Analysis of ADS-B Trajectories in the Republic of Korea with DAA Well Clear Metrics

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***Abstract*—Currently, a team of researchers from leading Universities and Government funded research institutes in the Republic of Korea are working together to enable mixed operation of manned and civil unmanned aircraft in the Korean National Airspace by 2020. In this paper, impacts of the detection range and angle of a generic Detect-And-Avoid (DAA) system on DAA Well Clear (DWC) metrics are investigated. Recorded Automatic Dependent Surveillance-Broadcast (ADS-B) trajectory data within about 150 nautical miles from the Inha University are used, which includes Incheon International Airport (ICN) and Gimpo International Airport (GMP). Efforts are made to provide a guideline for acceptable detection range and detection angles with respect to the risk level that reflects the air traffic characteristics of the Republic of Korea. The analyses show that, with ±70° of detection azimuth, ±30° of detection elevation, and 56,000 ft of detection range, more than 99 % of the threats can be detected by either the ownship or the intruder.**

***Index Terms*—Automatic Dependent Surveillance-Broadcast (ADS-B), Detect-And-Avoid (DAA), DAA Well Clear (DWC), Detection Rate**

I. Introduction

DAA is one of the most important components of Unmanned Aircraft System (UAS) to allow integrated operations of UAS with manned aircraft. Identifying suitable detection sensor performances are a continuing research topic. Park *et al.* performed fast-time simulations using Visual Flight Rule (VFR) traffic data in the Class E airspace combined with a large number of proposed UAS flights in the National Airspace System (NAS) of the United State of America [1]. The horizontal and vertical distributions of the relative positions of the intruders in the DWC violation situations were obtained assuming the UASs did not perform any avoidance maneuvers. Park *et al.* also investigated the impacts of generic sensor parameters such as azimuth, elevation, and range. Johnson *et al.* performed a similar analysis using the revised UAS mission profiles and various DWC alert levels [2]. By incorporating results from these preliminary researches, the Radio Technical Commission for Aeronautics (RTCA) officially published the Minimum Operational Performance Standards (MOPS) [3]. In the MOPS, four DWC alert levels are defined.

The current research attempts to analyze the air traffic characteristics of the Republic of Korea using the DWC alert levels from the MOPS. As general aviation traffic in the Class E airspace is almost non-existent in the Korean National Airspace, recorded ADS-B data of large transport aircraft are used. One of the previous researches performed by the authors investigated the traffic density and identified high risk areas using the ADS-B data and DWC criteria [4]. Instead of using the predicted UAS missions that can be somewhat arbitrary, this paper assumes every single aircraft in the traffic data to be the ownship, and all the other aircraft to be the intruders. The process is repeated over all the aircraft in the dataset. When investigating the sensor performances, every aircraft is assumed to have the same sensor. Detections are categorized by detection by the ownship and detection by the intruder.

Following this introduction, Section II explains how the trajectory data used for the study are collected and processed. Section III presents the DWC metrics with detailed equations. Section IV presents the impacts of three basic sensor performance parameters, horizontal azimuth range, vertical elevation range, and distance range, on the detection rates at various risk levels, and provides reference values that reflect the traffic characteristics of the Korean National Airspace. Finally, Section V concludes the paper with future plans.

II. ADS-B Trajectories

A. Selection of Data

Inha University has been recording track data using an ADS-B receiver since the end of 2016. Reception range is about 150 nautical miles that covers the most congested airspace in the republic of Korea including the two largest airports, ICN and GMP. For this study, among the data collected from February to December 2017, 30 days with high traffic volume and data quality were selected. ADS-B data processing and track point extraction are described in [4]. Fig.1 shows all the track points contained in the selected data set. Enlarged view reveals the complicated route structures near the two airports.

The selected data are the trajectories of 47,425 flights (About 1,581 flights per day). Most of the flights are departures and arrivals at ICN and GMP with some overflights within the reception range.

