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Analysis of Terrain Collision Risk Using Flown Trajectory Data

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This paper presents the results of calculating Ground Proximity Warning System (GPWS) and Forward-Looking Terrain Avoidance (FLTA) alerts using recorded trajectory data to analyze terrain collision risk. The GPWS is a critical safety system that provides real-time advisory and mandatory warnings to the crew about proximity to terrain, typically preventing Controlled Flight Into Terrain accidents. This study extends the application of GPWS by using it to identify high-risk terrain collision areas. The five GPWS mode functions presented in RTCA-DO 161, and one FLTA function included in the Enhanced GPWS, are utilized to calculate terrain collision risks. The flight trajectory data are collected from the network of Automatic Dependent Surveillance-Broadcast receivers operated by Inha University in the year 2022. The terrain data is derived from the Digital Elevation Model provided by the Korea National Geographic Information Institute. The GPWS and FLTA functions are redefined to suit the given set of data. After analyzing the terrain collision risk in Korea, two distinctive terrain feature and one airspace characteristics that causing the alerts are discovered. This approach offers crucial insights for enhancing aviation safety, improving situational awareness, and developing future strategies to better reduce terrain collision risks.

Nomenclature

CFIT = Controlled Flight into Terrain
GPWS = Ground Proximity Warning System
EGPWS = Enhanced Ground Proximity Warning System
FLTA = Forward-Looking Terrain Avoidance
ADS-B = Automatic Dependent Surveillance-Broadcast
DEM = Digital Elevation Mode
ϕ = Latitude of the flight from ADS-B
λ = Longitude of the flight from ADS-B
h_{ADSB} = Altitude of the flight from ADS-B
v_{ADSB} = Ground speed of the flight from ADS-B
ψ_{ADSB} = Heading of the flight from ADS-B
$\dot{h}_{ADSB}$ = Vertical speed of the flight from ADS-B
h_{DEM} = Terrain altitude from DEM
TC = Terrain clearance
CR = Closure rate
AD = Altitude loss after take off, but before reaching 700 ft
AL = Cumulative altitude loss
SR = Sink rate
AR = Altitude rate
Δt = Time step
D_{FLTA} = Remaining distance until FLTA occurs
dt = Remaining time until FLTA occurs

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I. Introduction

For many years, Controlled Flight into Terrain (CFIT) has been one of the most significant areas of fatality risk in aviation. According to the safety report of the International Civil Aviation Organisation (ICAO), it ranks as the second highest among the five high-risk categories [1]. The Terrain Avoidance Warning System (TAWS) was developed in 1970s to avoid CFITs, and it provides the Ground Proximity Warning System (GPWS). The GPWS is an aircraft-specific system that provides warnings or alerts that are not visible to the pilot along the flight path, including take-off, circling, approach, and landing areas, and is divided into five modes [2]. The standard GPWS relies on a radio altimeter, which has the disadvantage of not reflecting sudden changes in terrain. To address this issue, the Enhanced Ground Proximity Warning System (EGPWS) was developed. The EGPWS overcomes the limitations of radio altimeters by incorporating a global digital terrain elevation database and adding Forward-Looking Terrain Avoidance (FLTA) [3]. The FLTA function looks ahead of the aircraft along and below its lateral and vertical flight path and provides suitable alerts if a potential CFIT threat exists [4]. Threshold values for the FLTA function have been researched [5], and this paper uses the values proposed in [3]. Efficient computation of EGPWS using gridded terrain data has been investigated [6, 7]. These studies present a grid for calculating terrain collision risk from terrain data with a resolution of 300 m x 300 m, assuming constant aircraft speed. Additionally, a study has been conducted that calculated GPWS alerts using actual aircraft trajectory data [8]. [8] analyzed the reason for the GPWS MODE 2 error, even though there was no terrain collision risk to the aircraft.

This paper presents a method for calculating GPWS and FLTA functions using aircraft trajectory data and terrain data, and identifies areas with terrain collision risks in the Korean airspace. Since 2018, Inha University has installed ADS-B receivers across Korea to collect aircraft trajectory data. For this study, ADS-B data of year 2022 are used. The terrain data is derived from the Digital Elevation Model (DEM) provided by the Korea National Geographic Information Institute, featuring a resolution of 90 m x 90 m. Using these data, the five GPWS modes and one FLTA function are calculated. Determining landing configuration is important in order to calculate the GPWS function. The runway identification algorithm presented in [9] is first applied to the ADS-B data to identify the runway used by aircraft. Then, the distance from the runway and the aircraft's altitude are used to determine the landing configuration. For the FLTA, it evaluates whether the aircraft will intersect with the terrain within one minute.

