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LETTER

FMCW linear cell radar interference mitigation through control of signal delay in radio-over-fiber links

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Abstract To alleviate the danger of foreign object debris on runways, Frequency Modulated Continuous Wave linear cell radar based detection systems have been evaluated in the literature. This radar uses a 90 GHz millimeter wave and radio-over-fiber (RoF) to achieve high detection accuracy and low cost. This paper reports the experimental results of interference mitigation experiments at Kuala Lumpur International Airport. False images formed due to interference can be suppressed by performing simple signal processing on more than one radar image in which the transmission delay in RoF links is discrepant.

Keywords: FMCW radar, radio-over-fiber, Interference suppression
Classification: Microwave and millimeter-wave devices, circuits, and modules

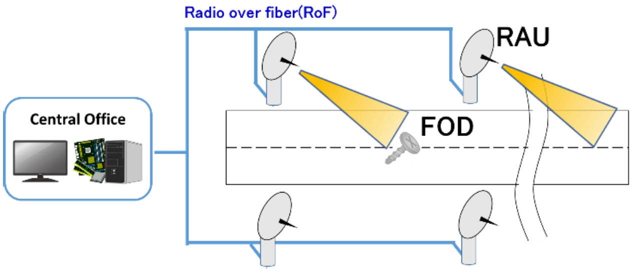

Fig. 1 Schematic of linear cell radar

1. Introduction

Detection of foreign objects on runways is indispensable to safe airport operation. According to a report from the United States Federal Aviation Administration (FAA), the total cost associated with foreign object debris (FOD) on the runway is estimated to exceed USD 1 billion [1]. For safety and economic reasons, the importance of detecting FOD is increasing. In addition, the number of air passengers worldwide is increasing, and the International Air Transport Association (IATA) expects it to reach 7.8 billion passengers in 2036 [2] and 8.2 billion in 2037 [3]. Since the interval between the takeoff and landing of a passenger aircraft is expected to be short, FOD detection on the runway needs to be performed automatically and at high speed.

Frequency Modulated Continuous Wave (FMCW) linear cell radar using millimeter waves in the 90 GHz band has been proposed [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. A schematic of a linear cell radar is shown in Fig. 1. Generally, millimeter-wave radar has high detection performance, high resolution, and high weather resistance [4].

However, the free space propagation loss and atmospheric attenuation in the millimeter wave band are large [28], so appropriate detection distances are hard to find in spaces as runways.

On the other hand, linear cell radar uses radio-over-fiber (RoF) technology, which transmits high-frequency electrical signals through optical fibers [4, 5, 6, 7, 29, 30]. This technology has solved the problems associated with millimeter-wave radar by arranging a large number of remote antenna units (RAUs) along the runway. The cost of the high-frequency circuit is also reduced by distributing the output of the radar signal source to each RAU through an optical fiber. RoF results in dispersion for long-distance transmission, but signal degradation can be suppressed by using double-sideband suppressed-carrier (DSB-SC) modulation [8].

However, owing to the arrangement of a plurality of RAUs, interference may occur among them. This paper reports the results of interference experiments and interference avoidance experiments performed at Kuala Lumpur International Airport using a large aircraft (B747-400). In addition, we study false image suppression by performing simple signal processing on multiple radar images acquired while changing the transmission delay on an RoF network.

2. Interference avoidance method

The radar system used in this experiment was an FMCW radar. The FMCW radar uses a chirp signal whose frequency increases and decreases over time with the transmission wave, and calculates the distance to the object using the frequency difference between the transmission wave and the reflected wave. Through cooperative control, none of the FMCW linear cell radar RAUs interfere directly with each other.

