Analysis of Alerting Criteria and DAA Sensor Requirements in Terminal Area

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***Abstract*—In this paper, DAA Well Clear (DWC) standards suitable for the terminal area are analyzed using Automatic Dependent Surveillance-Broadcast (ADS-B) data received in the Republic of Korea. A route-finding algorithm was developed to remove the controller intervention portion from the recorded trajectory. The analyses were performed using 100 days of data processed through the route-finding algorithm. It is discovered that the previously proposed DWC thresholds for terminal areas are also applicable to the Korean National Airspace. By applying these criteria, DAA sensor requirements are investigated. Regardless of the required detection rate, the azimuth limit of $\pm 90^\circ$ is sufficient, which is smaller than the limits proposed by DAA-MOPS. This is likely to be caused by the operations being tightly restricted by jet routes and instrument flight procedures. The tradeoff between sensor elevation limit and range limit can be observed. For a fixed detection rate, minimum elevation limit, minimum range limit, and optimal elevation and range limits are presented.**

***Index Terms*—Detect-And-Avoid (DAA), Automatic Dependent Surveillance-Broadcast (ADS-B), DAA Well Clear (DWC), Sensor Performance Requirement, Terminal Area**

I. Introduction

This paper analyzes the DWC alerting standards for terminal areas and the corresponding DAA sensor performance requirements using recorded ADS-B data around the Incheon International Airport (ICN) and the Gimpo International Airport (GMP), Republic of Korea's two largest airports that shares a single terminal area.

In the previous research [1], waypoints were directly extracted from the recorded ADS-B data, and all trajectories were regenerated using a trajectory generation model [2]. However, since these trajectories have been managed by the air traffic controllers, they already have acceptable risk levels. To address this problem, an algorithm has been developed to extract the original flight plans from the recorded ADS-B trajectories. Section II provides a brief description of this algorithm and explains the scenario used for the analyses.

In terminal areas, due to the increase in the aircraft density, separation is reduced compared to En-Route operations. However, since the separations between aircraft are structurally managed by the proven approach and departure procedures and tactically managed by radar vectoring by controllers, applying the En-Route alerting standard are expected to produce excessive alerts that are not necessary [3], [4].

In particular, the Republic of Korea's airspace is severely constrained because most of the airspace is managed by the military. Only narrow corridors around the jet routes are available to civil aircraft. Therefore, except for unavoidable situations, aircraft cannot fly beyond defined routes. This study analyzes the DWC standards for a terminal area containing two large airports, ICN and GMP, in this limited airspace environment.

In Section III the frequencies of the alerts are computed using the trajectories generated in Section II as the alerting standards are relaxed from the DWC-Phase 1 presented by DAA-MOPS [5] to DWC-Phase 2 proposed by NASA [3], [4] to find the suitable alerting criteria for the given terminal area.

In Section IV, the performance requirements of the DAA sensors are analyzed similar to the previous study [1], using the proposed DWC standards for the terminal area from Section III. In this section, the detection rates are calculated according to the limits of the azimuth, elevation, and range. Based on these analyses, several combinations of the sensor performance requirements are proposed. Finally, SectionV concludes the paper.

II. Scenarios

A. Route-Finding Algorithm

The route-finding algorithm tries to find the best match for the given ADS-B trajectory among the existing pool of routes including the Instrument Flight Procedures (IFP) available in the given airspace. The IFPs are pre-established procedures to ensure safety from obstacles in consideration of aerodrome, airport, and the surrounding environment during instrument flight [6]. Examples of IFPs are the Standard Instrument Departure (SID) and the Standard Terminal Arrival Route (STAR). This algorithm finds routes that consist of fixes (waypoint), which becomes the encounter scenarios between aircraft before the controller intervention. Details about the route-finding algorithm are currently being prepared as a separate research paper. A brief summary of the route-finding and scenario generation is given in the rest of this section.

- *Definition of Route Segment*

In this algorithm, a route refers to any path consists of fixes in the IFP or en-route airspace. Route information is provided by the relevant authorities. In the Republic of Korea, it is available through the Aeronautical Information Publication (AIP) issued by the Ministry of Land, Infrastructure and Transport (MOLIT), and it is open to the public [7]. Fix corresponds to the main waypoints and has location and altitude information. The route is represented by a sequence of the fixes, and the corresponding flight conditions are established for each section connecting the fixes. For this algorithm, track angle, lateral limits, and direction information are used from the route data, and coordinate is used from the fix data. In the case of routes in IFP, since the AIP does not provide the lateral limits, the performance standard of the Area Navigation (RNAV) corresponding to each procedure is regarded as the lateral limit. Based on the given information, a route segment is defined as a line segment connecting two fixes with assigned direction and lateral limit as shown in Fig. 1. A route is a sequence of route segments.

- *Step1: Route Filtering*

Comparing the ADS-B trajectory with all existing routes takes excessive computational time. To speed up the process, routes that do not contain any point of the ADS-B trajectory data inside the boundary described in Fig. 1 are filtered out. Each track point that consists the trajectory has time, latitude, longitude, altitude, speed, and direction information. If one of the route segments contains at least one track point inside the prescribed boundary, then the direction is compared. If the direction of the track point is within 45 degrees of the direction of the route segment, the route containing that route segment is not filtered out and becomes a candidate for the next step. Among the four routes shown in Fig. 2, ‘Route 1’, ‘Route 2,’ and ‘Route 5’ are filtered out, and ‘Route 3’ and ‘Route 4’ become the candidates.