The calculations reveal that a significant number of GPWS and FLTA alerts occur on the runway and its extensions, which is a natural consequence of aircraft landing. Excluding Mode 5 (glide slope deviation), the alerts on the runway and its extensions are disregarded. Even without considering runway extensions, these functions commonly occur when aircraft are preparing to take off or land near an airport. At Gimpo International Airport (GMP), many GPWS and FLTA alerts occur around Cheonggye Mountain, indicating that aircraft are significantly affected by this terrain during landing. At Incheon International Airport (ICN), many FLTA alerts occur when aligning with the runway around the MUNAN waypoint, which is part of the Standard Terminal Arrival Route (STAR) procedure.

Additionally, this study investigates instances where multiple GPWS modes and FLTA alerts are triggered simultaneously. The most frequent combined alerts involve Mode 5 and FLTA, followed by Mode 4 and FLTA. Meanwhile, Mode 4 and Mode 2a alerts are identified to frequently coincide with other alerts near Cheonggye Mountain.

II. Aircraft Trajectory Data and Terrain Data

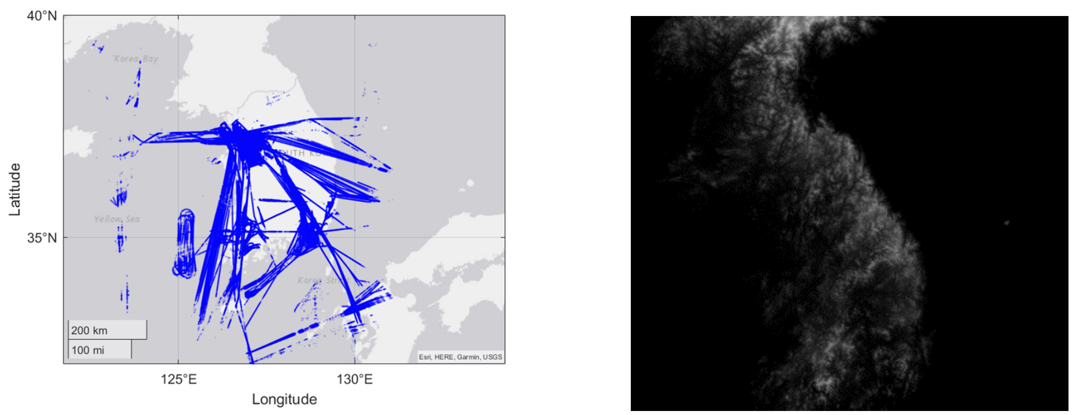
A. ADS-B Data

The ADS-B data is transmitted by aircraft equipped with transponders, which are received by ground or near-aircraft stations to share location information. This data includes details about an aircraft's position, speed, altitude, and heading. Since 2020, all civilian aircraft in the United States and Europe are required to be equipped with an ADS-B system. Since 2018, Inha University has installed ADS-B receivers at various locations across Korea to collect this data. This study utilizes the ADS-B data received by Inha University in 2022. Figure 1a visualizes the ADS-B data received on June 8, 2022.

The main purpose of ADS-B data is to broadcast aircraft information at intervals of one second or less. However, due to various reasons such as the condition of the aircraft's transmitter or the status of ground station receivers, there are times when data are not recorded. As a result, the ADS-B data used in this study does not always have consistent intervals. To address this problem, the trajectory data is synchronized to 1-second intervals using linear interpolation.

B. DEM Data

The DEM is a crucial tool for accurately representing and analyzing the Earth's terrain. The DEM captures the elevation data of the Earth's surface in a gridded format, where each cell or pixel contains an elevation value representing the terrain's height at that specific location. The DEM data used in this study is based on sea level, specifically the sea level of Incheon Port as a baseline for elevation measurements. This DEM model has a resolution of 90 meters by 90 meters, providing detailed topographical information. However, it is important to note that the DEM data primarily focuses on natural terrain features, excluding man-made structures such as buildings and other constructions. Figure 1b visualizes the DEM data.



(a) ADS-B data. **(b) DEM data.**

Fig. 1 Trajectory and terrain data.

III. GPWS and FLTA Calculation Methods

The GPWS/TAWS is a system that provides sufficient information and warnings to the crew to detect potential terrain collision risks so that the crew can take effective action to prevent a CFIT situation. In this study, the GPWS and FLTA functions contained in the GPWS/TAWS system are utilized to calculate terrain collision risk in Korean airspace. The GPWS function which presented in the Radio Technical Commission for Aeronautics DO-161A [2], serves as an indicator to warn of abnormal approaches when an aircraft is nearing terrain. It categorizes calculations into five modes based on the flight situation: excessive descent rate, excessive terrain closure rate, negative climb rate and accumulated altitude loss, flight into terrain with less than 500 feet, and glide slope deviation. For the GPWS, the mode calculation method differs depending on the landing configuration. Since the ADS-B data does not contain specific landing information, it is necessary to determine this configuration first. The runway is identified using the runway identification algorithm presented in [9]. An aircraft is assumed to be in a landing configuration if the following conditions are met: the distance between the aircraft and the identified runway is within 10 nmi, which corresponds to the maximum distance for final approach fixes as specified by ICAO, and the aircraft's altitude is less than 5,000 feet.

