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EVALUATION OF A NON-COOPERATIVE AIRCRAFT SURVEILLANCE SYSTEM BASED ON SHORT RANGE CONTINUOUS-WAVE RADARS

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Abstract—This paper presents an end-user evaluation of aircraft detection and identification capacity of the surveillance system deployed in Terminal 4 apron of Madrid-Barajas International Airport. The main goal of the system is to provide real-time surveillance information about aircraft and vehicles on the apron area, including stands, facilitating airport operation centre tasks concerned with delay minimizing and apron resources use optimizing. In order to describe system performance, a set of indicators are defined to quantify the output information reliability and to measure the capabilities of this system to automate routine airport operations.

1. INTRODUCTION

ASA (Aircraft Surveillance on Apron) system main goal is to display real-time surveillance information on an airport map containing all the aircraft and vehicles locations regardless of the climatological conditions: rain, fog and night. Deployed system extends airport surveillance to extremely congested multipath outdoor areas [1], such as inner taxiways, apron and stands. In these areas, conventional radar solutions do not provide coverage due to the difficulty of discriminating the aircraft false detections and the corresponding to non-aircraft (cars, trucks, trolleys and stairs) [2]. On the other hand, MLT (Multilateration) solution presents problems due to shadows, multipath, reflections and garbling near the terminal building that cause holes in coverage and degraded accuracy [3]. Alternative target localization systems could be provided by means of advanced ray-tracing techniques based on PO (Physical Optics) and GTD (Uniform Geometrical Theory of Diffraction) [4, 5].

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Users of the Airport Operation Centre can utilize the new system deployed and its capability to implement an A-SMGCS (Advanced Surface Movement Guidance and Control Systems) [6, 7] level I [8, 9] to make some everyday automatic tasks, such as in-block (event that occurs when the aircraft enters the parking area and is used to start the airline tax) and off-block (event that occurs when the aircraft leaves the parking area and is used to end the airline tax) aircraft registering driving us to describe statistics focused on system performance evaluation [10] on detection and identification from the end-user point of view. These statistics quantify the reliability of the data offered to the airport operator.

This paper presents the architecture of the ASA system composition deployed in Terminal 4 of Madrid-Barajas Airport (Fig. 1). The system is based on high-precision radars at millimeter wave band (76.5 GHz) [11, 12], integrated in a non-cooperative A-SMGCS system [13, 14]. Then, a set of system evaluation indicators are proposed and analysis results are given.

2. ARCHITECTURE

ASA system contains two different types of surveillance sensors (Fig. 2). OI (Optical Identifiers) recognizes aircraft tail numbers as they pass in front of them. SRR (Short Range Continuous-Wave Radars), 600 meters maximum range, determines target position with 2 meters range accuracy (stationary target), refreshing this information every second [15]. OI sensors are placed at each apron entry points to recognize the aircraft tail number as soon as possible. On the other hand, SRR sensors are placed at 20 meters high to guarantee

Figure 1. 3D view of ASA system.

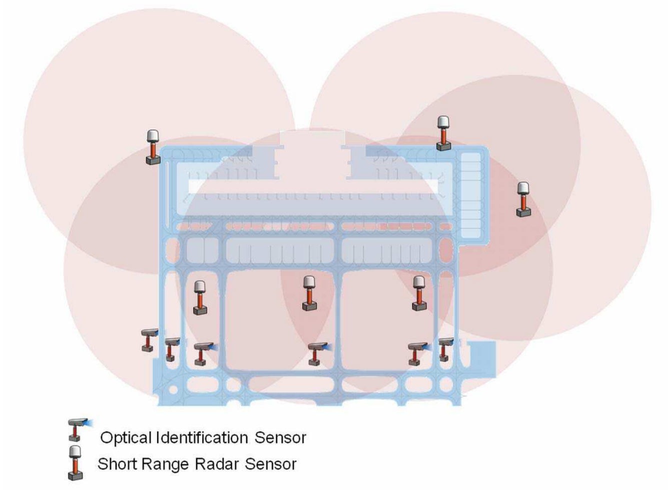

Figure 2. Sensors distribution in T4 of Madrid-Barajas Airport.

the optimal coverage. ASA system receives flight information from the main airport IT systems, using the tail number of the aircraft to correlate the flight plan. This valuable information enhances sensor performances. ASA HMI (Human Machine Interface) provides the user with two types of information about airplanes and vehicles on apron [16]: tracks and plots. Track data is presented with a classification of the target: Aircraft, Vehicle or Unknown, including tail number and flight number for the aircraft obtained from real-time operational airport systems (Fig. 3).