- *Step2: Route Scoring and Selection*

Among the candidates from the first step, the route with the highest score is selected in the second step. The scoring algorithm is conceptually explained in Fig. 3. The smaller the width of the boundary area is, the fewer the number of track points it contains. Route scoring gives higher scores to a candidate route with a relatively large number of track points that are included even if the size of the boundary area is reduced. ‘Route 3’ in Fig. 3 contains 13, 9, and 6 track points when the lateral boundaries are 400, 200, and 100 ft respectively. Route 4 includes 13 track points for the same set of boundary values. In this case, Route 4 is given a higher score by using (1).

$$RouteScore = \sum_i \frac{N(L_i)}{L_i^2}, \quad L_{i+1} = \frac{L_i}{5} \tag{1}$$

In (1), L_i is the lateral limit of the boundary area, and $N(L_i)$ is the number of track points contained within the corresponding boundary. The reason why L_i^2 is used for the denominator is to give higher scores to the track points included when the size of the region is small. L_i starts at 62,500 ft, which is about ten nautical miles and is reduced by a factor of five until it becomes twenty ft. (1) is applied to all candidate routes from step 1, and the route with the highest score is selected.

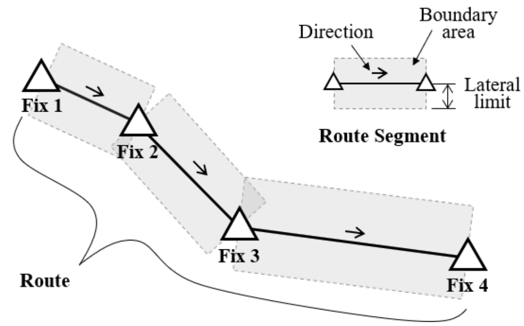

Fig. 1. Definition of Route Segment and Route

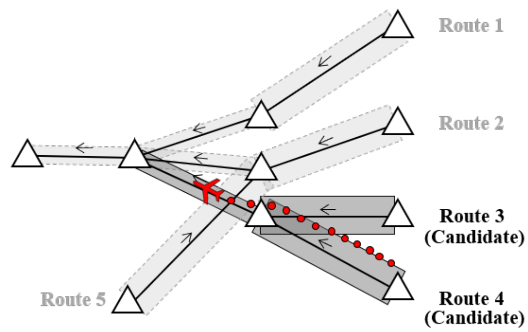

Fig. 2. Route Filtering Process

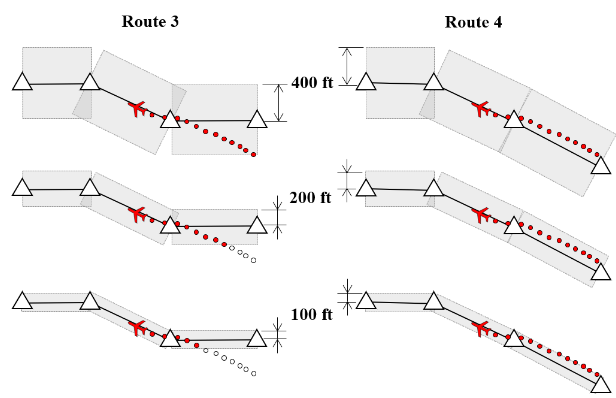

Fig. 3. Route Scoring Process

- *Step3: Additional Connections*

Some of the ADS-B trajectories have portions that extend to the en-route airspace. In this case, it is necessary to connect the IFP portion of the route to the corresponding en-route segment. Based on whether the selected route type is SID or STAR through the previous steps, the reference fix is identified, which is the last fix of SID or the first fix of STAR. Among the routes that connect to the reference fix, the

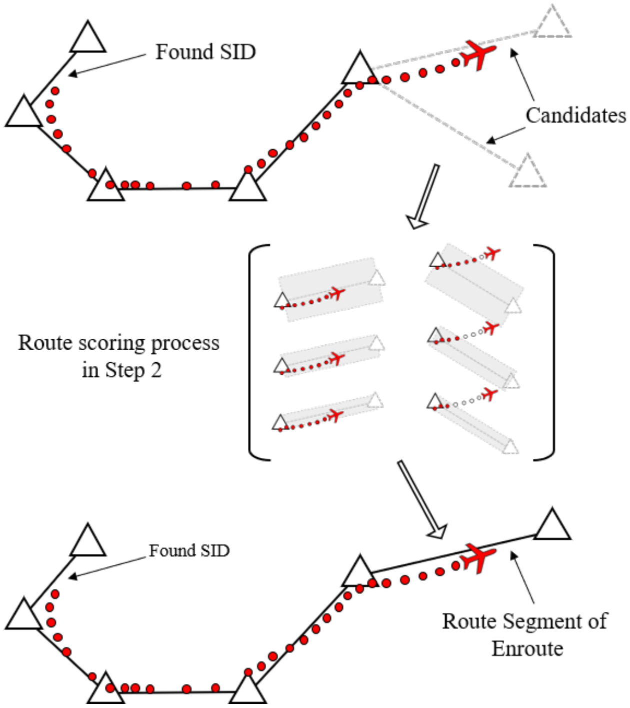

Fig. 4. Connection to En-Route Portion

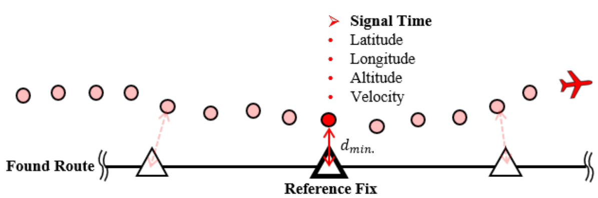

Fig. 5. Reference Fix (Waypoint)