Typically, the GPWS and the FLTA rely on sensors and radio altimeters on the aircraft. However, to utilize trajectory data for these calculations, it is necessary to redefine the metrics. The modified definitions of GPWS and FLTA parameters are given in Eqs. (1) through (9). Figure 2 shows a simplified visualisation of the parameters.

$$TC_i = h_{ADSBi} - h_{DEM}\left(\phi_i, \lambda_i\right) \tag{1}$$

$$CR_i = -\frac{d}{dt}\left(TC_i\right) = -\frac{TC_i - TC_{i-5}}{5\Delta t} \tag{2}$$

$$AD_i = \begin{cases} -\left(h_{ADSBi+1} - h_{ADSBi}\right) & \left(h_{ADSBi+1} < h_{ADSBi}\right) \\ 0 & \left(h_{ADSBi+1} \geq h_{ADSBi}\right) \end{cases} \tag{3}$$

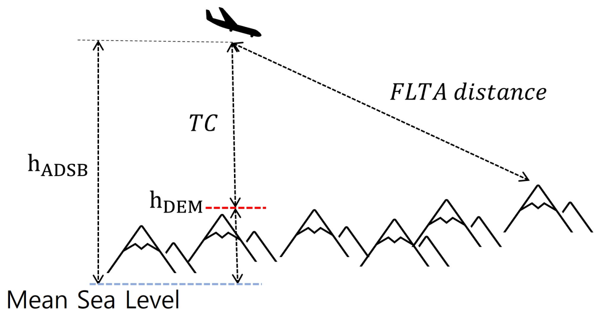


Fig. 2 GPWS parameters.

$$AL = \sum_i AD_i \tag{4}$$

$$SR_i = -\dot{h}_{ADSBi} \tag{5}$$

$$AR_i = \dot{h}_{ADSB_i} \tag{6}$$

$$v_n = v_{ADSBi} \cos\left(\psi_{ADSBi}\right) \tag{7}$$

$$v_e = v_{ADSBi} \sin\left(\psi_{ADSBi}\right) \tag{8}$$

$$D_{FLTA} = \left(\sqrt{{v_n}^2 + {v_e}^2 + SR^2}\right) dt \tag{9}$$

A. GPWS Calculation

1) MODE 1: Excessive Descent Rate
   This mode monitors the radio altitude and vertical speed, and generates an alert when the current flight path is descending at an excessive rate. The warning consists of three envelopes. It is calculated from the SR and TC shown in Eqs. (5) and (1). In this study, terrain clearance is used instead of the radio altitude.
2) MODE 2: Excessive Terrain Closure Rate
   This mode monitors radio altitude, calculated airspeed, and landing gear configuration and generates an alert when the current flight and terrain are approaching at excessive speeds. It is divided into two modes: Mode 2a and Mode 2b, which are calculated based on whether the aircraft is landing or not. Mode 2a is calculated for non-landing situations, while Mode 2b is calculated for landing situations. It is calculated from the CR and TC shown in Eqs. (2) and (1). In Eq. (2), if the Δt is set to 1 second, the calculation is highly affected by noise, so the time step is set to five seconds to calculate the average rate of change for five seconds.
3) MODE 3: Negative Climb Rate and Accumulated Altitude Loss
   This mode monitors radio altitude and aircraft altitude, and generates an alert when altitude loss or a negative climb rate occurs after take off. It is calculated when the aircraft is at an altitude of less than 700 feet immediately after take off. It is divided into two modes: Mode 3a and Mode 3b, which are calculated using completely different variables. Mode 3a is calculated from the SR and TC shown in Eqs. (5) and (1). Mode 3b is calculated from the AL and TC shown in Eqs. (4) and (1). When calculating AL, the cumulative loss is calculated by stacking the values of AD given in Eq. (3) at a one second intervals. TC is used instead of radio altitude.
4) MODE 4: Flight into Terrain with less than 500 feet
   This mode monitors radio altitude, landing gear configuration, landing flap configuration, and airspeed and generates an alert for insufficient terrain clearance when the aircraft is not in the proper landing configuration. The calculation method is divided into two methods: GEAR OTHER THAN LANDING CONFIGURATION

and GEAR AND/OR FLAP OTHER THAN LANDING CONFIGURATION, and in this study, the calculation is based on GEAR AND/OR FLAP OTHER THAN LANDING CONFIGURATION when not in a landing situation. The warning consists of three envelopes. It is calculated from the AR and TC shown in Eqs. (6) and (1). TC is used instead of radio altitude.

5) MODE 5 : Glide Slope Deviation
This mode monitors the radio altitude, glide slope deviation, and landing gear configuration, and generates an alert when the descent glide slope deviation exceeds the threshold. It is calculated from the glide slope deviation and TC as shown in Eq. (1). Figure 3 shows the visualization of how the glide slope deviation is calculated. Baseline glide slope of 3 degree is established from the runway threshold. As the deviation is indicated to the pilots using the number of dots, two envelopes for one dot and two dot deviations are constructed using the specifications given in Fig. 3. The altitude value is determined by the difference between the aircraft's ADS-B altitude h_{ADSB} and the runway altitude provided by the DEM $h_{DEM_{runway}}$, not using the TC.

