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A systematic review of radar technologies for surveillance of foreign object debris detection on airport runway

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ABSTRACT

Flights are projected to reach eight billion globally by 2037, demanding airport operators manage operations effectively, including safety on the runway due to the high number of aircraft movements. One crucial issue is any foreign object, commonly known as foreign object debris (FOD), that must be detected and cleaned immediately to ensure aircraft safety when taking off, landing, and taxing. The International Civil Aircraft Organization (ICAO) reported that FOD causes 10.08% of aviation accidents. Most airports manually monitor and detect FOD, which could be more effective and dangerous. Therefore, it is important to provide FOD detection systems with proper technologies. Radar technologies are potential FOD detection techniques that offer robustness to weather fluctuation. However, some factors must be considered properly to provide an effective FOD system. This paper reviews radar technologies for FOD detection on airport runways by considering factors, including types of debris, detection coverage, mode of radars, frequencies, and attenuation. It was found that all critical factors considered contribute to the quality of detection. This paper will provide guidelines for developing FOD detection based on radar technologies regarding airport necessities and its specific environment.

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1. INTRODUCTION

According to data from the International Air Transport Association (IATA), 8.2 billion travellers will use flight services in 2037, double the number from 2018 [1]. This increasing number corresponds to the needed number of flights that should also be anticipated by aviation stakeholders, including aircraft manufacturers, airport operators, airline companies, and governments as transportation regulators. Even though the flight number may fluctuate in some areas due to unexpected factors, for example, in Europe from 2020 until mid-2022, impacted by the Covid-19 pandemic, the number of flights has been remaining an upward trend for Asia, Latin America, and parts of Africa because of logistic purposes more increasing in that period [2]. The post-pandemic, which started at the end of 2022 in most countries, has recovered aviation industries, impacting the trend of flights back to normal.

The increasing number of flights impacts activities at the airport, such as airport operations, flight schedules, security checks, safety procedures, and providing supporting facilities. In most airports, passengers must be checked through the security checkpoint before entering airport buildings and boarding the plane before takeoff to avoid hidden weapons, illegal drugs, or other unpermitted or dangerous goods brought on the plane. These procedures are essential to ensure passengers safety on board from any possible crime incidents.

Another crucial safety concern for passengers on board and individuals in nearby areas of the airport, covering the management of takeoff, flight, landing, taxing, and aircraft maintenance, should be properly taken seriously to mitigate the occurrence of accidents and minimize the number of victims. Aircraft maintenance should be conducted routinely every 20 to 24 months or 6000 flight hours to ensure the aircraft's condition. Airport aircraft movement is related to the runway, taxiway parking, and apron area. Those areas must be monitored and maintained from objects that can endanger an aircraft. Possible sources of unwanted objects can come from activities supporting airport operations, such as baggage handling, catering, aviobridge, marshaller, and refuelling. The staff on duty must follow the procedures and safety standards to avoid any object left behind. Any objects left on the runway's surface must be removed immediately to minimize accidents and ensure safety.

A foreign object debris (FOD) is any debris that can result in an aircraft accident. An example is the French Concorde airliner that exploded in 2000 after takeoff due to a bold fuel tank hit [3]. Accidents that occur on the runway affect not only aircraft engines but also on-site airport officers. Accidents caused by FOD damage aircraft and airport infrastructure and cause flight delays that cost the airline business up to 4 billion in a year [4]. Therefore, any FOD must be monitored and handled immediately to prevent fatal accidents. A prevention system must be established, including technical monitoring and cleaning of any FOD found in runways. Airport officers are part of the FOD detection on airport runways to follow regulations related to the search for FOD, countermeasures, and use of technology [5]. Reducing the impact of FOD is mostly conducted with airport staff walking along the runway or utilizing vehicles with magnetic strips to catch any metal debris [6]. The manual method is less successful and risky for staff, and it is only possible if the weather is good and there are no frequent flights. Non-metallic objects that are detectable and accessible within the runway area must be immediately collected and appropriately removed.

Determining and developing accurate FOD detection technology that can work must follow the requirements standardized by regulations such as the Federal Aviation Administration (FAA). According to FAA regulations, radar detections must detect minimum debris-size golf balls [7]. Another The European Organisation for Civil Aviation Equipment–Document (EUROCAE-ED) standard from WG-83 specifies the kinds and sizes of items on the runway that fall into the six FOD categories that are compliant with FAA standards [8]. Meanwhile, the International Telecommunication Union (ITU) regulates frequency spectrums for FOD radar between 24 GHz and 100 GHz (ITU-R).

Recently, several airports have implemented technologies to detect FOD using radar, cameras, and hybrids [9]. FOD hybrid systems can be developed by using ultrasonic sensors, cameras, radar, and device methods to eliminate FOD on airport runways. The ultrasonic sensor offers the advantage of finding FOD with good location accuracy but is not weather-resistant [10]. The camera can visually identify FOD shapes but is limited in visibility due to night and weather conditions, especially rain [11]. However, applying a camera system requires a more complicated system, specifically computer vision, which automates the process of object classification [12]. The most common classification method employed in computer vision is you only look once (YOLO) to help staff identify the specific category of debris observed over the camera [13]. Although YOLO is effective for debris classification, it exhibits lower accuracy when detecting metal debris. Deep convolutional neural networks (DCNN) effectively classify metal debris of different forms, sizes, and colours [14]. Radar offers weather resistance and always works, but it is weak in determining the object type. The hybrid system takes advantage of all components to provide an optimum performance to detect FOD [15]. However, it demands high costs due to complexities and components [16].