same filtering method as in Step 1 is applied to find candidate routes. Then, the scoring of Step 2 is performed to connect the highest-scoring route segment. Fig. 4 illustrates the connecting procedure. Routes are repeatedly connected until there is no other connectable route segment.

- *Step4: Flight Plan Generation*

Through the previous three steps, a flight plan consisting of fixes is generated for each flight. However, since the fixes have only location and altitude information, it is necessary to add the time of arrival and speed information in order to generate the trajectory. As shown in Fig. 5, the fix closest to the track points of the ADS-B trajectory is designated as the reference waypoint, and the time of this track point is assigned to the reference waypoint as the time of arrival. For the rest of the waypoints, speeds according to altitudes and flight stages are applied using the Performance Table File (PTF) of the Base of Aircraft Data (BADA). Finally, the times of arrival at other waypoints are calculated using the distances from the reference waypoint and assigned speeds.

B. Trajectory Regeneration

Among the ADS-B data recorded since 2017, 100 days with the largest data size were selected. Large data size approximately corresponds to larger traffic volume with fewer data drop-outs. Fig. 6 shows the number of days selected by year and month. The total number of trajectories is 148,848, and fast-time simulations were performed using the trajectory generation model [2]. Figs. 7 and 8 compare the recorded ADS-B data with the regenerated trajectories. In the ADS-B trajectories in Fig. 7, the track points are generally concentrated along the defined routes, but they are also dispersed due to radar vectoring maneuvers. Fig. 8 shows no off-route track points, which enables the assessment of the risk before the controller intervention.

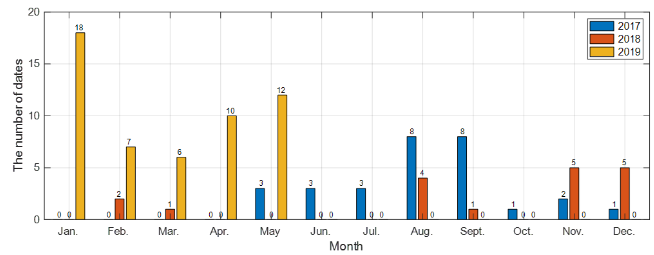

Fig. 6. Distribution of Selected Dates

Fig. 7. Recorded ADS-B Trajectories

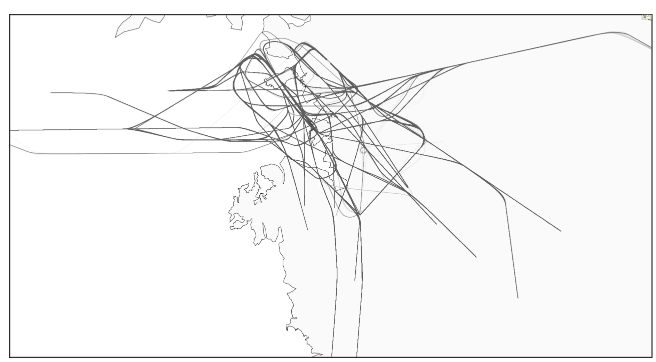

Fig. 8. Regenerated Trajectories

III. DAA Well Clear Analysis

DWC is the boundary of time and space for Unmanned Aircraft (UA) to maintain well clear of other aircraft. The parameters that define DWC are Modified Tau (τ_{mod}), Horizontal Miss Distance (HMD^*), and Vertical Separation (d_h^*). These parameters, which can be calculated from the relative distance and velocity vector between the two aircraft. The condition that UAs must avoid is called Loss of Well Clear (LoWC), which happens when the three conditions in (2) are satisfied simultaneously.

$$0 \leq \tau_{mod} \leq \tau_{mod}^* \ , HMD \leq HMD^* \ , |d_h| \leq d_h^* \qquad (2)$$

The symbols with a superscript * indicate the threshold values for each parameter. In the DWC Phase 1 corresponding to the en-route condition, the thresholds are defined as shown in Table I. Based on Table I, the thresholds are adjusted as shown in Table II to investigate the DWC standards applicable to the terminal areas.