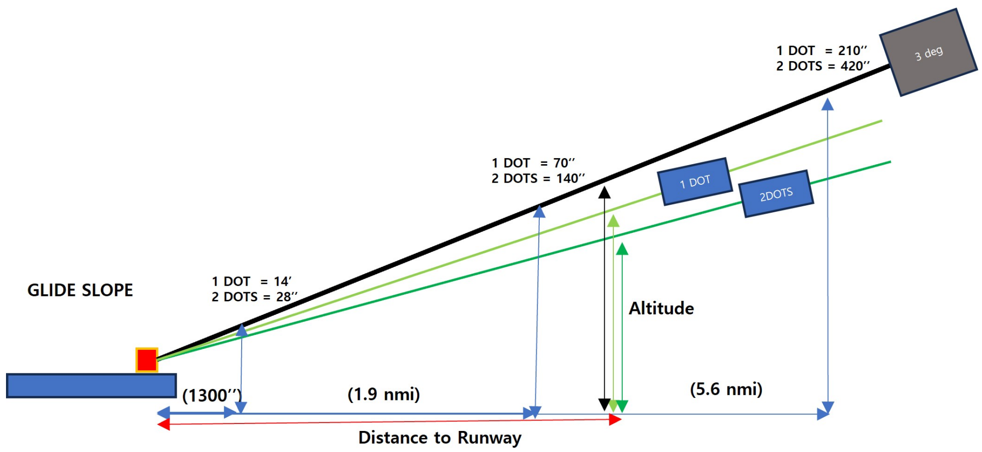


Fig. 3 Glide slope deviation method.

Table 1 GPWS modes.

Mode	Situation	Parameter	Configuration
Mode 1	Excessive descent rate	SR	All
Mode 2a	Excessive terrain closure rate	CR	Not in landing
Mode 2b	Excessive terrain closure rate	CR	Landing
Mode 3a	Negative climb rate before acquiring 700 feet	SR	Take Off
Mode 3b	Accumulated altitude Loss before acquiring 700 feet	AL	Take Off
Mode 4	Flight into terrain with less than 500 feet	AR	Not in landing
Mode 5	Glide slope deviation		Landing

All the GPWS modes, the x-axis parameter of the alert envelope and the configurations are summarized in Table 1.

B. FLTA Calculation

The FLTA function continuously correlates the aircraft's predicted flight path with an internal terrain elevation database up to one minute in advance. An alert is generated whenever the predicted flight path intersects with the correlated terrain elevations. The boundaries of the terrain detection range for the FLTA are defined in [4]. In this study, the risk level is classified according to the remaining time until the aircraft collides with the terrain, which is defined as

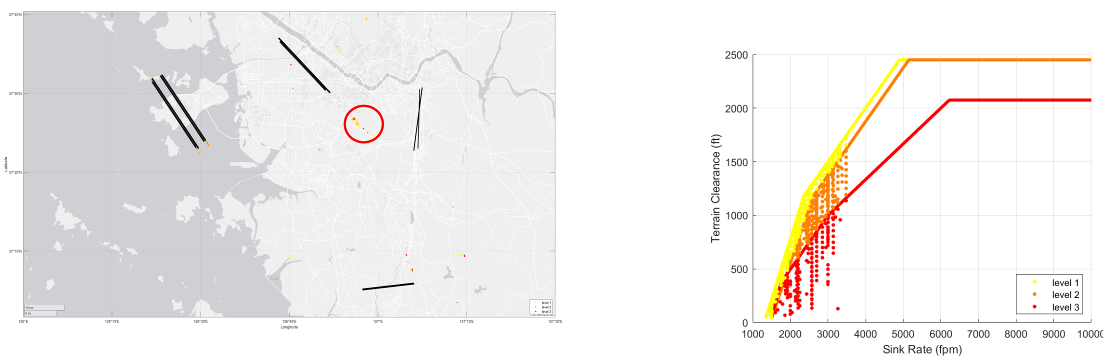
Level 2 and Level 1 at 30 and 60 seconds, respectively, using the method proposed in [3]. Aircraft's predicted flight path is calculated using v_{ADSB}, ψ_{ADSB}, and $\dot{h}_{ADSB}$ in the ADS-B data.

IV. Results

The following section presents the results of GPWS and FLTA analyses. Many GPWS and FLTA alerts are detected on the runways and their extensions. To focus on meaningful alerts that can potentially become a safety issue, alerts on the runways and their extensions are excluded, except for Mode 5, which detects glide slope deviations during aircraft landing. In this study, the runway extension is defined as twice the length of the runway threshold on both sides, with a width of 200 meters. This study examines the airspace around ICN and GMP where the traffic volume is large. Area near Gimhae International Airport (PUS) is examined only for the FLTA case due to its terrain characteristics. The black line segments shown in the following figures represent the runway extensions that encompass the runways.