Among technologies for FOD detection, radar-based millimeter-waves (mmW) have attracted attention due to their advantages over the lower radio waves in terms of wavelength, which can provide reasonable detection for FOD [17]. Radar technologies, specifically mmW radar, are highlighted due to their high-resolution capabilities, ability to operate in any weather, and high positioning accuracy. It operates at mmW frequencies and utilizes frequency modulated continuous wave (FMCW) radar for optimal precision [18]. The FOD detection based on mm radar technologies is promising to detect FOD due to its robust environment and affordable. The high positioning, sensitivity to small FODs, and accuracy in terms of distance and angle make radar an ideal technology for such a detection system. Furthermore, FMCW radar at mmW frequencies provides high resolution.

This paper systematically reviews radar technologies for airport runway detection by considering technical methods and environmental characteristics. The technical considerations include the type of runway, the type of radar system, the type of FOD, the placement of the radar system, and the performance parameters of a radar system. Assessing a comparison of radar performance will utilize indicators such as frequency, radar mode, and attenuation to approach those performance metrics.

a. Classification foreign object detection

FOD is characterized based on location, as illustrated in Figure 1. There are three FOD classifications based on location: ground, space, and airborne. In this paper, only FOD based on the ground is discussed. FOD ground area or runway area FOD can be caused by the environment, such as wildlife or animals around the runway, and bad weather that causes unwanted objects to be carried onto the runway. Aircraft activities in the runway area cause maintenance equipment, flight crew equipment, pieces of luggage, and even catering items to be left behind. Furthermore, finally, the activities that occur at the airport, construction work that is around the runway, which can accidentally cause FOD, broken concrete around the runway area, gravel or sand that is accidentally carried by the incoming wind, and wild plants that are accidentally carried by the wind enter the runway.

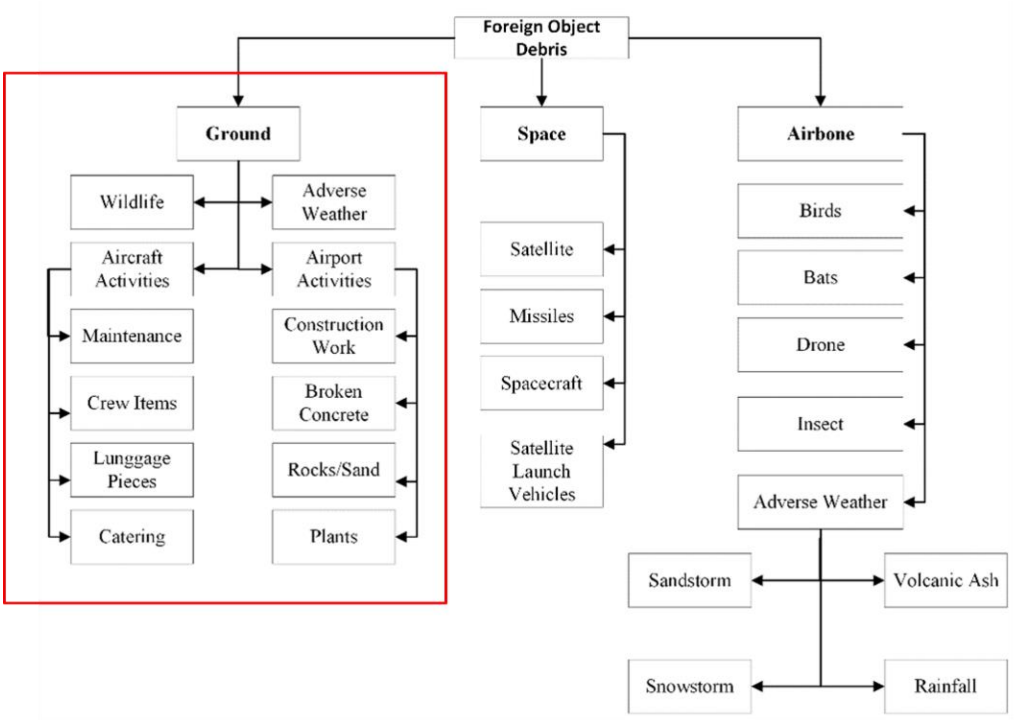


Figure 1. FOD classification diagrams

b. Radar waveform

Various studies on FOD detection using radar show several forms of radar waves, including continue wave, FMCW, and synthetic aperture radar (SAR).