B. Regeneration of Aircraft Trajectories

Upon examining the ADS-B data, it was discovered that the raw position and time data are not suitable for this kind of risk analysis due to intermittent data loss and unsynchronized

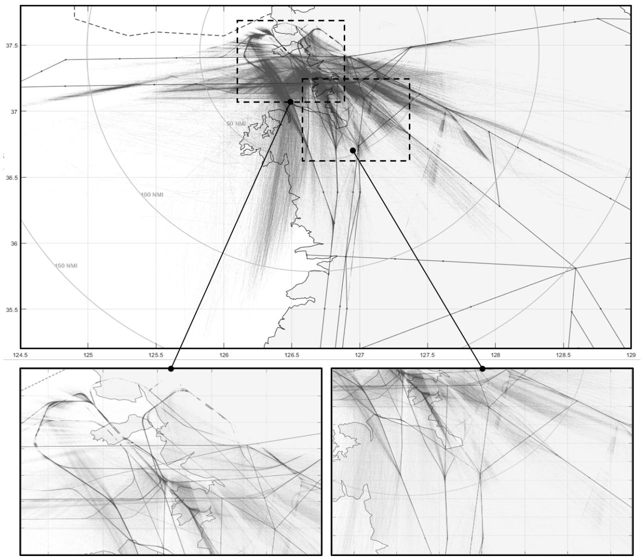

Fig. 1. ADS-B Data around 2 Major Airports in Korea

timestamps. For this study, the trajectories were regenerated by a trajectory generation model [5] with the recorded ADS-B data as a flight plan input. The Base of Aircraft Data (BADA) is used for the aircraft performance parameters. This trajectory generation model updates the position and states of an aircraft at each time step using the calculated flight path angle and heading error from the current state. The flight plans are produced by extracting waypoints from ADS-B data using the Ramer-Douglas-Peucker algorithm [6].

All trajectories are regenerated at a synchronized one second time step. For about 2.7% of the flights, trajectories are regenerated using linear interpolation because no compatible aircraft type can be found in BADA. Interpolated trajectories may not be realistic, but, due to the relatively small percentage, they are not expected to impact the overall results.

III. DAA Well Clear Metrics

A. DWC Definition

DWC is a measure of the risk for the DAA system of unmanned aircraft. For this study, the revised standards published in the RTCA document, "Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems" is used [3]. It mathematically defines the "Well Clear" boundary by calculating Modified Tau (τ_{mod}), Horizontal Miss Distance (HMD), and Vertical Separation(d_h) in (1) through (3) and by checking if the condition in (4) is satisfied. With the given threshold values for Loss of DAA Well Clear (LoWC), if (4) is satisfied, the two aircraft are in LoWC situation, which should be avoided by the DAA system.

$$\tau_{mod} = \begin{cases} 0 & (r_{xy} \leq DMOD) \\ \frac{DMOD^2 - r_{xy}^2}{r_{xy}\dot{r}_{xy}} & (r_{xy} > DMOD \ \& \ \dot{r}_{xy} < 0) \\ \infty & (r_{xy} > DMOD \ \& \ \dot{r}_{xy} \geq 0) \end{cases} \tag{1}$$

where

$$\begin{aligned} r_{xy} &= \sqrt{d_x^2 + d_y^2} \\ d_x &= x_2 - x_1 \\ d_y &= y_2 - y_1 \\ v_{rx} &= \dot{x}_2 - \dot{x}_1 \\ v_{ry} &= \dot{y}_2 - \dot{y}_1 \end{aligned}$$

$$HMD = \begin{cases} \sqrt{D_x^2 + D_y^2} & (t_{CPA} > 0) \\ r_{xy} & (t_{CPA} \geq 0) \end{cases} \tag{2}$$

where

$$\begin{aligned} D_x &= d_x + v_{rx} t_{CPA} \\ D_y &= d_y + v_{ry} t_{CPA} \end{aligned}$$

$$t_{CPA} = \frac{d_x \cdot v_{rx} + d_y \cdot v_{ry}}{\dot{v}_{rx} + \dot{v}_{ry}}$$

$$d_h = h_2 - h_1 \tag{3}$$

d_x and d_y represent the relative distance between the two aircraft in the horizontal plane (X-Y axis). v_x and v_x represent the relative velocity, h_1 and h_2 represent the aircraft altitudes. τ^*_{mod}, HMD^*, and d_h^* are the corresponding threshold values for LoWC, and they are 35 seconds, 4,000 ft, and 450 ft respectively.

$$[0 \leq \tau_{mod} \leq \tau^*_{mod}] \& [HMD \leq HMD^*] \& [abs(d_h) \leq d_h^*] \tag{4}$$

B. Risk Levels Related to LoWC

The determination of the risk is calculated from the current and predicted positions and states of both the ownship and the intruder. MOPS [3] defines the standards for each level of risk in order to predict the risk before a LoWC. Table I shows the standards for each level of risk including LoWC.