A. Mode 1: Excessive Descent Rate

Mode 1 evaluates the excessive descent rate of aircraft and generates an alert when the descent rate exceeds acceptable limits. Most of the alerts are detected when landing from South to North. For aircraft approaching GMP, alerts are concentrated around a small mountainous area, which lies directly under the approach path. The highest peak in this area is Cheonggy Moutain with an elevation of 616 m. For ICN, alerts are concentrated at the southern end of the runway extension, which are not likely to be real safety issue. The results are categorized into three envelopes to distinguish the severity of the risks. Figure 4 shows the results of Mode 1. Figure 4a shows the areas of the alert, and Fig. 4b shows the detected data points that are inside the envelope. The red-highlighted area in the Fig. 4a represents Cheonggye Mountain area.



(a) Mode 1 area. **(b) Mode 1 envelope.**

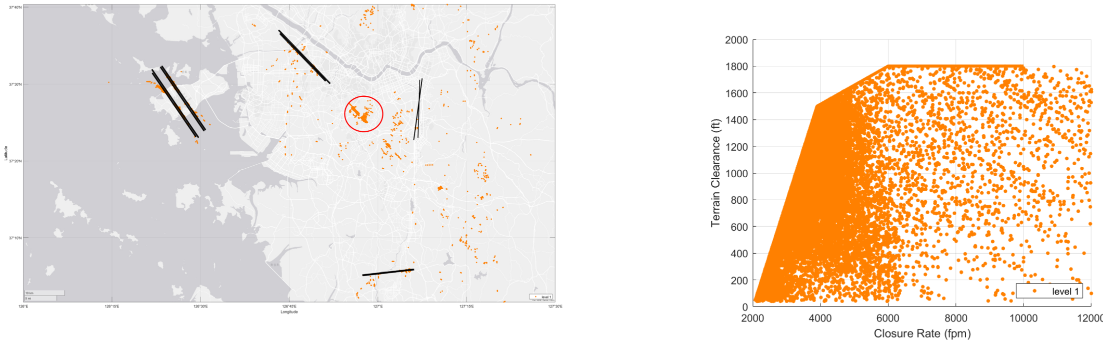
Fig. 4 Mode 1 results.

B. Mode 2: Excessive Terrain Closure Rate

Mode 2 evaluates the excessive closure rate with terrain and generates an alert when the aircraft's approach speed towards the terrain exceeds acceptable limits. Figures 5 and 6 shows the spatial distribution of the alerts and the detection envelops for Mode 2a and 2b, respectively. It can be observed that the closure rates are considerably larger due to the terrain not being flat even though the mountains peaks are not high. With the more stringent criteria of Mode 2b, it can be observed that the alerts are concentrated near the same Cheonggye Mountain area as shown in Fig. 6a. The results suggest that Cheonggye Mountain area requires a close attention; however, the Mode 2 can lead to an excessive false alerts in other areas.

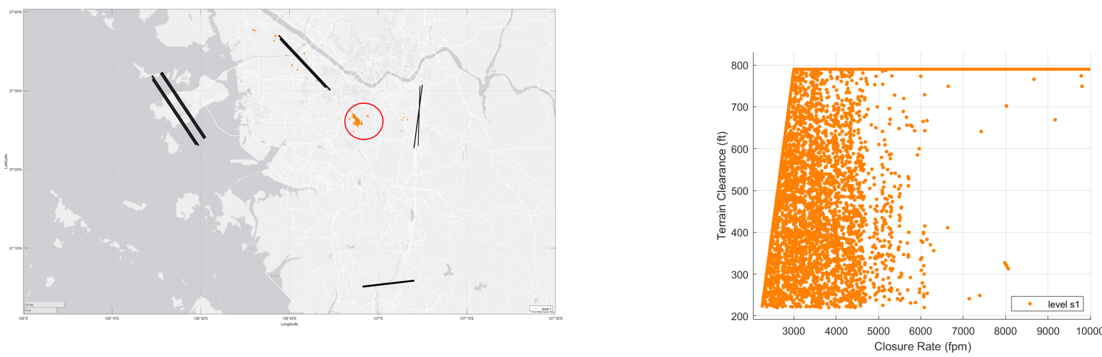
C. Mode 3: Negative Climb Rate and Accumulated Altitude Loss

Mode 3 evaluates the negative climb rate and altitude loss after take off and generates an alert when the mode-dependent variable is lager than the threshold value. Figures 7 and 8 show the alert locations and envelopes for Mode 3a



(a) Mode 2a area. **(b) Mode 2a envelope.**

Fig. 5 Mode 2a results.



