



LOW-ALTITUDE INTEGRATED AIRSPACE OPERATIONS OF AIRCRAFT FLYING UNDER VISUAL FLIGHT RULES: THE VERTICAL DIMENSION

Adriana Andreeva-Mori, Kohji Ohga, Keiji Kobayashi

Japan Aerospace Exploration Agency (JAXA), Mitaka, Tokyo, 181-0015, Japan

Abstract

Accurate altitude prediction is crucial for the safe and efficient integration of unmanned aircraft systems (UAS) and traditional airspace users (e.g., helicopters). Sufficient knowledge of the altitude and uncertainties can help airspace design and optimize operations in both the temporal and spatial dimensions. Helicopter operations under visual flight rules (VFR), however, are characterized by a high degree of flexibility and this makes altitude predictions considerably more difficult than those for instrument flight rules (IFR) operations. This paper considers the factors which affect VFR flight altitude and use real flight data to test the assumptions. Identifying these parameters lays the foundations to strategic VFR altitude prediction model to be developed in a follow-up work.

Keywords: airspace integration, helicopter flights, uncrewed aircraft systems (UAS), operation volume, separation

1. Introduction

At present, there exist only two types of flight rules: visual flight rules (VFR) and instrument flight rules (IFR). VFR operations are based on the “see and avoid” principle- separation is responsibility of the pilot, who relies on the view outside the cockpit, and any information which might be available from air traffic control (ATC) through radio. The latter is not a requirement, however, and in fact many VFR operations happen in uncontrolled airspace where aircraft may not be visible to ATC at all. VFR require good weather, as minimum visibility and clearance from clouds are part of the operation conditions. VFR operations, however, provide a lot of flexibility to the pilot. The pilot is required to file a flight plan prior to departure, but this flight plan does not contain detailed spatial and temporal information on the trajectory. The take-off and flight times, for example, are generally used in case of distress only and do not provide a reliable estimate for ATC planning purposes, for example. That is why VFR usually applies to less congested airspaces, low altitudes and small aircraft.

IFR operations, on the other hand, are possible in most weather conditions, as there are usually less regulations on minimum visibility, especially in the enroute part of the flight. However, to be able to perform such operations, aircraft must be equipped with instruments and navigation devices to allow the pilot to fly even in the lack of visual cues. Most importantly, separation is ATC’s responsibility, which in turn means that pilots have a lot less flexibility than in VFR operations. IFR operations require very detailed flight plan submission, which allows for strategic planning as well. In other words, IFR operations are very predictable, both spatially and temporally. This allows operations of more aircraft in the same airspace, which makes IFR suited for congested airspaces such as airport proximity.

Until recently, VFR operations were sufficient for low altitude airspaces (up to 3000 ft approximately). The advancement in uncrewed aircraft systems such as small drones and advanced air mobility vehicles such as Electric Vertical Take Off and Landing aircraft (eVTOL) has called for airspace integration, however [1], [2]. This raises the questions whether operations combining to a certain extent the flexibility of VFR and predictability of IFR are possible. Due to the existing trade-off between

these two properties, some constraints to the VFR operations need to be placed to increase both spatial and temporal predictability. The current work is particularly focused on the vertical predictability of the trajectory, as the vertical plane is considered to be where the operations are going to be segregated during the initial operations, at least.

The authors propose using mission type information and real track data to develop altitude prediction model which can be applied to pre-tactical mission planning, as well as an in-flight real-time prediction to monitor the conformance and provide diversion alerts to the pilot when necessary.

Most IFR operations are point-to-point transport of goods or cargo, such as the scheduled airline passenger or cargo flights. VFR operations, on the other hand, are much more diverse- point-to-point movement, reconnaissance along landmarks such as highroads and rivers, search and rescue, patrol, telecasting of sport events, etc. In this paper, first the factors which affect altitude selection are examined and discussed. The analysis is based on real flight positioning data, pilot interviews and helicopter flight tests conducted specifically for the purposes of VFR trajectory modeling.