TABLE I
DWC Thresholds (Phase 1)

DWC Thresholds	**Preventive Alert**	**Corrective Alert**	**Warning Alert**	**LoWC**
τ_{mod}^*	35 sec	35 sec	35 sec	35 sec
DMOD,HMD^*	4,000 ft	4,000 ft	4,000 ft	4,000 ft
d_h	700 ft	450 ft	450 ft	450 ft
Min.Avg.	55 sec	55 sec	25 sec	-
Late thresholds	20 sec	20 sec	15 sec	-
Early thresholds	75 sec	75 sec	55 sec	-

TABLE II
Range of DWC Thresholds for Terminal Areas

DWC	τ_{mod}^*	HMD^*	d_h^*	comment
DWC-T1	35sec	4,000 ∼1,000ft	450ft	Reduced HMD^*
DWC-T2	35 ∼0sec	4,000ft	450ft	Reduced τ_{mod}^*

In the first analysis, DWC-T1, for τ_{mod}^*, d_h^*, and alert time, the existing DWC Phase 1 threshold values are used. The number of alerts with respect to HMD^* change is investigated. In the second analysis, DWC-T2, HMD^*, d_h^*, and alert time are fixed using the DWC Phase 1 values, and the impact of change in τ_{mod}^* is investigated. d_h^* is not changed because the DWC Phase 1 value is considered sufficiently small.

Fig. 9 shows the result of changing the value of HMD^* using all regenerated trajectories. In the vertical axis of Fig. 9, the number of alerts is counted as ten if the risk between the two aircraft is maintained for ten seconds because the update time of the trajectory is one second. Fig. 10 shows the number of alarms with respect to τ_{mod}^* for each risk level.

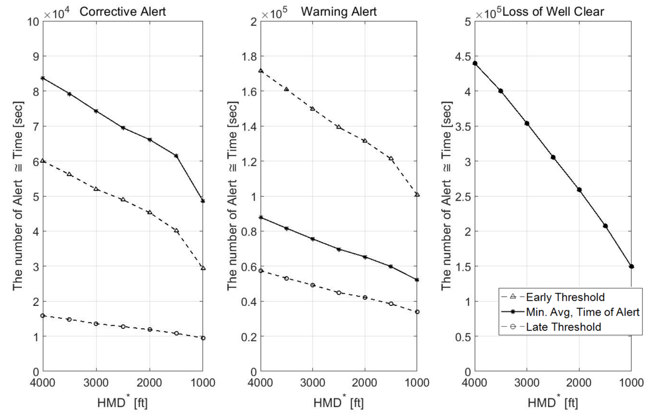

Fig. 9. Number of Alerts with Respect to HMD^*

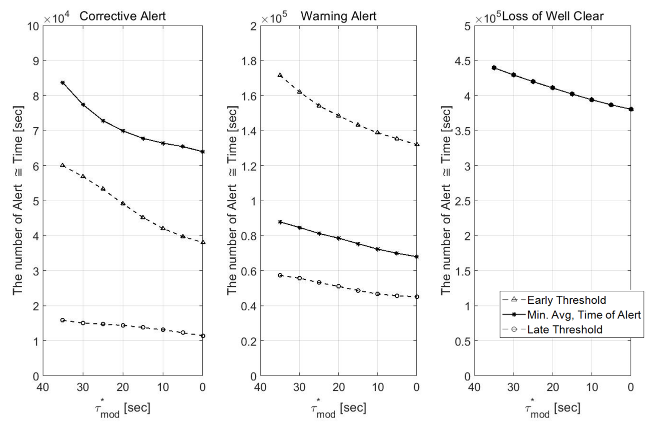

Fig. 10. Number of Alerts with Respect to τ_{mod}^*

In the case of HMD^*, the number of alerts decreases at a steady rate when HMD^* is reduced from 4,000 ft to 1,500 ft, but sharply drops when HMD^* is below 1,500 ft. The number of alerts also decreases when the τ_{mod}^* is reduced as shown in Fig. 10. In case of LoWC, reducing the HMD^* from 4,000 ft to 1,500 ft lowered the number of alerts about 55%. However, reducing τ_{mod}^* from 35 seconds to zero lowered the number of alerts about 15%, which suggests that it is not as effective as the HMD^*.

Based on these results, the terminal DWC standards proposed in [3], [4] can be considered to be applicable to the terminal area encompassing ICN and GMP of the Republic of Korea. For the following analyses, DWC for the terminal area is defined by $\tau_{mod}^* = 0$ seconds and $HMD^* = 1,500$ ft, which is summarized in Table III. In case of τ_{mod}^*, further investigation is necessary to assess the trade off between safety and reducing nuisance alerts.

IV. DAA Sensor Performance Analysis

Three generic DAA sensor parameters are used as in the previous study [1], which are azimuth, elevation, and range as shown in Fig. 11. The azimuth limits are from 0° to ±180°, and the elevation limits are from 0° to ±90°. The range, which

TABLE III
PROPOSED PARAMETERS FOR DWC IN TERMINAL AREA

DWC Thresholds	**Corrective Alert**	**Warning Alert**	**Loss of Well Clear**
τ^*_{mod}	15 or 0 sec	15 or 0 sec	15 or 0 sec
DMOD,HMD^*	1,500 ft	1,500 ft	1,500 ft
d_h	450 ft	450 ft	450 ft
Min.Avg.	55 sec	25 sec	-
Late thresholds	20 sec	15 sec	-
Early thresholds	75 sec	55 sec	-

means the detection distance, is from 4,000 ft to 100,000 ft. For a given combination of azimuth, elevation, and range limit parameters, it is assumed that all the aircraft are equipped with a DAA system with the same sensor performances.

A. Impacts of Aircraft Attitude

One of the concerns of the previous study [1] was that the attitude of the aircraft that affects the detection performance was not considered. The sensor on the ownship was always assumed to be pointing towards the horizon according to the heading of the aircraft without any bank angle. For this study, pitch and roll angles in addition to the heading are reflected when calculating whether an intruder is detected or not.