– Radar FMCW

Continuous transmission of high-frequency signals is configured for the continuous wave. The echo signal is constantly received and processed by preventing the direct signal destination from entering the receiver and determining the received echo in the time domain, and it can be measured over time. In general, the system sends signals continuously, and objects reflect echoes. If the object moves, the echo frequency will be different when transmitting the signal due to the doppler effect. By detecting the echo, the movement of objects can be known as radar detecting the echo. Continuous waves are typically used for low-cost, short-range, and radar applications, for example, speed guns, battlefield surveillance, and aircraft detection. With a doppler effect, the echo that returns to the radar is effectively compressed by moving objects. The faster the object, the greater the compression of the wavelength and an increase in the doppler frequency shift occurs. The concept discussed earlier is known as an unmodulated continue wave, which uses a tone to measure the doppler shift of a moving object. Unmodulated continue waves cannot be detected.

Stationary or static objects because the distance becomes ambiguous for the wavelength. This limitation can be corrected by modulating the sending signal. For example, the delivery frequency changes linearly with time. This way, changes in frequency values reflect changes in time delay and can describe changes in the distance; this type is called a FMCW. The time delay between the sending frequency and the echo signal frequency at any time is proportional to the object's distance.

A compact and cost-effective method for detecting FOD using an FMCW radar sensor operating between 73 GHz and 80 GHz was developed for FOD detection applications. It has excellent exposure and can simultaneously detect numerous objects [19]. Enhancing the system's performance and range by detecting FOD at 78 GHz using two distinct folded reflect array antennas with a cosec-shaped pattern has been implemented [20]. Mehdi and Miao [21] presented the design of a 26.5 GHz to 40 GHz FMCW radar for detecting FOD items and a low-cost FOD sensor using commercially available components. Other research on FMCW at frequencies 92.8 GHz to 93.4 GHz study explores methods to increase the detection sensitivity of the 90 GHz band mmW radar based on airport field evaluations [17]. As the prior study continues, this work investigates the possibility that clutter in obstructions degrades the detection performance of the FOD detection system, particularly for detecting small radar cross section (RCS) targets [18], [22]. Meanwhile, examines methods to increase the detection sensitivity of mmW radar in the 90 GHz region [23].

– SAR FMCW

SAR is similar to conventional radar; electromagnetic waves are successively sent using SAR, and the radar antenna then collects reflected echoes. SAR sensors are unique because they use frequency modulation in the form of pulse waves, often known as chirp signals. The chirp signal is the amplitude whose waveform is conveyed continuously during a time pulse, with variations in frequency. While the radar records the refracted echoes and keeps the received signal on board, it generates an echo window. At any time t, the distance between the radar movement, at a constant speed, and the target on the ground is described at coordinates (x, y, and z). SAR is a partial sampling system in a fixed area. It makes a signal processing method to convert measurements into reflectance estimates of multiple pixels, which can be finalized as desired. SAR can be implemented in remote sensing, military, and planetary exploration. SAR modes, in general, are strip map and spotlight. What makes the difference is the way it gets the data it collects and processes. The merging angle, where the data is collected, is called the integration angle. SAR systems generally obtain down-range resolution consistent with the inverse of the transmission waveform bandwidth and cross-range resolution that is proportional to the ratio of the signal wavelength to two times the integration angle. SAR is a high-resolution imaging device that operates robustly to weather.

However, the vast majority of SAR cannot detect moving targets. On the SAR image, only objects that are out of focus can be placed [24]. The paper discusses a spotlit circular SAR (SC-SAR) system designed for imaging small and weak objects on the ground. Among its potential applications is the identification and localization of FOD on runways [25]. The arc synthetic aperture radar (ArcSAR) system scans the surrounding area using an antenna attached to a rotating radome that extends from the platform's centre. ArcSAR can scan 360-degree scenes in a single pass, effectively expanding the field of vision. The approach suggested in this research uses interferometric ArcSAR to extract the digital elevation model (DEM) from scenes. The derived DEM is used to help with ArcSAR imaging [26]. The paper describes ArcSAR, which enhances the detection range to the same target twice to three times and successfully suppresses "flickering" clutters like rain and snow [27].

c. Range radar

Various studies related to FOD detection using radar based on the ability of the radar range. The classification of radar systems on distance, azimuth angle, and elevation considerations has three categories: short-range radar, medium-range radar, and long-range radar. The short-range radar has a range of 20 m to 60 m, an azimuth angle of approximately 80°, and an elevation angle of approximately 10°. The radar range of the medium range is between 75 m and 100 m, with an azimuth angle of around 40° and an elevation angle of about 5°. The long range is more than 200 m, the radar range's azimuth angle is approximately 15°, and the radar range's elevation angle is approximately 5°.

2. METHOD

This research adopts the review method of protocol, search, appraisal, data synthesis, analyze, report (PSALSAR) as in Figure 2, which consists of six steps to obtain comprehensive information.

a. The first step is protocol, which defines the limitations of the research topic. This research limits the topic to FOD radar, especially on runway-related issues.
b. The second step is search, which is searching for literature material by selecting prominent research databases and keywords that are most related to the research. Research materials were obtained by searching papers on IEEE Explore, and the papers obtained were of various types, such as journals and proceedings. The keywords used are FOD radar, runway, debris, radar cross-section, and range.
c. The third step is appraisal, which is selecting papers from the search process based on the quality of the paper. Papers obtained from the search process were selected based on the Scopus index scale and number of citations. The papers chosen are papers with a high Scopus index and many citations.
d. The fourth step is data synthesis, which is a collection of data that has been categorized and separated. The selected paper data is categorized based on the year of publication, radar type, coverage distance, FOD size, and frequency used. Additionally, the technology that is used or implemented is recognized and evaluated.

e. The fifth step is analysis, which is analyzing previous processes. The search data results are processed and analyzed by creating a table containing information on runway classification, FOD type, radar type, and attenuation comparisons for different frequencies. The articles that were categorized followed a thorough analysis, and the findings of this analysis can be presented in the form of narrative paragraphs and tables. In this step, an analysis was conducted on trend analysis and the technological gap.
f. The sixth step is reporting, which is the final process of writing reports and conclusions from research. The analysis result was finalized in this step, and the report could be used as an idea article for a wider audience. The article mentioned above outlines the study report and its concluding remarks.