Alert Time indicates the prediction time horizon from the current time. For example, Preventive Alert means (4) using the threshold values for Preventive Alert is predicted to be satisfied 55 seconds from the current time. Similarly, since the threshold values for Corrective Alert and Warning Alert are the same as the ones for the LoWC, they can be considered 55 and 25 seconds before LoWC respectively. For the values of the Alert Time, the Minimum Average Time of Alert from 'Hazard Zone Alert Threshold' defined in MOPS [3] is selected for this study.

TABLE I
Parameters for DAA Well Clear Alerts

Alert Type	Preventive Alert	Corrective Alert	Warning Alert	LoWC
Alert Time	55 sec	55 sec	25 sec	0 sec
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

IV. Analysis of Detection Ranges

Three basic elements in the detection sensor performance are selected: horizontal azimuth angle range, vertical elevation angle range, and distance range. Azimuth and elevation are analyzed at intervals of 5° from 0° to ±180°. Distance is analyzed at an interval of 4,000 feet.

To gain the general idea of the distribution of other aircraft with respect to the ownship, traffic density plot is generated. For every pair of trajectories, one aircraft is fixed at the center as the ownship, and the relative position of the track points of the other aircraft are plotted as the intruder. Fig.2 shows density by diving the number of track points contained in a cell by the area of the cell, using all the track points of 30-day data. It shows that the density is generally higher in the front side with the slight bias towards the left of the ownship.

For the rest of the study, only the track points with the at least Preventive Alert level of risk are plotted and counted.

A. Horizontal Azimuth

Fig.4 shows the track points of all intruders classified by four DWC levels. As can be seen from Fig. 3, a single intruder aircraft will leave multiple track points at different risk levels. To remove the clutter, only the points at which the risk level changes are sampled and plotted at Fig.4. Since the first three alerts applied to only closing geometries, it shows that corresponding points are mostly concentrated in the front of the ownship. Whereas, LoWC points are distributed in a small circular pattern around the ownship, since any track point that satisfies the distance requirements are considered LoWC regardless of closing or non-closing geometry. Fig.4 also shows that lower risk points are generally farther away from the ownship.

Figs.5-7 show examples of detection result with respect to azimuth range for Corrective Alert. The number of detected points are counted assuming all the aircraft have the same azimuth range. Detection distance is assumed to be infinite and the elevation range is assumed to be ±90°. The blue circles represent the track points detected by the ownship. The green triangles show the points detected by the intruder but undetected by the ownship. The red crosses are the points that are detected by neither the ownship nor the intruder.

Fig.8 shows the change in the detection rate as the azimuth range increases. If a track point is detected by the ownship or the intruder, it is considered detected. The Preventive, Corrective, and Warning Alert curves reach almost 99% detection rate at around ±70°. The results suggest that an azimuth range of ±70° can be a good reference value for establishing the required DAA sensor performance. In the case of LoWC, however, the detection rate increases very slowly compared with the other three predictive alerts. It is because the LoWC include both closing and non-closing cases as explained in Section III. If the DAA system actually maneuvers the aircraft with the detected alerts, the LoWCs are not likely to happen.