3. OI AND SRR SPECIFICATIONS

The main operational specifications of the OI (Fig. 4) and SRR (Fig. 5) sensors are displayed in the Table 1.

4. COVERAGE STUDY

SRR sensors work in the following terms of radio-frequencies:

- Working frequency range: 76.5 GHz ±250 MHz.
- Separation between radar frequencies: 30 MHz.
- Max. number of sensors without repetition frequency: 17.

As it can be seen in Table 2, and according to the above frequency distribution (Fig. 6), it is possible to position between twelve and

Table 1. OI and SRR specifications.

Optical Identifiers Specifications	
General Characteristics	
Range	50 to 330 feets
Pd	95%
Target velocity	1 to 35 knots
Illumination	All conditions
Short Range Continuous-Wave Radar Specifications	
Transmitter Characteristics	
Frequency	76 GHz
Peak power	$\prec$ 15 dBm
Transmit wave form	LFMCW
PRF	1000
Bandwidth	120 MHz
Pulse length	200 µsec
Receiver Characteristics	
Dynamic range	$\succ$ 70 dB
Noise figure	$\succ$ 10 dB
Antenna Characteristics	
Gain	32 dB
Elevation beamwidth	8°
Azimuth beamwidth	1.3°
Target Detection (single sensor)	
Azimuth coverage	360°
Azimuth resolution	0.75°
Pd	95%
Instrument range	30 to 600 meters
Range resolution	5 meters
Range accuracy (stationary target)	±2 meters
Range accuracy (target speed 140 Kts)	±15 meters
Target Detection (multiple sensors)	
Minimum range resolution	none, due to overlapping coverage
Maximum range resolution	none, dependent on number of sensors

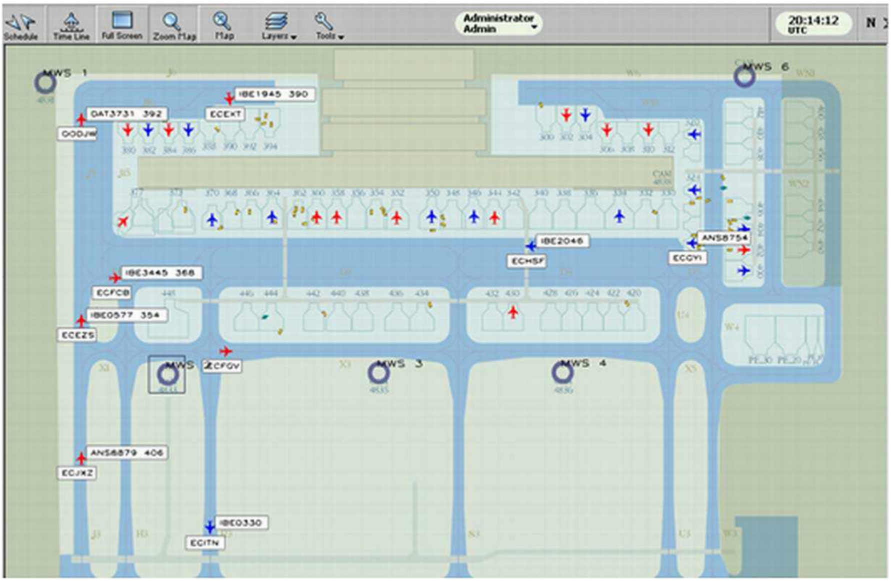

Figure 3. HMI of ASA system in Barajas T4 apron.

Figure 4. OI sensor.

fifteen sensors because there is sufficient frequency range. Therefore, there is no problem of causing interferences between them. However, due to the characteristics of the sensors (peak power of 10 mW), frequencies can be repeated without the risk of interfering with each other, provided they are placed at a distance guard [17].

Figure 5. SRR sensor.