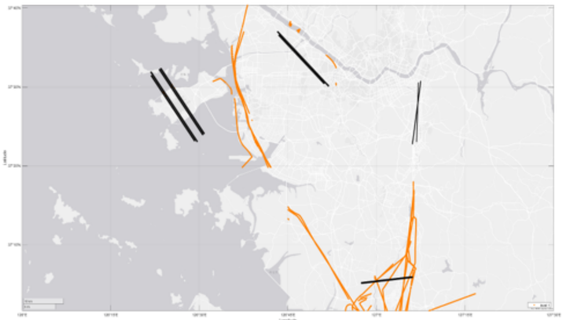
(a) Mode 2b area. **(b) Mode 2b envelope.**

Fig. 6 Mode 2b results.

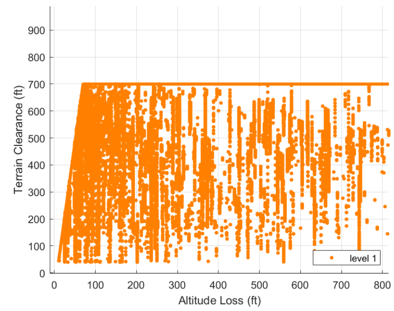
and Mode 3b, respectively. Among all the modes and FLTA, Mode 3 is the only risk metric for the takeoff phase. Unlike other modes, it does not reveal a particular region of high concentration. Further investigation is required for this mode.

(a) Mode 3a area. **(b) Mode 3a envelope.**

Fig. 7 Mode 3a result.



(a) Mode 3b area.

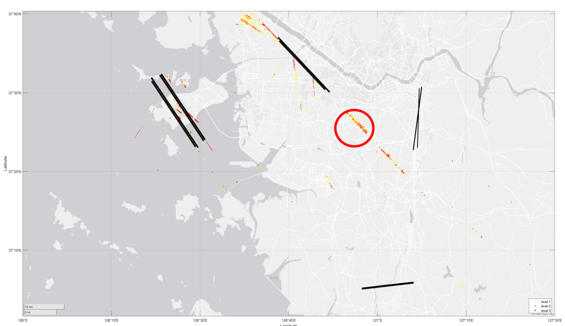


(b) Mode 3b envelope.

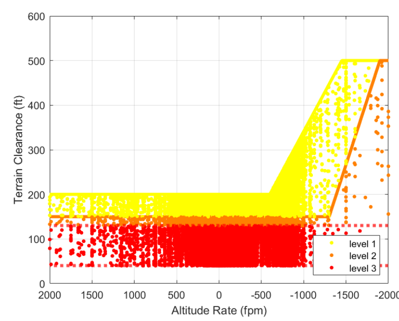
Fig. 8 Mode 3b result.

D. Mode 4: Flight into Terrain with less than 500 feet

Mode 4 evaluates the unsafe terrain clearance when the aircraft does not maintain a safe distance from the terrain and generates an alert when the aircraft's altitude is dangerously low relative to the terrain. Mode 4 alerts are mostly detected along the GMP's runway on both sides as shown in Fig. 9a. In addition, similar to Modes 1 and 2, alerts are concentrated near the Cheonggye Mountain area. The results are categorized into three envelopes to distinguish the severity of the risks shown in Fig. 7b.



(a) Mode 4 area.



(b) Mode 4 envelope.

Fig. 9 Mode 4 result.

E. Mode 5: Glide Slope Deviation

Mode 5 evaluates the glide slope deviation and generates an alert when the aircraft's below glide slope deviation is larger than the threshold value. Due to the characteristics of glide slope deviations, this mode has many alerts on runways and runway extensions at both GMP and ICN. As glide slope deviation is an important metric related to unstable approach and is not directly related to terrain characteristics, Mode 5 is not a focus of this study.

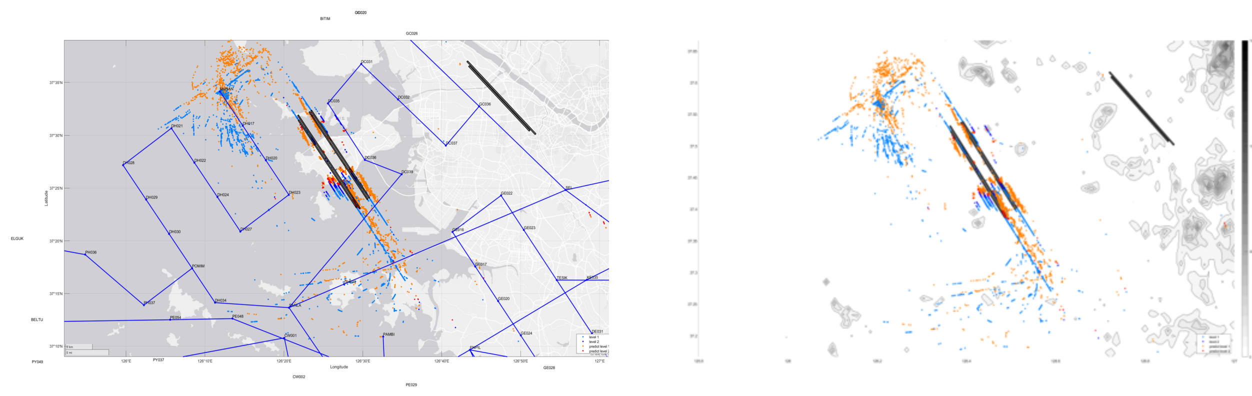
F. FLTA: Forward-Looking Terrain Avoidance

The FLTA function evaluates whether the aircraft's altitude intersects the terrain altitude and generates an alert when the terrain is encountered within one minute. As FLTA is not limited to any flight phases, it is the most widely detected alert.