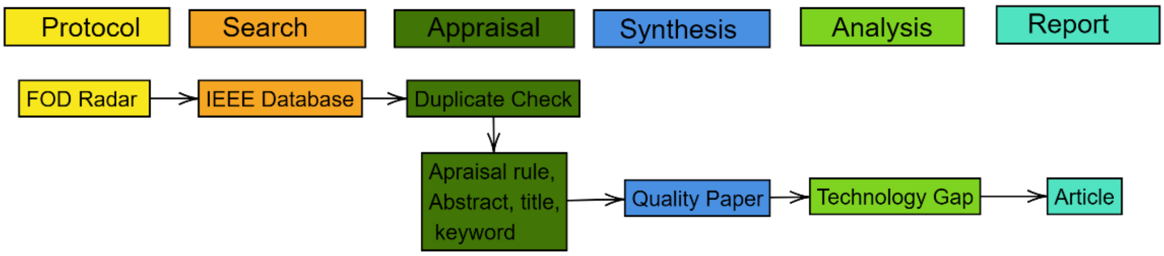


Figure 2. The PSALSAR method

3. RESULT AND DISCUSSION

3.1. Radar coverage for foreign object debris

The FOD radar range coverage has ranged from 20 m to 500 m [17], [23], [28]. The frequency and the RCS of the FOD object's size impact this in use. The larger the debris and object size, the farther away an item can be identified. Based on the FAA, several types of runways are classified into six, as shown in Table 1 [29], [30]. With this classification, the type of FOD radar suitable for use can be determined based on the length and width of the six existing runways.

Table 1. Classification runway

No	Aircraft	Length runway minimum (m)	Width runway minimum (m)
1	Small aircraft (speed less than 30 knots)	92	30
2	Small aircraft (speed more than 30 less than 50 knots)	244	30
3	Small aircraft (speed more than 50 knots, maximum takeoff weight 5,670 kg)	914	30
4	Small aircraft with fewer than ten passenger seats	823–975	45
5	Small aircraft with more than ten passenger seats	1,341	45
6	Large aircraft (takeoff weight of more than 5,670 kg up to 27,200 kg)	2,439	60

The EUROCAE-ED standard from WG-83 defines six classifications of objects called FOD on the runway that comply with FAA regulations and provides information on objects types and sizes, as shown in Table 2 [23]. These dimensions serve as a basis for further research in detecting smaller objects or identifying more specific objects. The runway has variations in length and width, length from 92 m up to 2,439 m and width from 30 m to 60 m. This variation relates to number radar; for example, radar with coverage of 30 m will result in different small runways compared to large runways, as shown in Table 1. Increased length runway will need more radar numbers. The deployment method shown in Table 3 divides existing FOD detection systems into three categories: tower, edge-light, and mobile types [31].

Table 2. Type of FOD sample specified by EUROCAE-ED-235

No	FOD sample	Dimension
1	Tire fragment	Height: 5 cm and width: 5 cm
2	Light	Diameter: 8.8 cm
3	M10 bolt and nut	Length: 4 cm
4	Fuel cap	Diameter: 4 cm and height: 1.5 cm
5	Chunk of concrete	Length: 4 cm
6	Piece of metal	Height: 7 cm and width: 5 cm

Table 3. Type of radar FOD detections system

Radar FOD detection system	Advantages	Disadvantages
Tower type	– The small number of detectors (coverage 300 m to 1000 m) – Lower price for the total system – Easy maintenance	– Easily affected by weather environment – The detection rate is average
Edge-light type	– Less affected by weather environment – The detection rate is good	– More number detectors (coverage of 60 m) must be installed on both sides – Need close-range installation – Installation and maintenance are overall high
Mobile	– Low-cost and can be used in multiple areas – Movable radar – Can scan, detect, and clean	– Cannot monitor real-time – Must close during detection – Only suitable for small airports or military ports

3.2. Foreign object debris detection research and development

Several frequency variations, ranging from 24 GHz to 96 GHz, are used in FOD radar research. Weather resistance, frequency usage regulations, and maximum range are also all factors in radar frequency preference. According to research, the higher the frequency, the more rain attenuation per km is essential to decide on the appropriate frequency based on the characteristics of the airport environment. In this paper, FOD Detection, which uses radar to find foreign objects on the runway, is covered in more detail, which is influenced by the frequency type, the capacity to recognize the minimal size dimensions and the kind of antenna employed by a variety of devices supported by research before.