However, when the transmission wave is reflected by an airplane or similar object, it may be received by another RAU as an interference wave stronger than the actual desired

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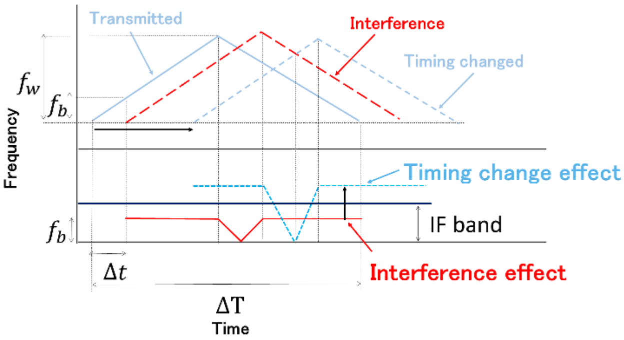

Fig. 2 Mechanism of interference avoidance

wave [23]. Further, when interference occurs in the FMCW linear cell radar, a false image occurs. False images create false alarms, as the system may mistakenly recognize an FOD where none exists on the runway.

As a method of avoiding interference in FMCW linear cell radar, we propose a method of changing the transmission timing by making the optical path length different in the RoF network of each RAU. In conventional radars such as marine radars, interference avoidance is realized by changing the cycle of the transmitted FWCW signal through software control. As each radar unit operates independently, the false images move randomly over the radar images. Therefore, we can suppress false images by averaging. On the other hand, RAUs in linear cell radar are controlled coherently by the central office using RoF links, whereby the cycle of the FMCW signal and the direction of beams can be synchronized. Thus, we can quickly suppress the false images by changing the configuration of the RoF links without using averaging. The optical path length is changed by adding an optical fiber. The length of the optical fiber required to avoid interference is expressed as

$$L_f = \frac{4R_{max}}{c}c' \tag{1}$$

where L_f, R_{max}, c, and c' denote the fiber length added to the RoF network, the maximum detection distance, the speed of light, and the propagation velocity in the optical fiber, respectively.

Fig. 2 shows the basic principle of interference avoidance. When the RAU receives an interference wave from another RAU, a false image that cannot be distinguished from the desired wave occurs. Here, the beat frequency of the false image is set at a higher value than the IF band by delaying the transmission timing of the RAU with respect to the other RAUs by a certain interval. By doing this, the RAU does not recognize the false image, and the effect of interference avoidance can be removed.

3. Experimental system using a large aircraft

Fig. 3 shows the experimental system in Kuala Lumpur International Airport in which RAU2, RAU1, and an airplane (B747-400) are arranged in a straight line. The distance between the main receiving system RAU2 and the airplane is 200 m, and the distance between RAU2 and RAU1 is 43.2 m. Each RAU is rotated synchronously once every four seconds by a control signal from the control unit. The control

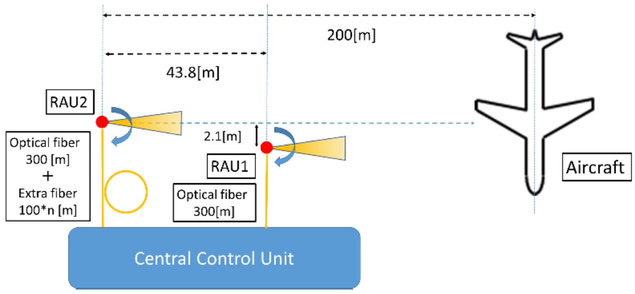

Fig. 3 Experimental system at Kuala Lumpur International Airport

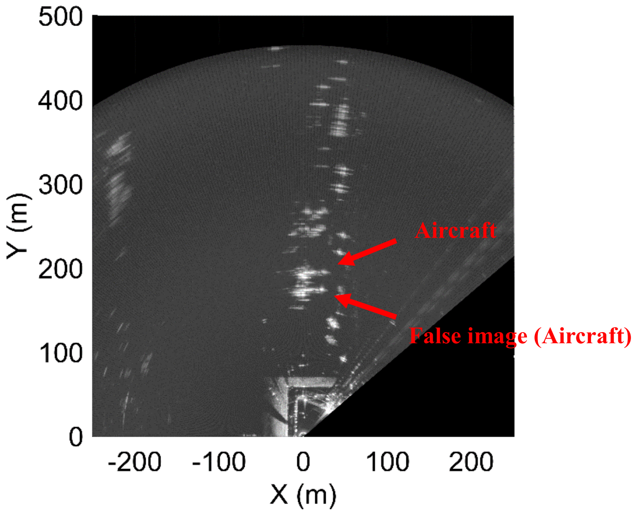

Fig. 4 RAU2 radar image (no additional optical fiber)