Figure 10a shows the alerts with the STAR procedures overlaid for ICN. The orange and red dots represent the potential collision locations for levels 1 and 2, respectively, while the light blue and dark blue dots indicate the location of the aircraft when the alerts are triggered for levels 1 and 2, respectively. It can be observed that most of the alerts are level 1, and the orange dots are mostly scattered over the sea, which means the alerts are not triggered by terrain characteristics. Figure 10b shows the terrain contours and also confirms that the potential collision points are not terrain features.

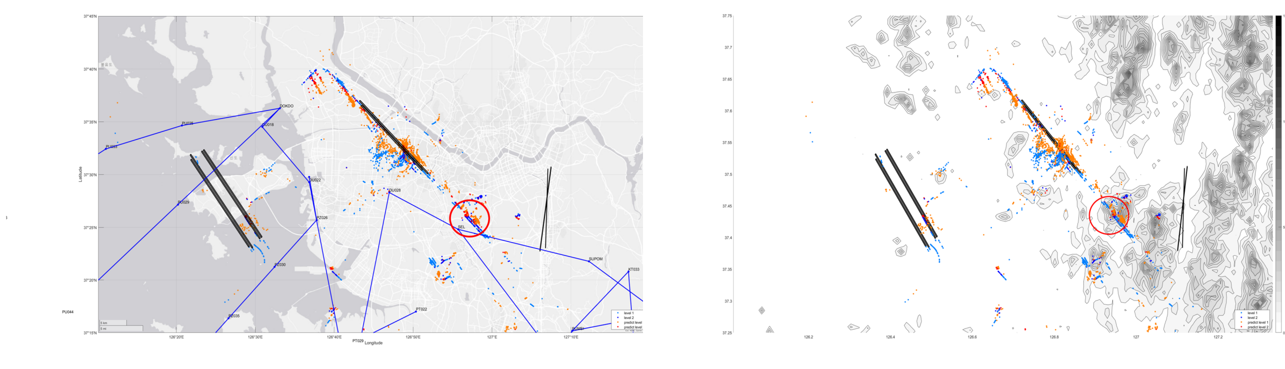
Figure 11a shows the alerts around GMP. Similar to ICN, for south flow, alerts are concentrated around the sharp right turn to the runway. However, for the north flow, alerts are concentrated around the Cheonggye Mountain area similar to other modes, which can be confirmed in Fig. 11b that shows the elevation contours.

For FLTA, the area around PUS shows the impacts of the terrain features. For this area, only seven month data from June to December 2022 are analyzed. A large number of level 1 FLTA alerts are detected north of the runway near the Sinei Mountain area. It can be observed that for the aircraft approaching PUS from north that make a sharp right turn to land experience FLTA alerts towards the Sinei Mountain area, which can be seen in Fig. 12 marked with a red circle.



(a) RKSI FLTA area. **(b) RKSI FLTA area with 3D contours.**

Fig. 10 RKSI FLTA result.

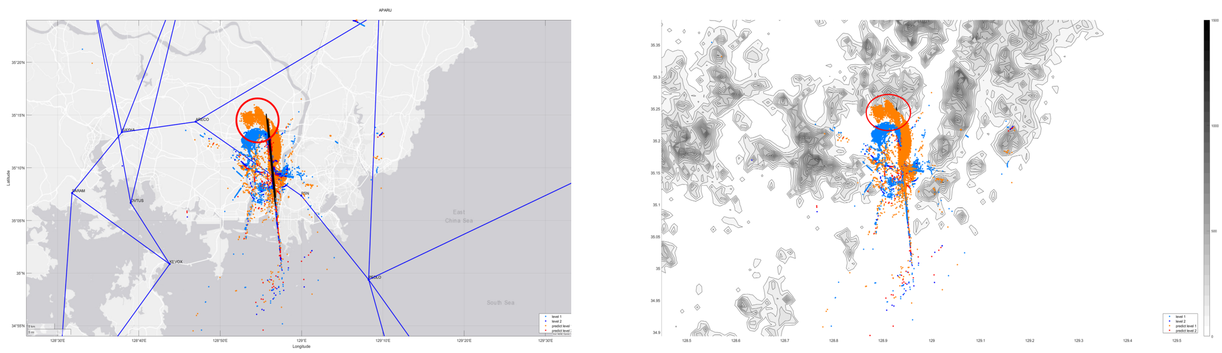


(a) RKSS FLTA area. **(b) RKSS FLTA area with 3D contours.**

Fig. 11 RKSS FLTA result.