2. Altitude Predictions and Conformance Monitoring

2.1 Concepts for Diverse Vehicle Integrated Operations

There are many concepts to integrate various vehicle types in the low altitude airspace. In many of those, separation in the vertical plane is assumed: drones fly at altitudes less than 150 m (or 400 ft in some cases), next layer is to be occupied by helicopters and eVTOLS, and upper layers are for civil aircraft such as airliners. In some concepts, operation volumes around the planned trajectories are defined, and aircraft are expected to complete their missions only within the assigned operation volumes. In non-segregated airspaces, alerts can be issued when other vehicles are in the vicinity. In all cases, however, the altitude prediction is a key factor. Most small uncrewed aircraft systems (drones), however, rely on GPS altitude only. The lack of common reference is a known issue raised by many researchers [3], [4], with several potential solutions being proposed as part of the ICARUS project. The current research does not investigate in detail the instrument measurement errors, and focuses only on pilot control and fluctuations in the GPS altitude compared to the predicted altitude, which is considered equivalent to the elevation plus the target AGL.

2.2 Factors Affecting VFR Altitude Profiles

When aircraft fly under visual flight rules, they submit a flight plan which may contain planned altitudes for different flight segments. Unlike flights under instrument flight rules, however, there are no performance requirements and pilots have a lot of flexibility in both lateral and altitude control. The altitude profiles of VFR operations are much more complicated than the ones of traditional IFR airline flights, for example, which could be divided into climb, enroute and descent, with the enroute portion often conducted at a more or less constant altitude. Preliminary data analysis, literature review and interviews with helicopter pilot indicated that the following factors affect the VFR altitude profile.

(1) Mission type

Most IFR airliner missions are point-to-point transport of cargo and/or passengers, and schedule flights follow established air routes deviating only to accommodate adverse weather and air traffic control instructions. In the case of low-altitude VFR flights, however, missions are very versatile, ranging from point-to-point transport to search and rescue missions, reconnaissance, firefighting, medical evacuation, leisure, law enforcement operations, and news gathering, to name a few [5]. Many of those missions are of interest for advanced air mobility vehicles, as well, so airspace integration is crucial [6], [7]. Below are a few examples of altitude profiles for different mission types. The top panel of Figure 1 shows a profile of a training mission, the middle one- point-to-point transport, and the lower one- information/news gathering over a point of interest. Information gathering over a point of interest is often performed as the helicopter circles around maintaining a more or less constant altitude to assure stable view of either the camera or the crew in charge of information gathering. Broadcasting missions share similar characteristics. Pilots indicated that the exact altitude would vary and might depend on the day and flight conditions. In practice, the pilot will confirm with the camera crew that the current altitude is suitable and maintain it throughout the mission.

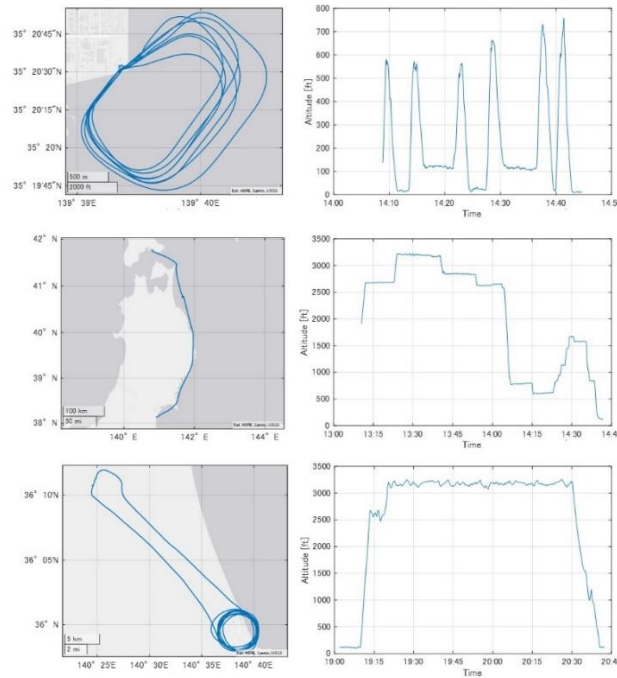


Figure 1 – Different flight profiles for various missions.

Take for example the information gathering missions over a point of interest. Figure 2 shows the lateral and vertical profiles of six point-of-interest flights. Note that these data were collected on different days but the target location was the same. Several observations can be made. First, once the turns around the point-of-interest begin, the altitude is somewhat stable. Second, this nominal altitude differs among the flights and varies between 2000 and 3800 ft. For such type of missions, airspace segregation is possible as UAS can fly at altitudes lower than the helicopter's nominal altitude. However, it might be difficult to establish the nominal altitude prior to the flight, which causes a challenge for strategic planning.

Integrating UAS and helicopters flying missions with frequent altitude changes such as touch-and-go training missions or fire-extinguishing missions might be more challenging, however. The lateral and vertical profiles of 4 touch-and-go training flights are shown in Figure 3. Note that the duration of a single cycle varies between 6 and 15 minutes, which makes any strategic planning very challenging.