units and each RAU are connected by optical fibers 300 m in length. In this setup, the receiving system is RAU2, and the optical fiber on the RAU2 side can be changed by 100 m. RAU2 receives the reflected wave generated by its own transmission wave, and the interference wave from RAU1. Owing to receiving two signals with different routes, the display shows real and false airplane images. Fig. 4 shows a radar image when no optical fiber is added to the RAU2 side. An image of the airplane can be seen at Y = 200 m, and a fake image of the airplane can be seen at Y = 180 m.

4. Interference-avoidance experiment

By generating a delay in the RoF network and changing the transmission timing of RAU2, interference avoidance is realized. The radar image in Fig. 5 displays when a 400 m optical fiber is added to the RAU2 side. The addition of the optical fiber causes a transmission wave delay in the RoF network. As a result, the frequency difference between the interference wave and the transmission wave changes, and the position of the false image shifts. However, an insufficient delay time in the 400 m optical fiber causes the difference frequency from the interference wave to be within the IF band, meaning the false image cannot be removed. The length of the optical fiber required to remove the false image is

$$L_f = \frac{2(R_f + R_{max})}{c}c' \tag{2}$$

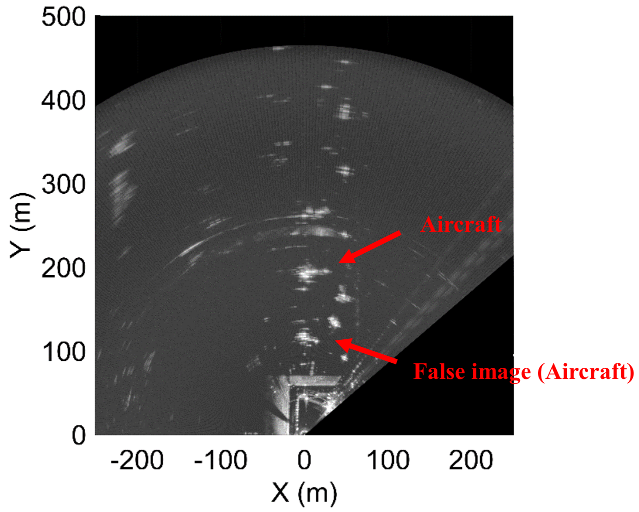

Fig. 5 RAU2 radar image (optical fiber 400 m added)

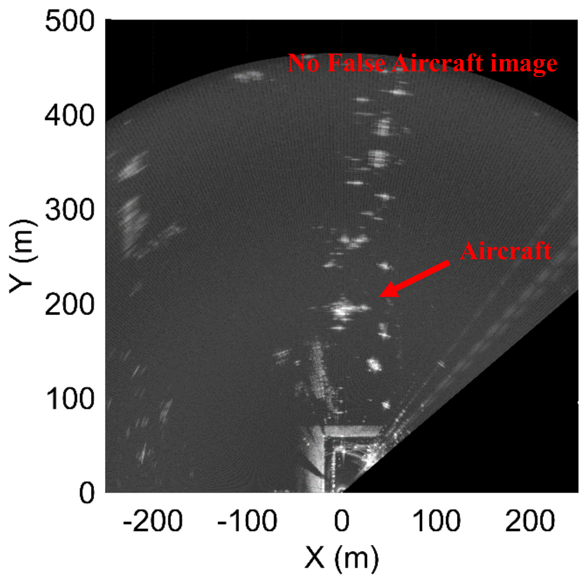

Fig. 6 RAU2 radar image (optical fiber 1000 m added)

where R_f is the location of the false image occurrence.

