measurements focused on evaluating the RCS of TTCRs at nine distinct positions across the runway with particular attention to how placement relative to the runway slope influences the radar return. The RCS is quantified based on the strength of the backscattered signal received by the radar relative to the incident power density. This metric is inherently dependent on several factors, including the operating frequency, target orientation (aspect angle) and the polarization of the incident wave [13].

In the case of trihedral reflectors, the reflected signal is also influenced by the radar wavelength and the reflector's edge length. Therefore, to investigate size-dependent performance of three TTCR sizes 0.1 m, 0.2 m, and 0.3 m were selected for characterization.

Figure 3 provides a detailed side-view representation of the TTCR deployment illustrating the spatial relationship between the radar system and the reflectors positioned across the runway surface.

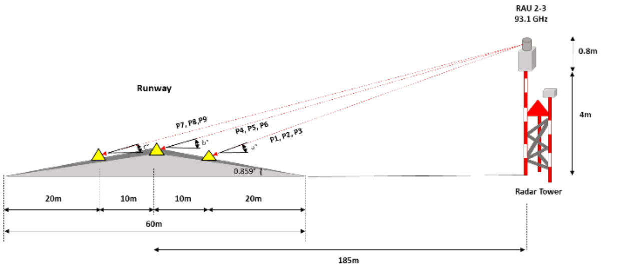

Figure 3. TTCR measurement setup on runway (side view).

The three primary range placements from the RAU 2-3 tower to the TTCR array are set at 177 m, 187 m, and 197 m respectively. These distances were chosen to evaluate the radar's sensitivity and response to variations in range and slope within an operational runway environment. The experimental evaluation aims to validate the suitability of TTCRs as calibration targets for small object detection in millimetre-wave radar systems by correlating their RCS performance against the incident radar power density.

3. RESULTS AND DISCUSSION

The radar characterization experiments were successfully conducted for three different sizes of TTCRs. The measured RCS values were analysed corresponding to reflector sizes of 0.1 m, 0.2 m, and 0.3 m respectively as shown in Figure 4, 5 and 6.

From the analysis, it was observed that the RCS values increased progressively as the TTCRs were positioned from the nearest placement points (P1, P2, P3 at 177 m) toward the centreline of the runway (P4, P5, P6 at 187 m). This trend is attributed to the favourable radar-target geometry and alignment at mid-range distances. However, a noticeable reduction in RCS was recorded at the farthest placements (P7, P8, P9 at 197 m), likely due to increased signal path loss and slight misalignments introduced by the runway's transverse slope and reflector orientation.

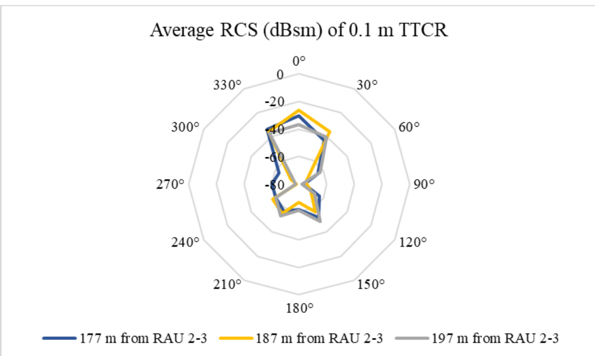

Figure 4. Radar chart of average RCS for 0.1 m TTCR.

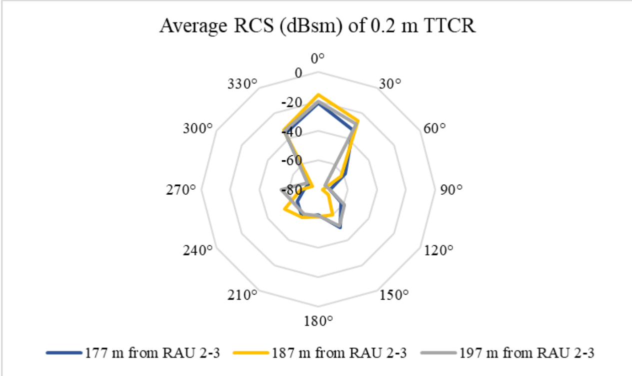

Figure 5. Radar chart of average RCS for 0.2 m TTCR.

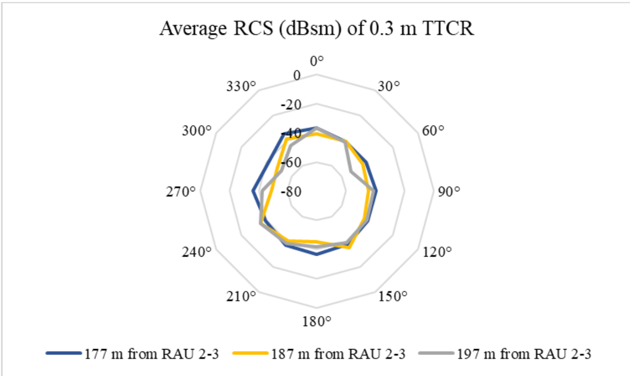

Figure 6. Radar chart of average RCS for 0.3 m TTCR.