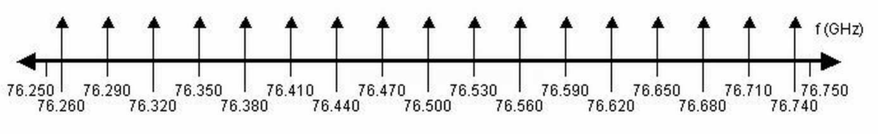

Figure 6. Possible frequency distribution.

Table 2. Frequency range of SRR sensors.

Specific Frequency Range		
Band	*Nominal frequency range*	*Alocations for ITU region 2*
W	75 to 110 GHz	76 to 81 GHz and 92 to 100 GHz

For the location of the sensors, a study of shadows (areas within the range of the sensor which make no detections because there are obstacles that impede it) was taking into account according to the main elements of Terminal T4 (buildings, aprons, fingers, control towers and parked aircraft). In terms of coverage, SRR sensors have a sensing range ensured that varies depending on weather conditions [18]. The minimum coverage occurs for a rain rate of 16 mm/h and the maximum coverage of the sensors occurs in the absence of rain. In Fig. 7, the red circles represents the maximum range of the sensors, approximately 600 meters, the blue circles represents the minimum range, approximately 431 meters and the black circles represents the minimum range for safety margin (maximum distance that can be placed OI sensors to SRR sensors). This placement of the sensors ensures SRR detection for the same aircraft within the whole apron area, having further double coverage of the majority of the apron.

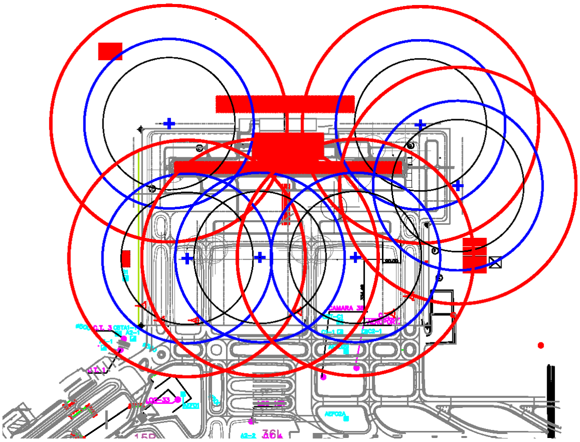

Figure 7. SRR coverage. Blue circles: degraded; Red circles: optimal; Black circles: safety margin.

5. PERFORMANCES STUDIES

Evaluation main objective is to determine user-based system performance focused on aircraft detection and identification capacity. An aircraft can be found on apron in four different situations:

(i) Moving towards a stand after landing: Arrival.

(ii) Moving towards a runway to take-off: Departure.

(iii) Moving between two locations within the airport: Tow.

(iv) Parked on a stand.

The first three situations are grouped as *movement*. Due to the different problems the system must cope with in *movement group* and fourth situation, indicators [19] are calculated independently: *movements* on one hand and *parked* on the other. Weighted values are calculated later.

5.1. Detection

The study focuses on the detection of aircraft as radar tracks presented in the operator position. Each track of aircraft displayed by the ASA system may correspond to:

- A real aircraft.
- A real target but is not an aircraft (such as a vehicle).
- A false target (in that place there is no object).

Indicators used to evaluate system detection capacity are defined. The meaning and the calculation method for these indicators are described in detail in the paper.

(i) Probability of Detection (P_D): The possibility of a real aircraft, presented on the apron, is represented as an aircraft target

$$P\_D = ((A_{ex} - A_{nd} - T_{un})/A_{ex}) * 100\% \tag{1}$$

where A_{ex} is the number of aircraft expected, A_{nd} is the number of aircraft non-displayed and T_{un} is the number of unknown targets.

(ii) Extended Probability of Detection ($P_D_$Extended): The possibility of a real aircraft, presented on the apron, is represented as an aircraft target or as an unknown target

$$P\_D\_\text{Extended} = ((A_{ex} - A_{nd})/A_{ex}) * 100\% \tag{2}$$

(iii) Probability of False Detection (P_FD): The possibility of anything other than an actual aircraft is represented incorrectly as an aircraft target

$$P\_FD = (A_{nrd}/(A_{ex} - A_{nd} - T_{un} + A_{nrd})) * 100\% \tag{3}$$

where A_{nrd} is the number of non-real aircraft displayed.