Equation (1) gives the length of the optical fiber required to remove false images at any position in the radar detection range, while Equation (2) provides the length of the optical fiber required to remove false images at a specific position.

The length of the optical fiber for removing the false image at 180 m in Fig. 4 is calculated to be 870 m using Equation (2). Fig. 6 shows the radar image that results when a 1000 m optical fiber is added to the RAU2 side. With a 1000 m optical fiber, the difference frequency from the interference wave was outside the IF band, and the false image was successfully removed.

5. Interference-suppression processing

As shown in Fig. 6, the effect of interference can be avoided by adding an optical fiber of a specific length. The fiber length required to remove all false images in this radar is approximately 1260 m from Equation (1). If a fiber of this length is added, there is a possibility that the detection performance will be reduced due to a decrease in transmission power caused by transmission loss.

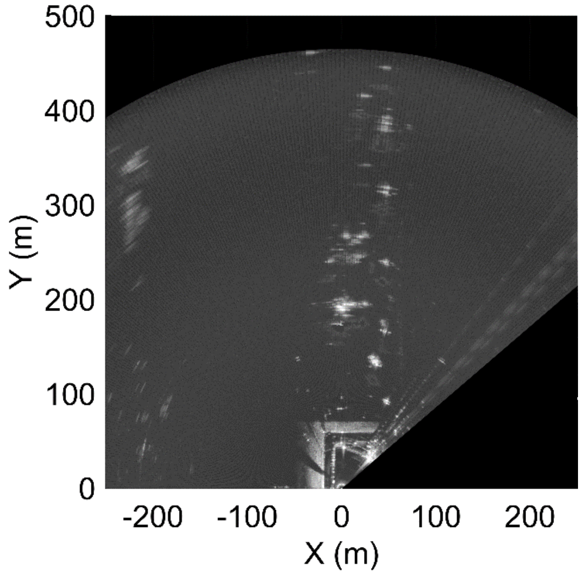

Fig. 7 Radar image with false image suppression processing

Therefore, this paper proposes a false image suppression process using the fact that the position of the false image shifts when the fiber length is changed. By performing the logical AND operation on a plurality of radar images obtained with different fiber lengths, the false image is suppressed. The AND process can be defined as follows: 1) When the difference between two inputs is smaller than a threshold, the output equals the input. 2) When the difference is larger than the threshold, the output is set to zero. When performing the logical AND process on images shown in Figs. 4 and 5, the received powers at the same position are compared to generate the output. The threshold was set to 5 dB. When the difference is larger than the threshold, the output defaults to the noise floor of the actual radar system. A false image of the airplane is seen at approximately 180 m in Fig. 5 and approximately 120 m in Fig. 4. Fig. 7 shows the image obtained by the logical AND process on the images shown in Figs. 5 and 6. The two false images were successfully suppressed.

It is also necessary to consider the detection of objects moving on the runway. In this process, if the FOD is moving on the runway due to wind or a similar force, there is a possibility that it will be recognized as a false image by the AND process and will disappear. However, if the length of the optical fiber to be added to the RAU is known in advance, the shift in the position of the false image on the radar image can be known. It would then be possible to take measures against the moving FOD by detecting and suppressing the false image of the shift amount corresponding to the length of the added optical fiber.

Therefore, by acquiring a radar image and performing the AND processing while constantly changing the optical path length in the RoF network, it is possible to suppress only the false images. In addition, because the position of the false image only needs to be shifted, interference can be avoided by adding a short optical fiber. Thus, false image suppression by AND processing can counteract the decrease in transmission power due to addition of the optical fiber.

6. Conclusion

This paper presents a field experiment on interference mitigation in an FMCW-based 90 GHz radar system consisting of many RAUs connected by RoF links. A field experiment using a large aircraft (B747-400) was performed at Kuala Lumpur International Airport. By using logical AND signal processing on more than one radar image, the false images caused by reflection on the surfaces of the aircraft were suppressed. In the future, we plan to study a dynamic RoF network to automatically change the optical fiber route and to enhance the interference suppression processing for moving objects.

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