3.2.1. Range detection

There are various criteria for radar range detection. Short-range criteria recognize FOD at a distance of 20 m, considering the size of a metal object to be 4 cm in diameter and 3 cm in height, as demonstrated in the study by [32]. In SAR mode research, researchers have extended the radar range for detecting glass FOD objects to 60 m [33]. During research on the mobile radar [34], the optimal range achieved by the radar is 30 m. A medium-range radar employing ArcSAR (an evolution of SAR), offering a detection range of 60 m and capable of eliminating the flicker effect caused by rain or snow [27]. Another study employed an algorithm to reduce false alarms, extending the detection range to 70 m [35]. For long-range requirements, simulations by [36] in 2018, using SAR mode and vehicle radars with a frequency of 36 GHz, suggest that the radar range can exceed 210 m. According to Saleem and Mahmood [37], a 25 GHz FMCW radar was constructed with an impressive range of 500 m. Furthermore, according to the findings of Futatsumori *et al.* [18], by boosting the gain to 42 dBi, a range of 500 m can be achieved.

3.2.2. Radar cross section dimensions detecting

The minimum FOD target, a metal cylinder with a diameter of 4 cm and a height of 3 cm, was detected at a distance of 20 m [32]. The airport runway FOD detection system, based on vehicle SAR, can successfully detect objects with a height of 3 cm and a cross-sectional area of 0.05 m square at a distance of 210 m [36]. Research conducted by Nsengiyumva *et al.* [38] using W-band demonstrates that mmW measurements can be used to reconstruct objects with excellent shapes, such as brake pads with a length of 17 cm and glass debris with a length of 4.8 cm. A detailed study in research Herricks *et al.* [30] showed that locating small foreign objects with a 5 cm RCS accuracy of less than 1 m is achievable at a distance of 500 m. In another investigation, a 1 cm-wide item was identified at a distance of 75 m [27].

Further research, highlights the identification of a 10 cm object within a 70 m range [39]. According to the findings of research Futatsumori *et al.* [18], the maximum RCS of a metallic cylinder within a 300 m range measures about 1.25 cm. To illustrate detectable objects, the presents an example of a 2 cm-diameter metal ball with a 35-dBsm RCS detectable at a range of 30 m [40].

3.2.3. Frequency used for radar detection

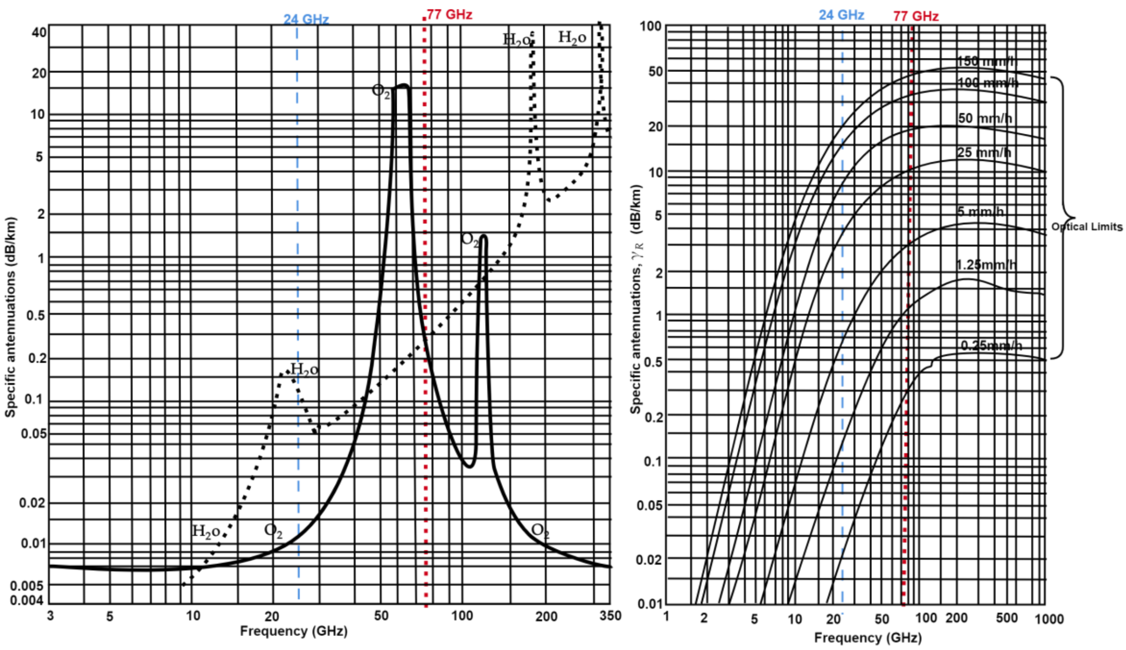
Various frequency ranges are employed in FOD radar research, spanning from 24 GHz to 96 GHz, as outlined in Table 4. The focuses on FOD radar operating within the frequency range of 78 GHz to 96 GHz [17], [27], [28], [34], [35], [40]-[42]. This choice is due to the high-resolution range and the atmospheric window with low attenuation within this frequency range. On the other hand, FOD radar in the 24 GHz to 36 GHz frequency range [32], [36], [37]. The relatively reduced expenses of acquiring and maintaining radar systems trace this preference. In addition to the rationales mentioned earlier, this study explores radar frequency preferences by examining additional elements, including durability against weather conditions, regulatory restrictions on frequency usage, and the maximum operational range. Therefore, this paper explores the reasons mentioned earlier and delves into weather resistance, frequency usage regulations, and maximum range, all of which play crucial roles in determining radar frequency preferences.