Figs. 12 and 13 show the relative positions of the intruders when the alerts from the ownship occur at four alert levels of DWC Phase 1 using the minimum average time of the alert. Fig. 12 does not consider the attitude of the ownship while the roll and pitch angles of the ownship is used in Fig. 13. As can be seen from Figs. 12 and 13, the difference is very small, so it may not be necessary to consider the attitude for macroscopic studies.

By the definition of DWC, if two aircraft fly straight in the hazard zone while maintaining speed and direction, the alerts will appear continuously. On the other hand, if the ownship maneuvers, the continuous change in the velocity vector causes the number of alerts to be small. So, the results from the previous study are still valid. However, the ownship attitudes are used for all the subsequent analyses, because it may be necessary to closely investigate the maneuvers in the future.

B. Azimuth Limits

Azimuth limits are analyzed by assuming infinite detection range and ±90° elevation limits.

Fig. 14 shows an example of the detection results using the alerting criteria for the terminal area (Table III, minimum average time of the alert) when the azimuth limit is ±30°. The yellow (corrective alert) and orange (warning alert) markers in front of the ownship represents detection by the ownship. The olive (corrective alert) and brown (warning alert) markers outside the azimuth limits represent detection by intruders as can be seen from one example intruder to the northwest of the ownship. Undetected intruder positions are represented in gray. For this case, only about 80% is detected either by the ownship or the intruders.

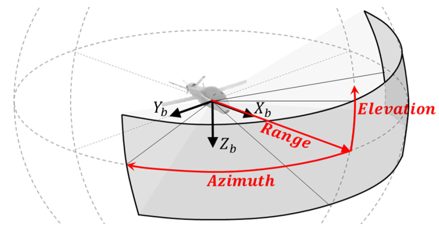

Fig. 11. Three Generic Parameters of a DAA Sensor

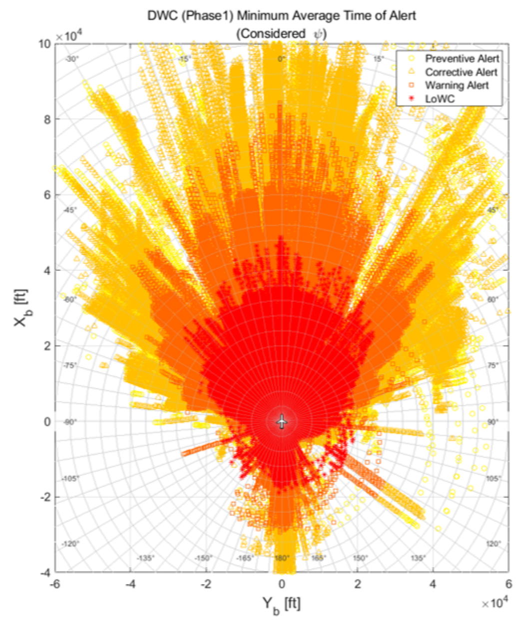

Fig. 12. Intruder Positions (Heading Only)

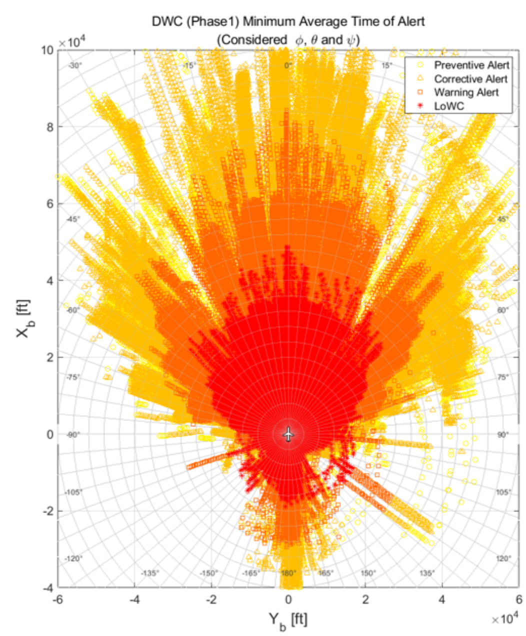

Fig. 13. Intruder Positions (Heading, Roll, and Pitch)

Fig. 15 shows the detection rate with respect to azimuth limits. The detection rate is defined by the ratio of the risk detected by the ownship or intruder to all the risks identified from the DWC computation. If the azimuth limit is above ±60°, more than 90% of all risk can be detected. The detection rate of 100% is reached when the limit is ±90°.

C. Azimuth and Elevation Limits

Fig. 17 shows an example of applying the elevation limits in addition to the azimuth limits of ±60°. The detection rates with the limited elevation performance show a significant difference compared with the case when only azimuth limits are considered. This is because the relative distance on the horizontal plane is considerably larger than the altitude, so even a small increase in the elevation limits significantly increases the altitude range that the sensor can detect. However, it should be noted that increasing the elevation limit may be difficult due to detection hardware limitations. In the case of Air-To-Air Radars (ATAR), the antenna array should be increased, which causes increased panel size, power consumption, and cost. Therefore, an optimal combination of azimuth and elevation limits must be derived to achieve optimal detection performance.