G. Combined Alerts: Multiple GPWS Modes and FLTA

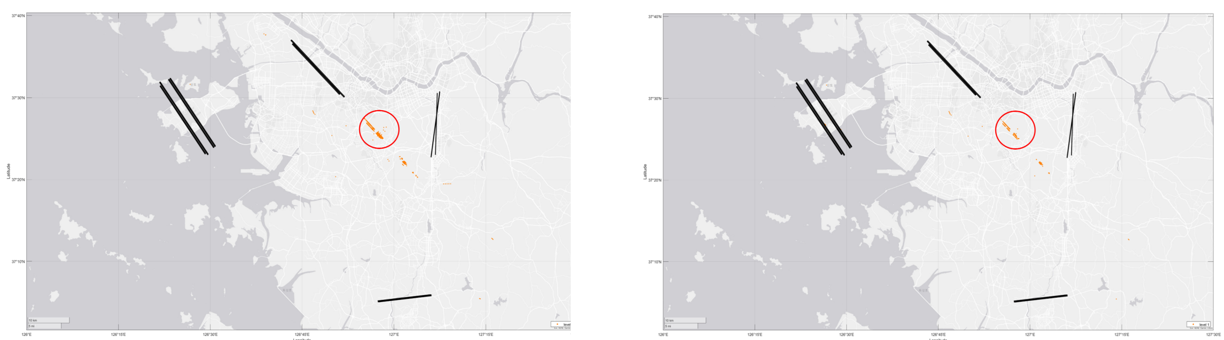
This study analyzes instance where multiple GPWS modes and FLTA alerts are triggered simultaneously. By comparing cases when GPWS and FLTA occur, the research identifies the location where multiple alerts occur at the same time. The findings reveal that FLTA alerts frequently occur in combination with other GPWS modes. The most frequent combined alerts are Mode 5 and FLTA, followed by instances where Mode 4 and FLTA occur together, and then Mode 2a and FLTA. Additionally, Mode 2a and Mode 4 frequently occur with other alerts, and these combined alerts are often found near Cheonggye Mountain, indicating it as a significant risk area. Figure 13a shows the area where the Mode 2a and FLTA alerts occur simultaneously, and Fig. 13b shows the area where the Mode 2a and Mode 4



(a) RKPK FLTA area. **(b) RKPK FLTA area with 3D contours.**

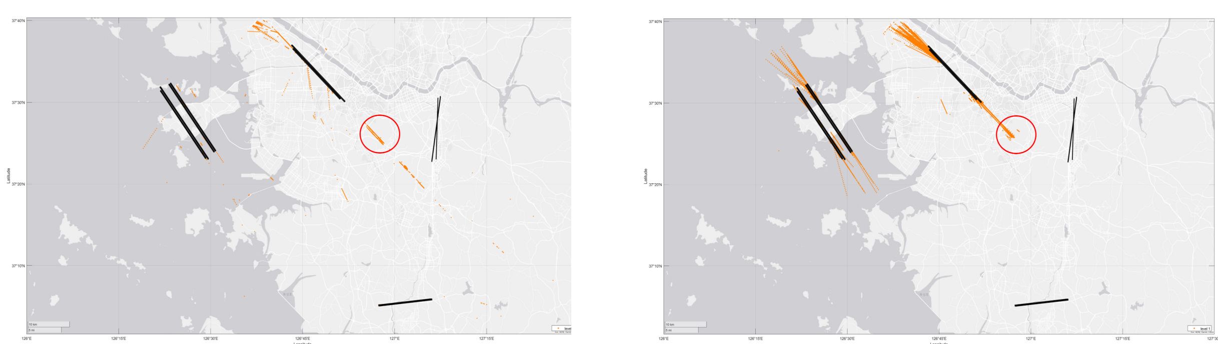
Fig. 12 RKPK FLTA result.

alerts occur same time. Figure 14a shows the area where the Mode 4 and FLTA alerts occur simultaneously, and Fig. 14b shows the area where the Mode 5 and FLTA alerts occur same time.



(a) Mode 2a and FLTA area. **(b) Mode 2a and Mode 4 area.**

Fig. 13 Combined alerts with Mode 2a.



(a) Mode 4 and FLTA area. **(b) Mode 5 and FLTA area.**

Fig. 14 Combined alerts with FLTA.

V. Conclusion

In this study, the GPWS and FLTA functions are redefined to be calculated using ADS-B flight trajectory data and terrain data. By utilizing ADS-B data and DEM data, these functions are calculated to identify potential terrain collision risk areas in Korean airspace. In terms of terrain features, the Cheonggye Mountain area for GMP approach and Sinei Mountain area for PUS approach are identified as the risk areas. However, the analysis revealed that the sharp turn at the north of ICN due to blocked airspace frequently triggers alerts. Using this analysis, it will be possible to increase terrain collision safety by mapping out the collision risk as well as false alarm possibility so that the aviation community can have a clear view of the situations.

Acknowledgments

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