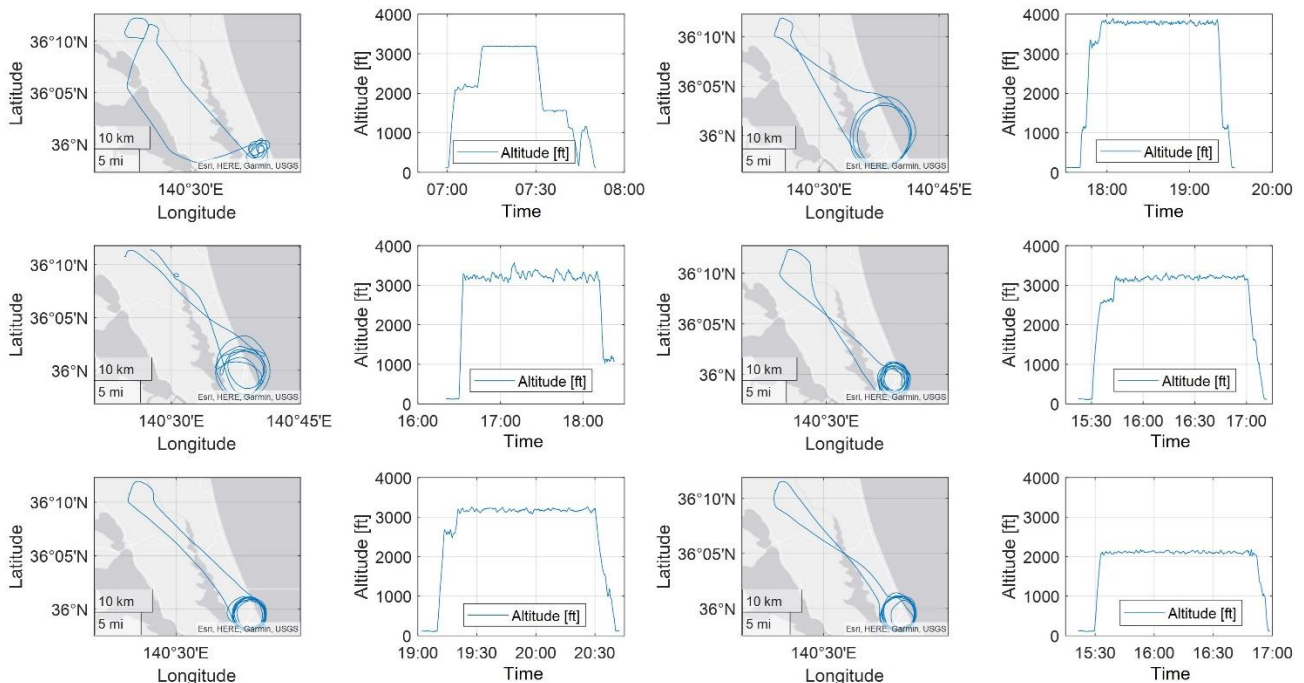


Figure 2 – Sample profiles of information gathering missions over point-of-interest missions.

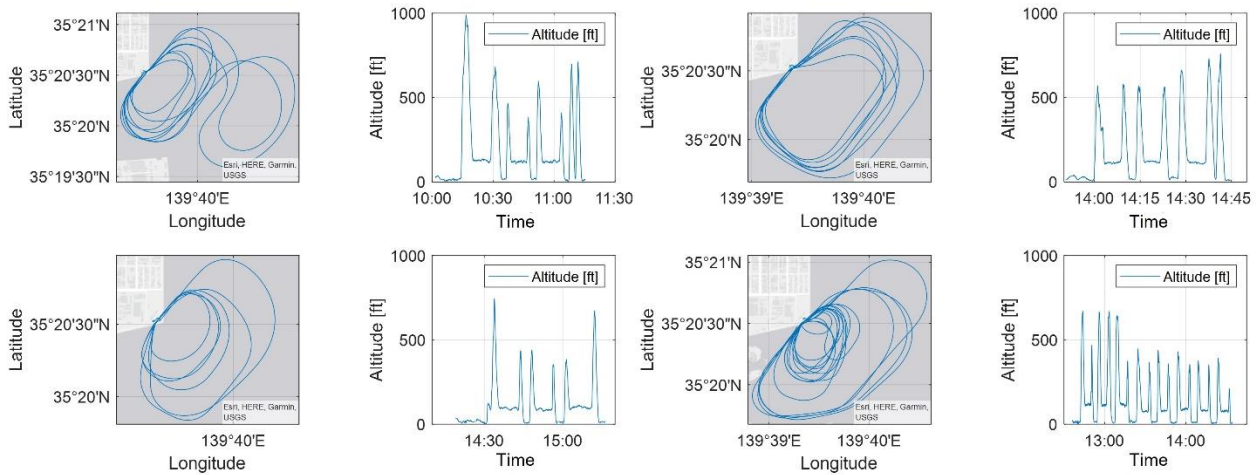


Figure 3 – Sample profiles of touch-and-go training flights.