Table 4. State of the art research FOD

No	Reference	Years	Frequency (GHz)	RCS dimension (m^2)	Coverage (m)	Tx power (dBm)	Gain
1	[40]	2010	78	-	-	-	-
2	[32]	2017	10; 24; 77	0.03	20	-	-
3	[41]	2018	84.7	-	-	-	-
4	[36]	2018	36.4	0.00051	210	-	-
5	[42]	2019	76; 81	0.17	60	-	-
6	[43]	2020	8.2-12.4	0.005	-	-	-
7	[37]	2020	25	0.005	500	-	-
8	[27]	2020	76-77	0.0001	75	14	32
9	[35]	2022	96	0.1	70	-	-
10	[17]	2021	92.8-93.4	0.05	500	18	42
11	[34]	2022	93	0.02	30	-	-
12	[26]	2022	94	250	0.02	-	-
13	This paper	2023	24	0.002	150-300	20	32

3.3. Weather resistance

Figure 3 is a rain attenuation and atmospheric attenuation graph used to calculate the link budget attenuation when designing a radar system related to propagation with extreme rainfall, as happened in Indonesia on December 19, 2019. An example case in Indonesia from the meteorology, climatology and geophysics agency (BMKG), which recorded more than 150 mm/h from December 31, 2019 to January 01, 2020, rainfall in Indonesia has reached its highest or extreme point [44]. The highest recorded since 1866 reached 377 mm/h and was reported at Halim Perdana Kusuma Airport [45]. Furthermore, Figure 3 shows several variations in rainfall: very light rain, light rain, moderate rain, heavy rain, very heavy rain and extremely heavy rain. Rain attenuation at 24 GHz frequency is 23 dB per km for rainfall exceeding 150 mm/h and is more than twice as much at the 77 GHz frequency, which is 48 dB per km. The observed precipitation indicates that radar systems operating at a frequency of 24 GHz exhibit greater resilience to environmental disturbances, specifically those caused by rainfall.



No	Frequency (GHz)	Attenuation (dB/km)						
		0.25 mm/h	1.25 mm/h	5 mm/h	25 mm/h	50 mm/h	100 mm/h	150 mm/h
	24	0.02	0.14	0.7	4	8	16	23
	77	0.25	1	3.1	11	19	34	48

Figure 3. Graphic rain and atmospheric attenuation [46]

Atmospheric attenuation values, specific attenuation per km, within the frequency bands commonly employed for research, ranging from 24 GHz to 140 GHz. According to Freeman [46], it can be concluded that the excess attenuation rate of atmospheric absorption varies in each frequency band due to the phenomenon of atmospheric absorption. The 24 GHz to 42 GHz frequency range, the attenuation rate is calculated at 0.13 dB per km. Similarly, in the 75 GHz to 95 GHz range, the attenuation rate is calculated to be 0.4 dB per km. Lastly, within the 125 GHz to 140 GHz frequency range, the attenuation rate is 1.8 dB per km. Notably, the 24 GHz to 42 GHz bands exhibit lower atmospheric attenuation per km than the 75 GHz to 95 GHz bands. Rain and atmospheric attenuation at 24 GHz are notably lower than at 77 GHz. This discrepancy significantly affects aviation operations within airport regions, where radar enhances security.

3.4. Frequency usage regulations

In compliance with the frequency utilization guidelines outlined in the 2020 version of the ITU Radio Regulations and the International Mobile Telecommunication (IMT) technology framework, it has designated the 24.25 GHz to 27.5 GHz frequency range for terrestrial communication. However, any application service can use that band because the radio regulations do not prioritize it. FOD objects dependent on clutter in asphalt runways can be found at a frequency of 24 GHz [32]. In FOD, research implements FMCW modulation at a frequency of 25 GHz [37]. Similar to the 24 GHz frequency, 37 GHz to 43.5 GHz, or parts thereof, are identified for the terrestrial component of IMT and may be used for any application. With SAR modulation mounted on the vehicle, the radar uses the 36.4 GHz frequency to find FOD on the runway [36].