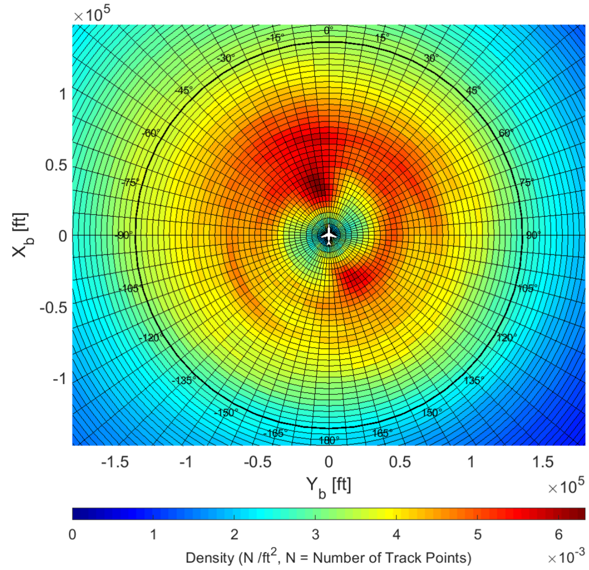

Fig. 2. Relative Horizontal Traffic Density

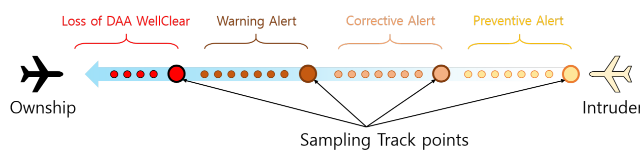

Fig. 3. Sampling Track Points to Display

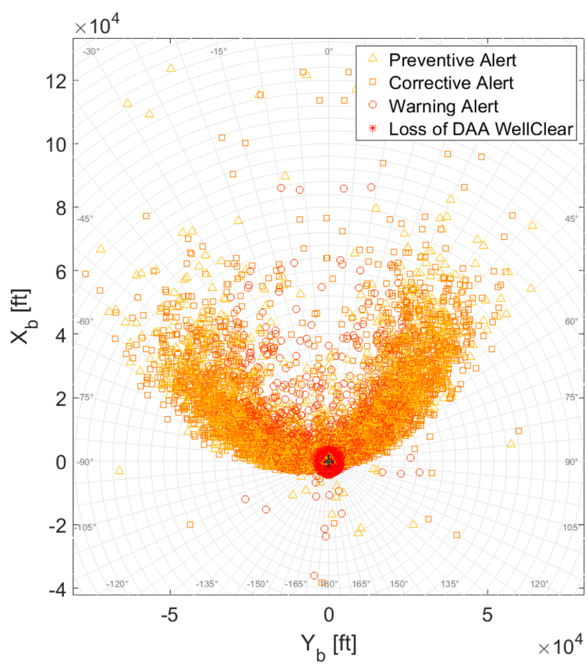

Fig. 4. All Intruder's Track Points with DWC

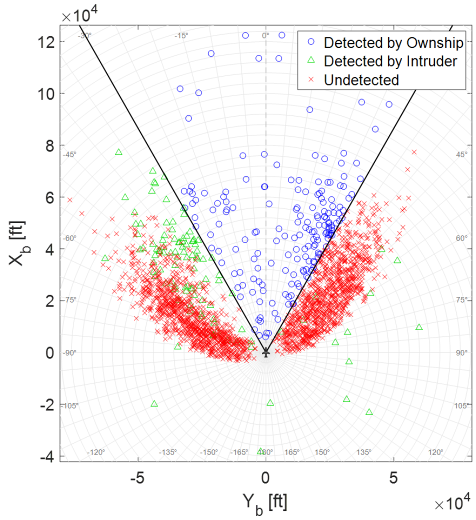

Fig. 5. Detection at ±30° of Azimuth Range

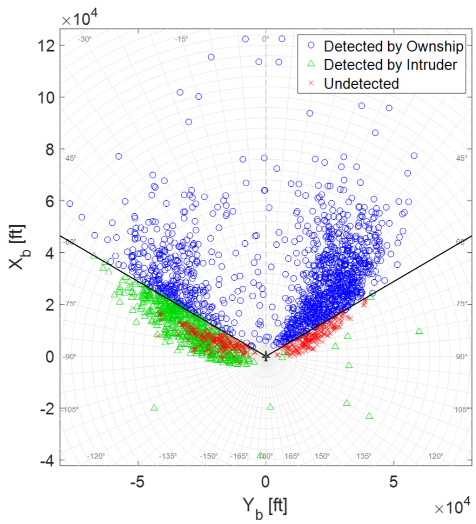

Fig. 6. Detection at ±80° of Azimuth Range

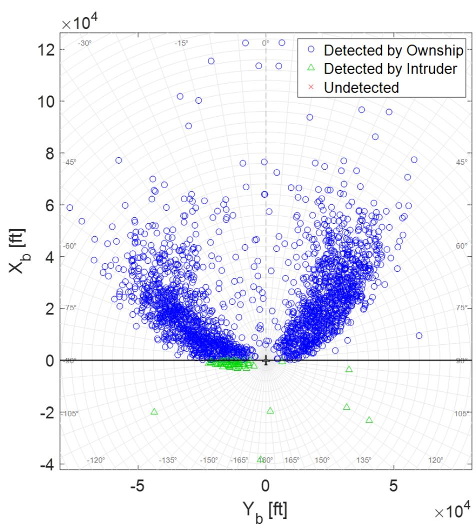

Fig. 7. Detection at ±90° of Azimuth Range

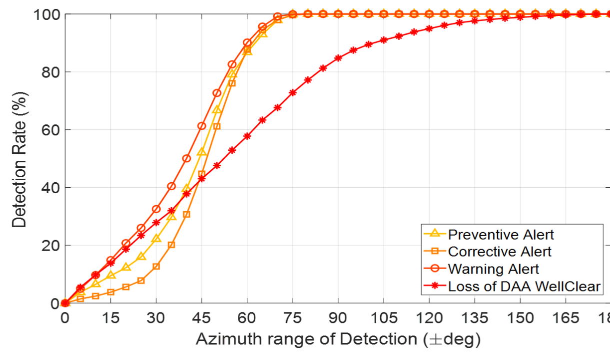

Fig. 8. Detection Rate with Respect to Horizontal Field of View

B. Addition of Elevation Range to the Azimuth Range

The previous analyses assumed ideal sensor performance in terms of the range of vertical elevation angle. In this section, elevation angle limits are imposed in addition to the horizontal azimuth angle ranges. Figs.9-10 show examples of detection results with combinations of azimuth range and elevation range for Corrective Alert. It is discovered that the detection rate is more sensitive to the change in elevation range than azimuth range.

The trade-off between the two ranges are investigated, and the contour plots for constant detection rate are shown in Figs. 11-14 for the four DWC levels. Solid black lines with '100' label represent combinations that achieve 100% detection rate. As can be seen, the detection rates become very insensitive to angle ranges when the elevation range becomes greater than ±20° and the azimuth range becomes greater than ±70°.

C. Distance Ranges

Finally, the impact of the detection distance is investigated. Figs.15-16 show two example detection results with detection distance limits added to azimuth and elevation limits. To gain insight into the impacts of distances, detection rates are plotted in Fig.17 with respect to distance range assuming the azimuth and elevation ranges are not restricted. As most of the track points with DWC alerts are within 80,000 ft, the detection rates become close to 100% at 80,000 ft. 90% detection rate in terms of the Corrective Alert and Warning Alert is achieved with distance limits of 56,000 and 28,000 ft, respectively. For LoWC case, 99.8% are detected within 4,000 ft, and 100% within 8,000 feet, because the HMD threshold is 4,000 ft.

Based on these analyses, three combinations of the minimum required detection ranges are presented in Table II.

V. Conclusion

In this paper, 30 days of ADS-B data are collected around ICN and GMP to analyze the busiest airspace in the Republic of Korea. Using the trajectories generated from the ADS-B data, DWC metrics that consists of three prediction phase alerts and LoWC are computed. Detection rates for the for the four risk levels, either by the ownship or the intruder, are analyzed by limiting the sensor performance in terms