(iv) Probability of Right Heading ($P_$Right_Heading): The possibility of a real aircraft, presented on the apron, is represented as an aircraft target with the right heading

$$P\_\text{Right\_Heading} = ((A_{ex} - A_{nd} - T_{un} - A_{nhd})/A_{ex}) * 100\% \tag{4}$$

where A_{nhd} is the number of aircraft displayed with a non-right heading.

(v) Probability of Stand Arrival Detection ($P_$Detection_IN): The possibility of a real aircraft arriving to the stand (parking area) is represented as an aircraft target until this operation is completed

$$P\_\text{Detection\_IN} = ((A_{ad} - A_{nd} - T_{un})/A_{ad}) * 100\% \tag{5}$$

where A_{ad} is the number of arrival aircraft displayed.

(vi) Probability of Stand Departure Detection ($P_$Detection_OUT): The possibility of a real aircraft leaving the stand is represented as an aircraft

$$P\_\text{Detection\_OUT} = ((A_{dd} - A_{nd} - T_{un})/A_{dd}) * 100\% \tag{6}$$

where A_{dd} is the number of departure aircraft displayed.

5.2. Identification

Indicators used to evaluate system identification capacity are defined. The meaning and the calculation method for these indicators are described in detail in the paper.

(i) Probability of Identification (P_ID): The possibility of a real aircraft, displayed as an aircraft target, has the right tail number associated

$$P\_ID = ((A_{ex} - A_{nd} - T_{un} - A_{ci} - A_{ii})/(A_{ex} - A_{nd} - T_{un})) * 100\% \quad (7)$$

where A_{ci} is the number of aircraft correctly presented in the system but that have no associated identification tag and A_{ii} is the number of aircraft correctly presented in the system with an incorrect associated identification tag.

(ii) Probability of False Identification (P_FID): The possibility of a real aircraft, displayed as an aircraft target, has a wrong tail number associated

$$P\_FID = (A_{ii}/(A_{ex} - A_{nd} - T_{un})) * 100\% \quad (8)$$

(iii) Probability of No Identification (P_no_ID): The possibility of a real aircraft displayed as an aircraft target has no tail number associated

$$P\_\mathrm{no}\_ID = 100 - (P\_FID - P\_ID)\% \quad (9)$$

(iv) Probability of False Identification Displayed (P_FID_D): The possibility of a displayed aircraft target has a wrong tail number associated

$$P\_FID\_D = ((A_{ii} + NA_{tn})/(A_{ex} - A_{nd} - T_{un} - A_{ii} + NA_{tn})) * 100\% \quad (10)$$

where NA_{tn} is the number of non-real aircraft displayed with a tail number associated.

(v) Probability of Tagged Detection (P_D_LABEL): The possibility of a real aircraft present on the apron is represented as an aircraft target with a tail number associated

$$P\_D\_LABEL = ((A_{ex} - A_{nd} - T_{un} - A_{ci})/N) * 100\% \quad (11)$$

(vi) Probability of Detection and Identification (P_D_ID): The possibility of a real aircraft present on the apron is represented as an aircraft target with the right tail number

$$P\_D\_ID = ((A_{ex} - A_{nd} - T_{un} - A_{ci} - A_{ii})/A_{ex}) * 100\% \quad (12)$$

(vii) Probability of Stand Arrival Identification (P_ID_IN): The possibility of a real aircraft arriving to the stand is represented as an aircraft target with the right tail number until this operation is completed. This indicator is very important because it measures how many arrivals can be automatically introduced in the Airport Operation IT System by publishing in the airport bus the *Airplane x on stand y* event

$$P\_ID\_\mathrm{IN} = (A_{aid}/A_{aex}) * 100\% \tag{13}$$

where A_{aid} *is the number of real aircraft displayed with a correct tail number associated until arrives to stand and* A_{aex} *is the number of arrival aircraft expected.*