The 77.5 GHz to 78 GHz frequency band will be limited to short-range radars, including automotive radars. According to Zeitler *et al.* [40] uses a frequency of 78 GHz to detect FOD by making an antenna with a characteristic pencil-shaped radiation pattern to make it more focused. The study conducted Mollo *et al.* [32] aims to establish the capability of the 77 GHz frequency in detecting FOD caused by clutter, specifically asphalt from the runway. This research builds upon previous investigations conducted at a frequency of 24 GHz. A fan explicitly allocates the frequency band from 84 GHz to 86 GHz for fixed satellite services. However, it is essential to note that its usage is restricted solely to feeder links inside the broadcasting satellite services that operate in geostationary orbit. However, Liu *et al.* [41] showed that a fan radiation pattern was used to identify FOD and a reflector on the antenna to obtain the best gain. For frequency, 86 GHz to 90 GHz is used for radio navigation. At a frequency of 90 GHz, efficient measurement setups are used to get scattering measurements with spatial and polarisation diversity [38]. The goal is to use SAR modulation to detect FOD. The frequency band 92 GHz to 100 GHz is generally used for radio astronomy and satellite radio navigation. Zhang *et al.* [27] used a SAR, ArcSAR type, to avoid strong radiation power, a potential problem for aviation equipment. According to Futatsumori *et al.* [17] evaluate FOD radar's performance by testing the radar range, FOD type, and false alarm detection. Develops an algorithm detecting small sizes and long ranges [26], [34], [35]. Considering existing regulations and literature studies, it can be concluded that frequencies 24 GHz, 77 GHz, and above 90 GHz can be used for FOD radar technology.

3.5. Maximum radar range

Previous references have detailed radar specifications as part of research endeavours. In this study, the predetermined parameters for the radar system include a transmit power (Pt) of 1200 mW, an antenna aperture (A) of 0.001948 m, a factor of 0.8, and a RCS ranging from 0.01 to 0.1. The distance to debris size was calculated using (1) and (2), as illustrated in Figure 4. Assumed that the to-be-designed radar specifications with a carrier frequency of 24 GHz and 77 GHz, the size of the debris and a surface area of 0.01 m^2 to 0.1 m^2 or -20 dBsm, transmit/receive antenna gain (G_T and G_R) of 32 dBi, Pt of 10 dBm, noise figure (NF) of 7 dB, system losses (L_s) of 3 dB, sweep frequency (f_m) of 1 KHz, power continues wave (P_{cw}) of 10 dBm, SNR of 15 dB, and power receive (P_r) of -122 dBm. Detection distance can be achieved using two frequencies of 24 GHz and 77 GHz with a minimum distance threshold of 150 m. At the 24 GHz frequency, the minimum achievable detection range is 125 m with an RCS size of 1 cm, and the maximum possible detection range is 225 m with an RCS size of 10 cm. At the 77 GHz frequency, the minimum detection range is 75 m with an RCS size of 1 m, and the maximum detection range is 110 m with an RCS size of 10 cm. Based on the results of this simulation, the detection range at 77 GHz does not satisfy the specified threshold distance. As shown in Figure 4, the selection of the frequency to detect objects has a significant impact on the radar's range. From all of the discussions, we combined the parameters as shown in Table 4. Which shows the state of the art of existing research on FOD.

$$P_r = \left[\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}\right] \quad (1)$$

$$R\left[\frac{P_{cw}G_T G_R \lambda^2 \sigma_T}{(4\pi)^3 K\cdot T\cdot NF\cdot fm\cdot L_s\cdot SNR_{Out}}\right]_{max} \quad (2)$$

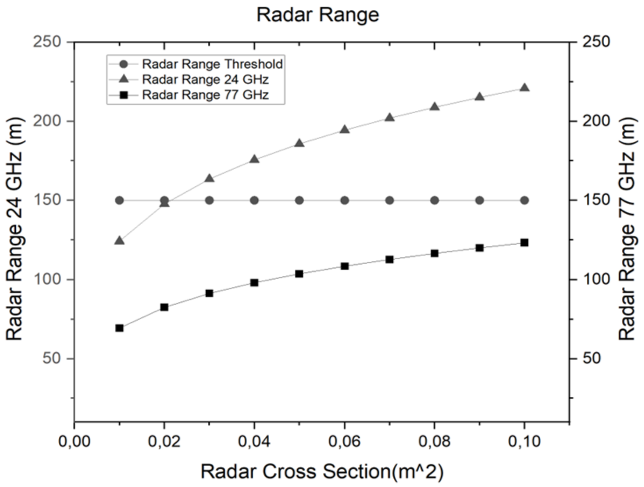


Figure 4. Simulation RCS 24 GHz versus 77 GHz

3.6. Implementation of foreign object debris radar at airports worldwide

There are many FOD products used in international airports around the world. There are five types of FOD radar, as shown in Table 5 [47]. The Kuala Lumpur International Airport (KLIA) has recently invested in FOD detection technology to bolster its security measures. According to the airport's official statement, the second phase of the high-end field experiment commenced after the first test phase in 2019. Beijing Daxing International Airport and Hamat International Airport are building FOD detection systems. These airports have chosen to deploy a FOD detection system developed by X sight system Ltd., an Israeli business. Orlando International Airport in the United States is testing the iFerret performance rating system. Plextek services provide the FOD detection systems utilized at Incheon Airport in South Korea. According to Partner [48], data regarding the countries that have initiated the implementation of FOD detection systems is available. Within the geographical expanse of the North American continent, three distinct sovereign entities: the United States, Canada, and Mexico. The European continent recognizes sovereign nations such as France, Germany, Italy, the United Kingdom, and Russia. The Asia Pacific region encompasses a variety of countries, including Singapore, Malaysia, Indonesia, Japan, Australia, China, South Korea, and Australia. The Middle East and Africa areas comprise South Africa, Saudi Arabia, and the United Arab Emirates. The continent of South America encompasses the countries of Brazil and Argentina.