Fig. 18 shows the detection rate contour with respect to the azimuth and elevation limits. 100% detection rate is only possible if the elevation limit is ±90° at all risk levels. At lower detection rates, such as 80% or 90%, a tradeoff between the two sensor parameters can be observed. The detection rate of 90% contour shows that increasing the elevation limit above ±40° does not lower the required azimuth limit, and increasing the azimuth limit above ±80° does not lower the required elevation limit. So, the optimal combination of the two parameters can be found in the lower-left corner regions denoted by the dashed red oval.

D. Azimuth, Elevation, and Range Limits

The range is the most important factor in DAA Sensor performance. It also significantly affects the hardware design such as the frequency band and transmission power of an ATAR. In this section, the detection rates when all three performance parameters are limited are presented.

Fig. 19 shows the surface of azimuth, elevation, and range combination to achieve 90% detection rate for three alert levels. The surfaces display three-way tradeoff between the three parameters.

The red line represents the fixed azimuth limits of ±90°, which was previously identified to achieve 100% detection rate if elevation and range are not considered. From the surfaces, it is clear that even when all three limits are applied, it is not necessary to increase the azimuth limit beyond ±90°.

Along the red line, three points can be identified. The point denoted by a white circle towards the bottom represents the minimum elevation limit. Minimum range point is denoted by the gray circle towards the top. An optimal combination of all three parameters can be found near the corner denoted by a red circle. For example, for the warning alert detection rate

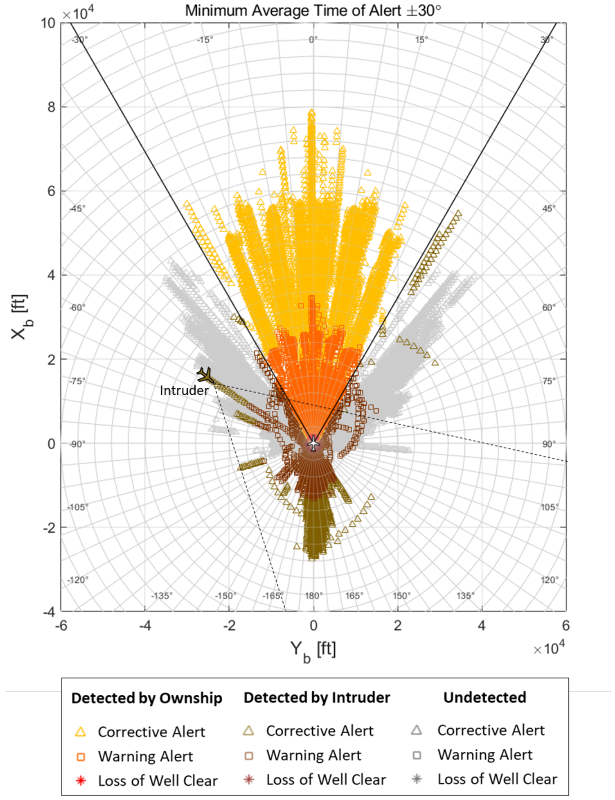

Fig. 14. Example for ±30° Maximum Azimuth Range

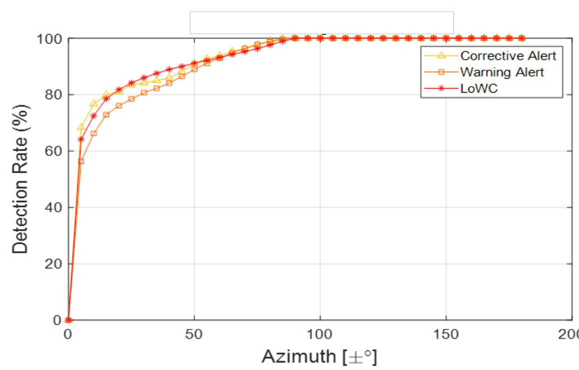

Fig. 15. Detection Rate with Respect to Azimuth Limit (τ^*_{mod} = 0 sec)

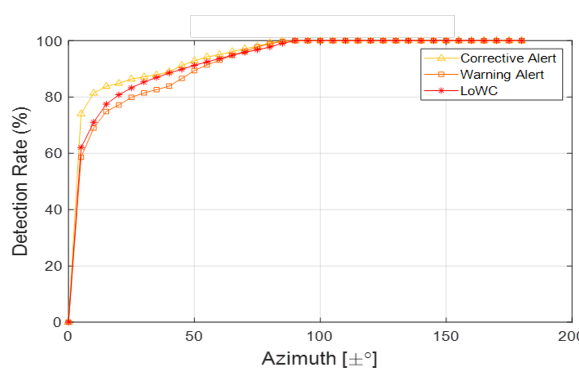

Fig. 16. Detection Rate with Respect to Azimuth Limit (τ^*_{mod} = 15 sec)

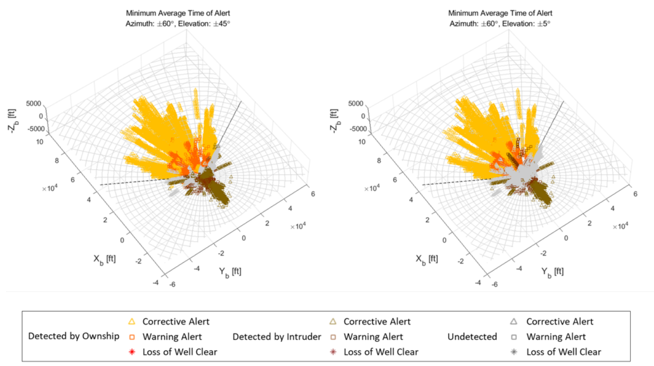

Fig. 17. Intruder Positions with Azimuth and Elevation Limits

of 90%, the maximum detection azimuth of ±90°, elevation of ±28°, and range of 16,000 ft is a combination that well balances the sensor performance requirements without any