(viii) Probability of Stand Departure Identification (P_ID_OUT): The possibility of a real aircraft arriving to the stand is represented as an aircraft target with the right tail number until this operation is completed. This indicator is very significant because it measures how many departures can be automatically introduced in the Airport Operation IT System by publishing in the airport bus the *Airplane x out of stand y* event

$$P\_ID\_\mathrm{OUT} = (A_{did}/A_{dex}) * 100\% \tag{14}$$

where A_{did} *is the number of real aircraft displayed with a correct tail number associated until leaves the stand and* A_{dex} *is the number of departure aircraft expected.*

(ix) Probability of Correct Tailnumber Recognition (P_Read): The possibility of the system successfully recognizes the aircraft tail number at the apron entry

$$P\_\mathrm{Read} = (A_{rd}/A_{din}) * 100\% \tag{15}$$

where A_{rd} *is the number of arrival aircraft with a tail number associated by the OI and* A_{din} *is the number of aircraft detected by the OI.*

5.3. Hypothesis

System evaluation is carried out considering the following assumptions:

(i) Same movement duration of 5 minutes for arrival, departure, tow.

(ii) Same parking duration of 40 minutes.

(iii) In case of a failure in the detection or identification of a movement or parking takes place, the error counter is increased proportionally to the length of the error.

6. RESULTS

The tests were carried out for 4 days in January 2012, covering about 28 hours. Table 3 shows the movements (arrivals, departures and tows) observed in this interval.

Average probabilities results are divided and compared in response to the weather conditions in the following categories (in the case of a heavy snow, the system does not provide a proper operation due to reflections produced in the radar signal):

(i) Sunny day.

(ii) Cloudy day.

(iii) Rainy day.

Results of probabilities obtained are represented in four figures according with the main aircraft surveillance functionalities: probability of detection for movements (Fig. 8), probability of detection for occupations (parked aircraft) (Fig. 9), probability of detection and identification for arrivals and departures (Fig. 10) and probability of false detection and false registration for movements and occupations (Fig. 11). The behavior patterns of the system are explained according with the different weather conditions in the next section.

Table 3. Types of movements studied.

Types of Aircraft Movements		
Arrival	*Departure*	*Tow*
704	870	23

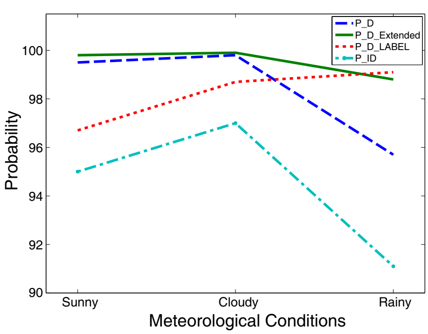

Figure 8. Probability of detection for aircraft in movement.

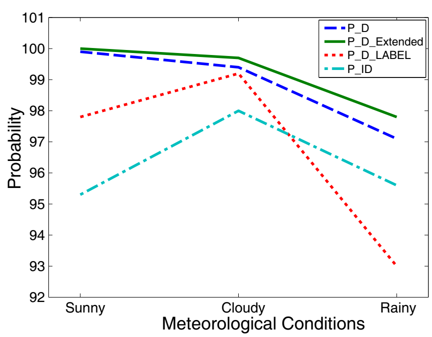

Figure 9. Probability of detection for occupations (parked aircraft).

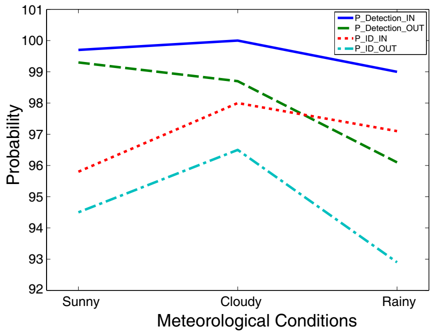

Figure 10. Probability of detection and identification for arrivals and departures.

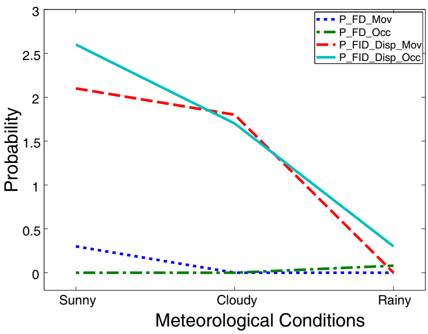

Figure 11. Probability of false detection and false identification for movements and occupations (parked aircraft).