Table 5. Summary of FOD product

No	Product (manufactured)	Technology	Frequency (GHz)	Max range (m)	Range resolution
1	Tarsier radar (Qinetiq)	mmW radar	94	1500	-
2	FOD finder (TrexEnterprises)	Mobile mmW radar	78-81	140	3
3	FODetect (Xsight system)	mmW radar with an optical camera	77	50	30
4	iFerret (Stratech)	optical camera	-	-	-
5	FOD detection system (Hitachi Kokusai electric)	mmW radar over fiber with HD camera	92-100	500	-
6	Plextek	mmW radar, mobile mmW radar	-	-	-

3.7. Radar foreign object debris specification recommendation

In order to minimize cost, how to design a radar with a frequency lower than 25 GHz, a maximum detection range of up to 500 m, a maximum RCS object size of 0.005 m square, a minimum transmitter power of 100 mW, and a maximum gain of 32 dBi [48]. A study has shown that to effectively detect objects, the vertical beamwidth should be no less than 2.8° [49]. Additionally, the maximum horizontal beamwidth required for detection purposes is 75°. Furthermore, research indicates that a system loss of at least 3 dB and a minimum noise figure of 3 dB is required to obtain more precise detection findings [18]. Based on various research findings, Table 4 recommends research utilizing the 24 GHz frequency due to its ability to reach far distances, resistance to weather changes, and cost-effective construction compared to higher frequencies.

The radar specifications provided in Table 6 for research use the 24 GHz frequency, which can reach far enough, is resistant to weather changes, and the construction costs are low compared to the high frequencies. It allows one to estimate the maximum possible range. Similarly, the appropriate system can be classified if associated with the radar system type in Table 3. The distance between the FOD detection system tower and the runway is considerable, given the anticipated range of 300 m, with a minimum range of 60 m and a 77 GHz frequency. Figure 5 shows that the edge-light type is the best option.

Table 6. Radar FOD specification recommendations

Parameter	Value
Frequency	24–24, 25 GHz
Bandwidth	250 MHz
Distance	150–300 m
RCS minimum area	0,002 m^2
Gain	≥32 dBi
Beamwidth horizontal	75
Beamwidth vertikal	5
Power	120 mW
Noise figure	6 dB
Loss	3 dB

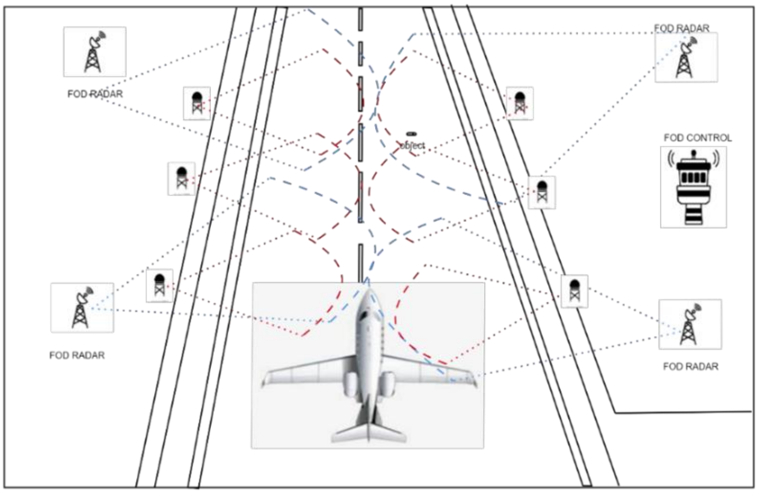


Figure 5. Recommendation scheme of radar placement on runway

Detection resolution, directly tied to radar frequency, influences the challenge in FOD radar related to object (debris) detection precision. The higher the frequency, the more precise the resolution. Most radars now implement hybrid technology that includes a camera to improve accuracy [9]. Radar frequencies above 73 GHz have good detection resolution; however, when using 24 GHz or 36 GHz, the accuracy for debris objects is at least 90% [50]. Under the regulations set forth by the FAA, the radar system must be able to accurately ascertain and determine the dimensions or size of any potential debris objects. One advantage of radar technology lies in its capability to detect objects across considerable distances, operate continuously throughout the day, and exhibit resilience in adverse weather conditions. In radar that uses mmW, several bands have low rain attenuation and atmospheric attenuation compared to other bands. The band with a low attenuation character is the 24 GHz to 42 GHz spectrum [46].

4. CONCLUSION

Radar technology has shown to be the best option for developing automated, high-precision FOD detection systems. This conclusion was drawn based on the exceptional qualities inherent in radar technology. Radar systems operating within the frequency range of 24 GHz to 42 GHz exhibit a relatively low attenuation of 10 dB, rendering them highly suitable for deployment in regions characterized by frequent precipitation and extensive runway infrastructure. Moreover, FMCW modulation in radar systems is prevalent for identifying FOD in radar applications. Furthermore, it is imperative to consider the feasibility of developing a radar system that adheres to regulatory standards and can operate within the frequency range of 24 GHz to 42 GHz by employing FMCW modulation. In addition, the system must possess ease of production and affordability.

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