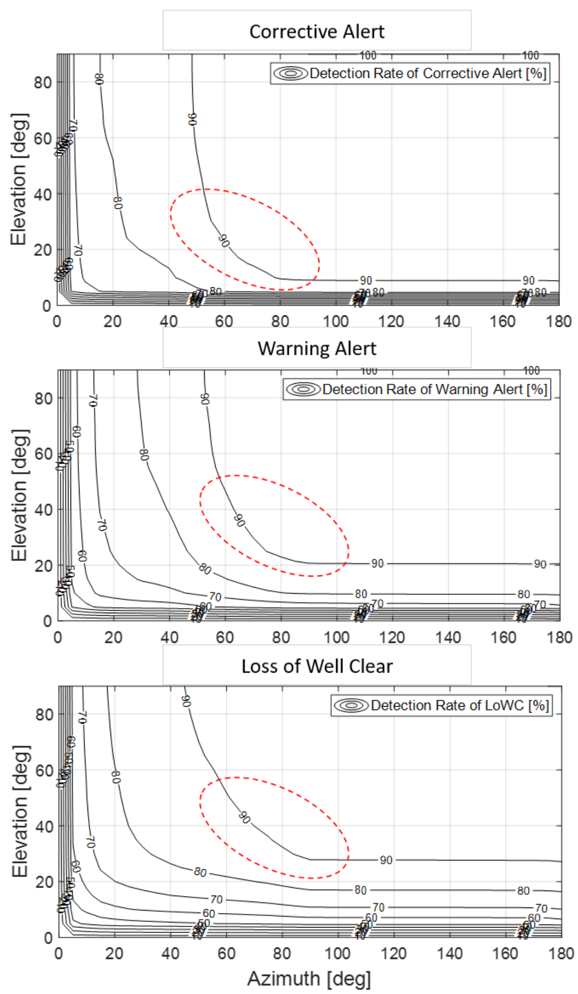

Fig. 18. Detection Rate Contours with Respect to Azimuth and Elevation Limits (τ^*_{mod} = 0 sec)

inefficiency.

Since LoWC occurs only when the distance is within 1,500 ft, any detection range above 1,500 ft does not change the detection rate. The tradeoff between azimuth and elevation still exits.

Fig. 20 shows the surface when the detection rate is increased to 95%. It can be observed that, to increase the detection rate, the elevation and range limits should be increased. The conditions for 95% detection rate are summarized in Table IV assuming ±90° for the azimuth limit. For each alert level and alter time, three combinations are presented that are minimum elevation limit, minimum range limit, and optimal. It should be noted that the optimal condition simply represents one point chosen from the corner so that the actual

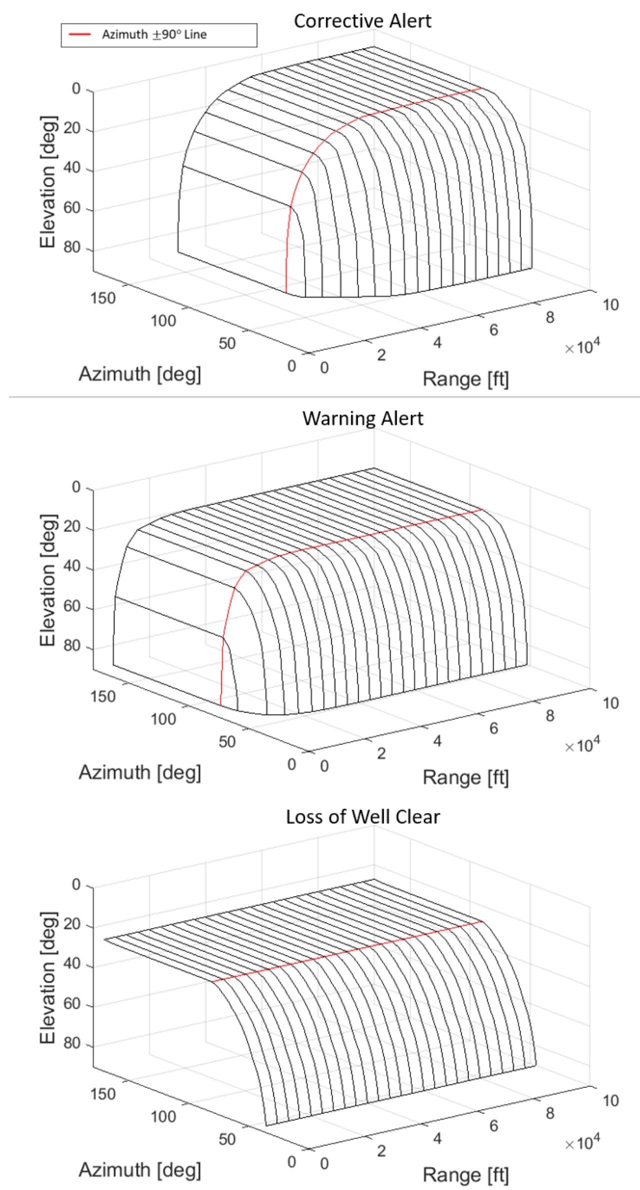

Fig. 19. 90% Detection Rate Surface (τ^*_{mod} = 0 sec)

values can change depending on the other requirements.