Inconsistencies were also observed in specific angular orientations particularly at 90°, 270°, and 300° for the smaller TTCR sizes (0.1 m and 0.2 m). These anomalies are likely due to the reduced radar cross-sectional area presented to the radar at certain angles which becomes more prominent as the physical size of the reflector decreases. The effect is less significant for the 0.3 m TTCR whose larger surface area maintains higher reflectivity across the full range of rotational angles.

Given the TTCRs were rotated through twelve angular positions (from 0° to 330° in 30° increments), the apparent shape and effective reflective area of the reflector varied from the radar's point of view. This angular variation directly influenced the RCS measurements reinforcing the importance of both size and orientation in radar target characterization.

Overall, the results validate the suitability of TTCRs for evaluating the detection capabilities of high-frequency FMCW radar systems under realistic runway conditions. The findings suggest that larger reflector sizes yield more stable and reliable RCS measurements across various distances and orientations, making them more effective as reference targets in radar calibration for FOD detection.

4. CONCLUSION

This study presented an experimental characterization of a 92–100 GHz FMCW radar system using TTCRs as passive calibration targets for potential FOD detection on airport runways. Measurements were conducted at Runway 2 of KLIA, with TTCRs of three sizes (0.1 m, 0.2 m, and 0.3 m) deployed at varying distances and orientations relative to the RAU 2-3.

The results demonstrate that the RCS is influenced not only by the size of the reflector but also by the reflector's angular orientation and placement along the runway slope. The 0.3 m TTCR consistently exhibited higher RCS values and more distinct angular patterns making it the most effective among the three sizes for high-frequency radar calibration. The radar charts further confirmed the presence of repeatable patterns across reflector placements highlighting the suitability of TTCRs in performance evaluation tasks.

Despite minor fluctuations in signal strength due to orientation or environmental factors, the experimental data revealed a consistent and interpretable relationship between RCS and reflector positioning. These findings reinforce the viability of TTCRs for validating radar system performance in realistic airfield conditions particularly for enhancing automated FOD detection capability.

Future work may extend this study by incorporating adverse weather conditions varying radar elevation angles and surface materials to further evaluate the robustness of millimetre-wave radar systems under operational constraints.

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REFERENCES

[1] Zhang, H., *The current status and inspiration of FOD industry in international civil aviation.* Civ. Aviat. Manag, 2015. **295**: p. 58-61.

[2] SRI, I., *The economic cost of FOD to airlines.* 2008.

[3] Wang, X., et al. *A practical application of runway Foreign Object Debris detection system at the airport*. in *2018 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*. 2018. IEEE.

[4] T. E. Organisation, C.A.E., O. Europ, and A. Civile, *Minimum Aviation System Performance Specification for Foreign Object Debris Detection System, no. ED-235.* 2014.

[5] Alathari, B., et al., *A framework implementation of surveillance tracking system based on PIR motion sensors.* Indonesian Journal of Electrical Engineering and Computer Science, 2019. **13**(1): p. 235-242.

[6] Fizza, G., Idrus, S. M., Iqbal, F., Hassan, W. H. W., Shibagaki, N., Kashima, K., ... & Kawanishi, T. , *Line of sight visibility analysis for foreign object debris detection system.* In Journal of Physics: Conference Series, 2021. **1878**: p. 012006.

[7] Kawanishi, T., A. Kanno, and N. Yamamoto. *Concept of sensor over fibres and its application to high resolution millimetre-wave radar*. in *2017 19th International Conference on Transparent Optical Networks (ICTON)*. 2017. IEEE.

[8] Kawanishi, T., Miura, T., & Inagaki, K., *Mitigation of interference mitigation in RoF-based linear cell radar system.* In Asia Communications and Photonics Conference, 2019: p. T3E-3.

[9] Miura, T., et al., *FMCW linear cell radar interference mitigation through control of signal delay in radio-over-fiber links.* ieice electronics express, 2020. **17**(15): p. 20200228-20200228.

[10] Kawanishi, T., A. Kanno, and N. Yamamoto. *90-GHz linear-cell systems for public transportation systems*. in *2018 20th International Conference on Transparent Optical Networks (ICTON)*. 2018. IEEE.

[11] Kim, Y.-B., et al., *Fixed and Moving Automatic FOD Detection Test using Radar and EO Camera.* Journal of Advanced Navigation Technology, 2020. **24**(6): p. 479-484

[12] Algafsh, A., M. Inggs, and A.K. Mishra. *The effect of perforating the corner reflector on maximum radar cross section*. in *2016 16th Mediterranean Microwave Symposium (MMS)*. 2016. IEEE.

[13] Malachias, N., et al. *Design and Experimental Evaluation of a Novel Type Radar Reflector for use in the Marine Environment*. in *Conference Proceedings of ICMET*. 2019.