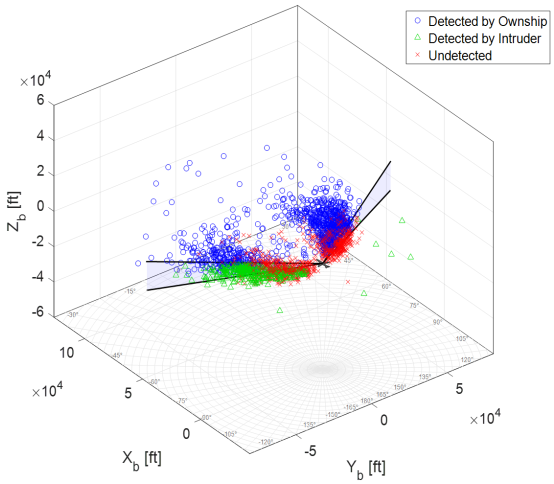

Fig. 9. Detection at ±60° of Azimuth and ±5° of Elevation

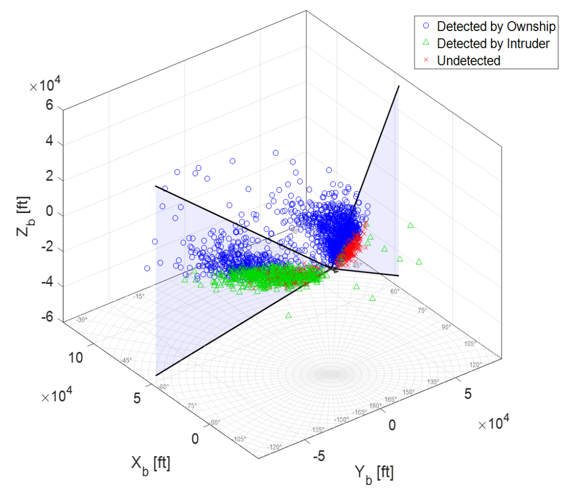

Fig. 10. Detection at ±80° of Azimuth and ±30° of Elevation

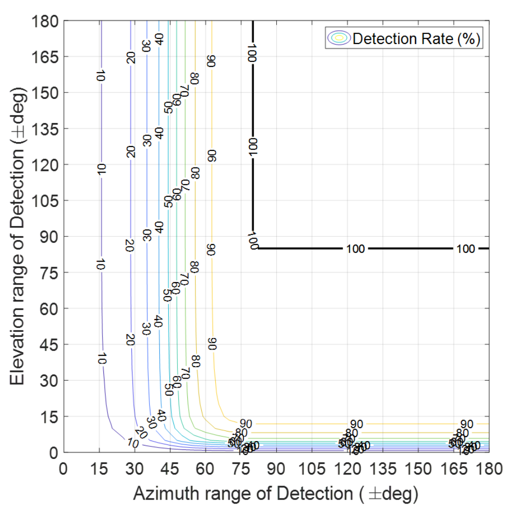

Fig. 11. Detection Rate at Preventive Alert

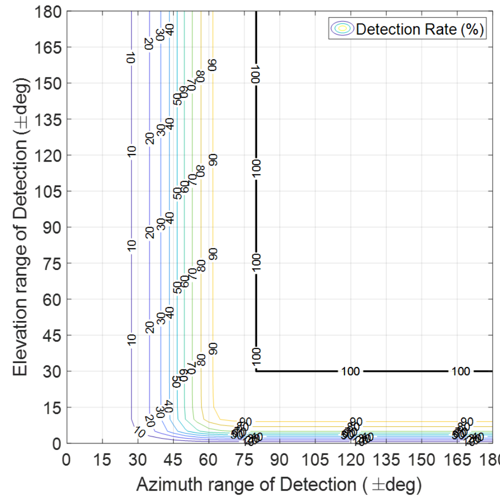

Fig. 12. Detection Rate at Corrective Alert

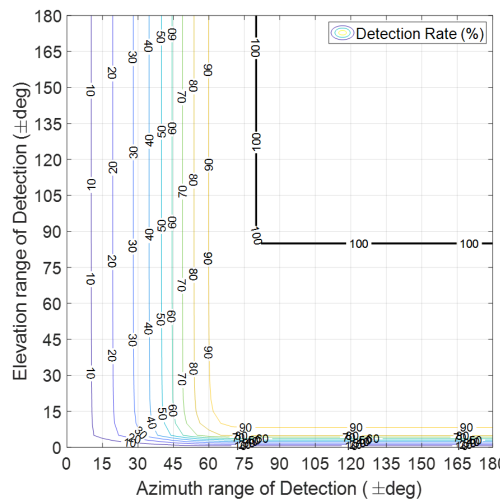

Fig. 13. Detection Rate at Warning Alert

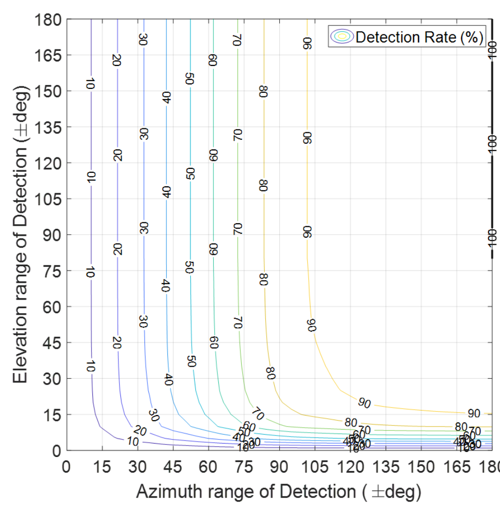

Fig. 14. Detection Rate at Loss of DAA Well Clear

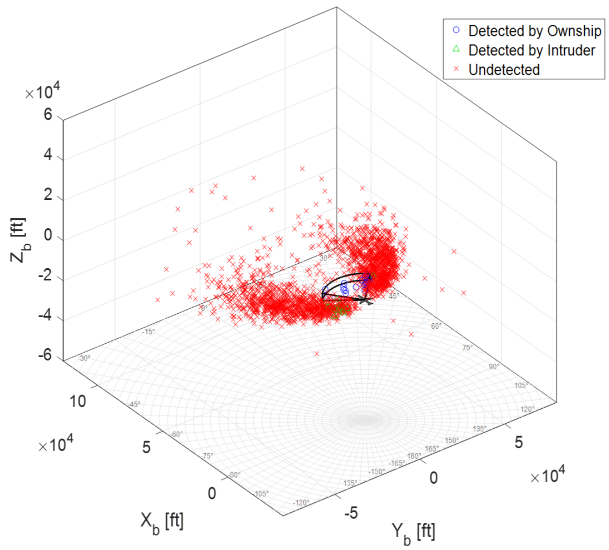

Fig. 15. Detection at ±45° of Azimuth, ±5° of Elevation, and Distance 20,000ft

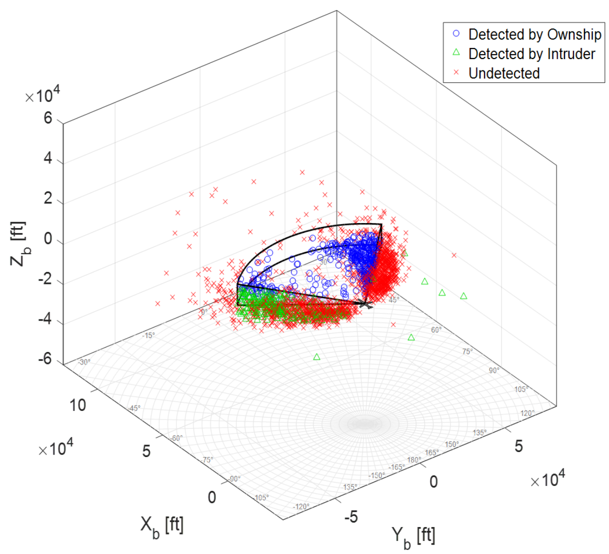

Fig. 16. Detection at ±45° of Azimuth, ±5° of Elevation, and Distance 60,000ft

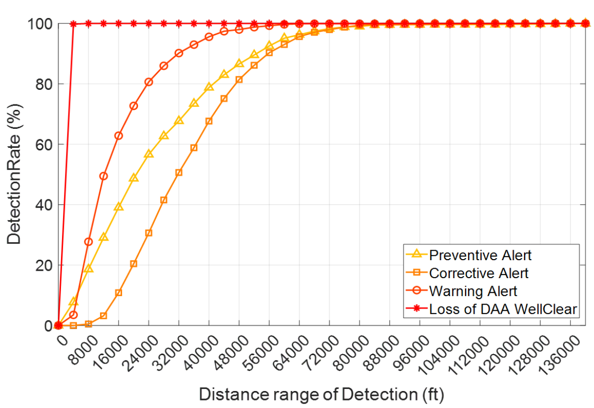

Fig. 17. Detection Rate by Distance

TABLE II
COMBINATION OF RANGE ELEMENTS

		Azimuth	Elevation	Distance
Case 1		± 65°	± 20°	56,000 ft
	Detection rate	*Preventive Alert*		81.99 %
		Corrective Alert		84.61 %
		Warning Alert		93.66 %
		LoWC		58.95 %
Case 2		± 70°	± 25°	56,000 ft
	Detection rate	*Preventive Alert*		88.00 %
		Corrective Alert		88.23 %
		Warning Alert		97.56 %
		LoWC		64.59 %
Case 3		± 70°	± 30°	56,000 ft
	Detection rate	*Preventive Alert*		99.55 %
		Corrective Alert		89.95 %
		Warning Alert		98.58 %
		LoWC		70.34 %

of horizontal azimuth angle, vertical elevation angle, and distance. Three reference values for azimuth, elevation, and distance limits are identified, which are ±70°, ±20°, and 56,000 ft, respectively. It is shown that by slightly varying the limits from the reference values, it is possible to achieve high detection rates. This study only investigated the detection aspect. Future studies will include avoidance algorithms so that the complete DAA system performances can be analyzed.

ACKNOWLEDGMENTS

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