V. Conclusions

This paper analyzes DWC alerting criteria suitable for the terminal area using 100 days of selected ADS-B trajectories recorded around two largest airports in the Republic of Korea, ICN and GMP. To correctly assess the risk before the controller intervention, a route-finding algorithm is developed, and the trajectories are regenerated using this algorithm. It is discovered that the proposed DWC alerting criteria for the terminal area in [3], [4] are applicable to the Korean National Airspace. However, further investigation is necessary to assess the trade off between safety and number of nuisance alerts for τ^*_{mod}, since the reductions in number of alerts were small for τ^*_{mod} below fifteen seconds.

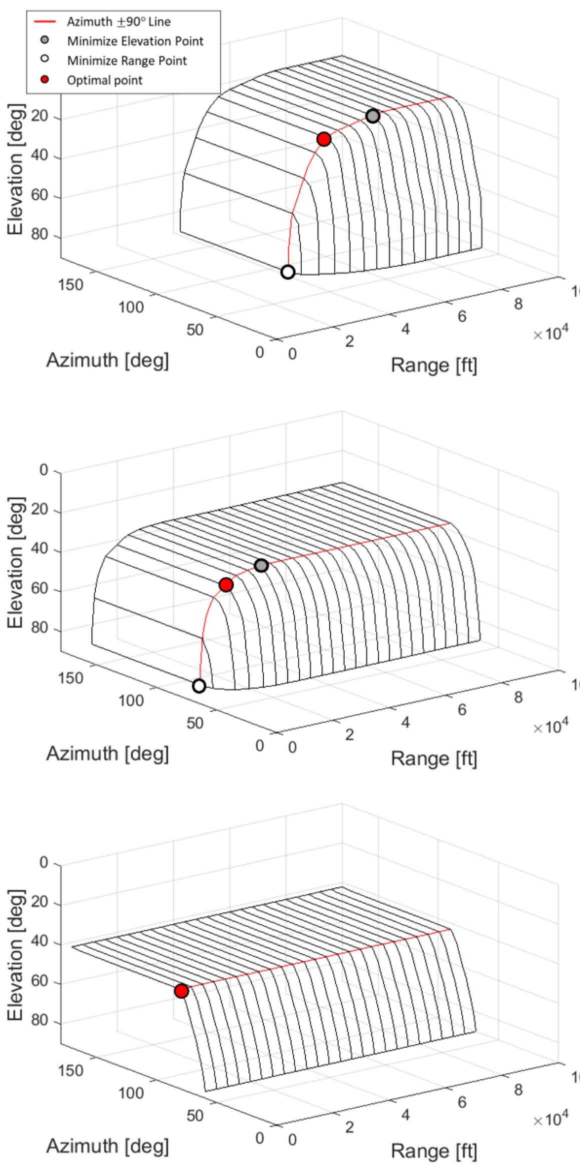

Fig. 20. 95% Detection Rate Surface (τ^*_{mod} = 0 sec)

TABLE IV
Condition for 95% Detection Rate with the Azimuth Limit of ±90° (τ^*_{mod} = 0 sec)

Alert Type	**Alert Time**	**Minimize, Optimize**	**Elevation** (±,°)	**Range** (ft)
Corrective Alert	Early	Elev.	11.83	100,000
		Range	90	72,420
		Optimal	20	80,630
	Min. Avg.	Elev.	19.48	76,000
		Range	90	42,300
		Optimal	26.24	56,000
	Late	Elev.	35.51	32,000
		Range	90	13,280
		Optimal	40	21,660
Warning Alert	Early	Elev.	29.34	80,000
		Range	90	29,620
		Optimal	41.6	44,000
	Min. Avg.	Elev.	36.22	32,000
		Range	90	11,130
		Optimal	42.38	20,000
	Late	Elev.	37.84	24,000
		Range	90	7,133
		Optimal	42.8	12,000
LoWC	Early	Optimal	42.84	4,000
	Min. Avg.	Optimal	40	4,000
	Late	Optimal	39.95	4,000

Using this alerting criteria, the required DAA sensor performances in terms of azimuth, elevation, and range are investigated. The azimuth limit is not required to be more than ±90°, which is smaller than ±110° proposed through simulations over the entire United States of America in [8] and ±140° proposed for non-cooperative conditions in [9]. This is likely to be caused by the more structured and restricted operational environment of Korean National Airspace.

The elevation and range limits show strong tradeoff. 90% detection rate can be achieved by an elevation limit as small as ±12°. However, it requires excessive detection range of over 100,000 ft. Similarly, the range can be reduced to 22,000 ft at the cost of a large elevation limit of ±40° for the same 95% detection rate. Optimal combination of the three parameters is proposed for each alert level and alert time.

The findings of this study will help to establish the specifications and requirements for the DAA system to enable safe operations of UAs in the terminal area.

Acknowledgment

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