6.1. Sunny day

Table 4 shows the results of probabilities obtained for the four testing days, evaluating both, movements and parked groups in sunny days. Results show the following behavior patterns of the system:

(i) The detection errors in aircraft movements occurs in a small range without detection. No successive appearances-disappearances occur in the system.

(ii) Detecting errors in parked aircraft typically occur before the pushback maneuver. Its duration is brief, but when a plane is removed from the stand does not reappear until it begins to move.

(iii) The identification errors often occurs during the movement of the aircraft, as they often result from errors in reading the tail number at the entry of the platform, which prevents that at no time the aircraft is properly identified.

(iv) The probability of detection (1) is greater than 99%, which implies that an aircraft on the platform is showed in the HMI with an aircraft symbol with a high probability. In the case of parked aircraft, this probability is slightly higher than in the movement since if something goes wrong in the system and temporarily the aircraft symbol lost, usually this occurs during the movement of the aircraft and not when they are stationed.

(v) On the other hand, when an aircraft is not represented erroneously by the symbol of an aircraft, it is represented with a symbol of undetermined mobile, so that the probability of detection extended (2) reaches 99.9%.

Table 4. Summary of total probabilities in sunny days.

Probabilities in Sunny Days			
Detection			
Probability	*Movements*	*Parked*	*Total*
P_D	99.5	99.9	99.8
P_D_Extended	99.8	100	99.8
P_FD	0.3	0	0.03
P_Right_Heading	98.8		
P_Detection_IN	99.7		
P_Detection_OUT	99.3		
Identification			
Probability	*Movements*	*Parked*	*Total*
P_ID	95.0	95.3	95.2
P_FID	2.1	2.5	2.4
P_no_ID	2.8	2.1	2.2
P_FID_D	2.1	2.6	2.5
P_D_LABEL	96.7	97.8	97.7
P_D_ID	94.6	95.3	95.2
P_ID_IN	95.8		
P_ID_OUT	94.5		
P_Read	95.8		

(vi) Even in case that an aircraft cannot be displayed with an aircraft symbol or an unknown movement, a cloud of radar detections (raw video) will appear.

(vii) The probability of showing the aircraft with the aircraft symbol in the in-block (5) and pushback (self-propelled or output) (6) maneuvers respectively is greater than 99%.

(viii) The probability of false detection (3) was found to be 0.3% in the case of movements, being below 1 per thousand for the occupation. During the days of the test were carried out works in the south-west of the platform, resulting in the movements that probability of false detection (3) exceeded 1 per thousand, a value that would be achievable under normal conditions.

(ix) In terms of identification, should be noted that the system is only able to acquire the aircraft identification at the entrance to the platform, when the optical sensor reads the registration of the aircraft. If the tail number is not correctly recognized, the aircraft will lack identification throughout their stay on the platform.

(x) The basic indicator that describes the system performance about the identification of aircraft is the probability of reading (15), which is around 96%. In the 4% remaining is assigned an incorrect registration or is not assigned any tail number. The types of errors that can occur when recognizing tail numbers are confusion of characters and shadow phenomenon, affecting aircraft type CRJ (Canadair Regional Jet) because engine of the aircraft projects a shadow over a part of the tail number, so that a portion of the tail number is in shade and some not. In response, the system is unable to resolve tail numbers properly by 30% of the sun/shade cases.

(xi) Directly related to the probability of correct reading of the registration of an aircraft (15) refers to the probability that an arriving aircraft to a stand display as an aircraft and with the correct tail number status until the In-block (13). This probability is around 96%, so that nearly equals the (15). The importance of this indicator is that for aircraft with arrival identified is possible to publish the event *arrival of aircraft X to Y stand* so that automates this event, of great importance for the airport.

(xii) As for the probability that an output operation (pushback / self-propelled) is shown with the correct registration (14), this is slightly lower, standing at 94.5%. Drops due to the problems that can occur during parking and during the output operation (more complex than the input).

(xiii) The probability that a tail number showed was not correct (10) is around 2%.

(xiv) Finally, other probabilities refer to how aircraft is displayed in the system: with proper tail number (12), no tail number (9) or wrong tail number (8). These values are on average 95%, 2.8% and 2.1% respectively for the movements.

6.2. Cloudy day

Table 5 shows the results of probabilities obtained for the four testing days, evaluating both, movements and parked groups in cloudy days. Results show the following behavior patterns of the system:

Table 5. Summary of total probabilities in cloudy days.

Probabilities in Cloudy Days			
Detection			
Probability	*Movements*	*Parked*	*Total*
P_D	99.8	99.4	99.5
P_D_Extended	99.9	99.7	99.7
P_FD	0	0	0
P_Right_Heading	99.0		
P_Detection_IN	100		
P_Detection_OUT	98.7		
Identification			
Probability	*Movements*	*Parked*	*Total*
P_ID	97.0	98.0	97.9
P_FID	1.8	1.7	1.7
P_no_ID	1.2	0.3	0.4
P_FID_D	1.8	1.7	1.7
P_D_$LABEL$	98.7	99.2	99.1
P_D_ID	97.0	97.5	97.4
P_ID_IN	98.0		
P_ID_OUT	96.5		
P_Read	98.0		

(i) In the absence of sunlight, the system performance in the probability of identification of aircraft's tail numbers (15) improved to 98%. This increase in the parameters that measures the ability of system identification is due to the disappearance of the sun-shade effect on tail numbers of certain aircraft, extensively discussed previously.

(ii) The detection capability is similar to that of a clear day.

6.3. Rainy day

Table 6 shows the results of the probabilities obtained for the four testing days, evaluating both, movements and parked groups in rainy days. Results show the following behavior patterns of the system:

Table 6. Summary of total probabilities in rainy days.

Probabilities in Rainy Days			
Detection			
Probability	*Movements*	*Parked*	*Total*
P_D	95.7	97.1	96.9
P_D_Extended	98.8	97.8	97.9
P_FD	0	0.08	0.07
P_Right_Heading	99.0		
P_Detection_IN	99.0		
P_Detection_OUT	96.1		
Identification			
Probability	*Movements*	*Parked*	*Total*
P_ID	95.1	95.6	95.5
P_FID	0	0.2	0.1
P_no_ID	4.9	4.2	4.4
P_FID_D	0	0.3	0.3
P_D_LABEL	99.1	93.0	92.8
P_D_ID	99.1	92.8	92.7
P_ID_IN	97.1		
P_ID_OUT	92.9		
P_Read	98.0		

(i) In the absence of sunlight the system performance in the probability of identification of aircraft's tail numbers (15) improved to 98%.

(ii) Rain causes attenuation and reflections in the radar signal (76 GHz), which results in a decrease of range of each SRR.

(iii) The radar system is designed to keep your benefits until the rainfall intensity exceeds 16 mm/h. From this limit the system performance can begin to degrade. The limit of 16 mm/h is defined in the international standards for A-SMGCS surveillance systems.

(iv) In practice, a rain intensity of 16 mm/h can be seen during severe storms in a very short period of time. As an illustrative example, in the day during which the statistic for a rainy day was carried out, which was one of the rainiest days of autumn, overcame a rain intensity of 16 mm/h in only 4 periods of 10 minutes. Total rainfall during 24 hours was about 15.9 mm/h.

7. CONCLUSIONS

This paper provides an overview of a novel application that uses millimeter-wave radar technology based on high-precision electromagnetic sensors for aircraft surveillance in airports, with a strong focus on the practical implementation, testing and performance aspects of the ASA system.

The set of proposed indicators, under different weather conditions, can be used to evaluate the aircraft surveillance system deployed on Madrid-Barajas Terminal 4 apron from the point of view of an end user in the AOC (Airport Operation Centre). It is possible to apply this method to evaluate different aircraft surveillance systems on apron when oriented to facilitate AOC tasks, no matter the technology it is based on. In case the surveillance system is used in an ATC (Air Traffic Controller) context, a different set of indicators may be required. Deployed system extends airport surveillance to extremely congested areas where other surveillance solutions have serious drawbacks.

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