(2) Target altitude, incl. navigation considerations

Many VFR missions are flown using landmarks as navigation aids. For example, post-disaster reconnaissance missions are often flown along a highway, river, or railway to evaluate damages and look for people in need of rescue. Such missions were modeled, and multiple flight tests were conducted with JAXA's experimental helicopter [8]. Interviews with pilots indicated that the pilot maintains a constant altitude (within a certain margin) to secure a stable flight so that the disaster response crew at the back of the vehicle can visually conduct the reconnaissance mission smoothly. Data indicates, however, that the margin depends on the presence of target altitude- the pilot was more conscious of maintaining a constant AGL when they were instructed in advance to do so (see Figure 4).

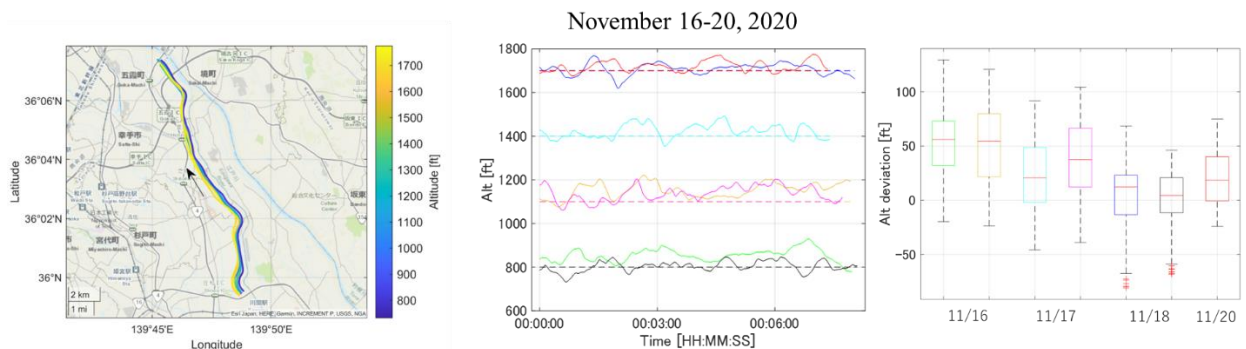


Figure 4 – Sample reconnaissance missions altitude profiles with target altitude.

(3) Flight mode

The altitude profile depends on the flight control mode as well, with manual control requiring higher workload to maintain a constant altitude. Some helicopters are equipped with autopilot, and depending on the automation capabilities, the pilot might opt to use of the control modes available.

(4) Topology/ terrain

Since most VFR missions are flown at low altitudes, many below 3000 ft AGL, the terrain may require adjustments to the planned altitude. In Figure 4, the terrain was relatively flat, so the deviations in the altitude can be treated as errors. This is not the case for mountainous regions, for example. Consider the sample flight trajectory shown in Figure 5. During the flight, altitude data was collected but not used to provide any real-time situation awareness. Detailed elevation data is obtained [9] and together with the position data, is used to calculate the altitude AGL. This is a point-to-point flight moving southwest, as shown in the left panel. The GPS altitude data is shown in the color bar. As seen from the data, for a large portion of the flight the altitude is somewhat stable at 2100 ft. It increases significantly in the middle of the flight, where the pilot flies over some mountains, with elevation reaching 2000 ft at times (see the blue line around 8:11 in the right panel). The pilot did not try to maintain strictly AGL of 2000 ft, however. As a result,

the AGL plunged by more than 1000 ft at 8:11. On other occasions, when the terrain elevation changes were small, the pilot did not adjust their altitude, as seen from the grey highlighted areas in the right panel. Interviews with pilots (not the ones in control of the helicopter which data is used here) indicated that a safety altitude of around 1000 ft AGL is maintained, but there is no need to adhere to the original planned AGL (2000 ft or so). The changes in the altitude seem more gradual than the terrain, so predictions of the AGL become non-linear and more complicated.

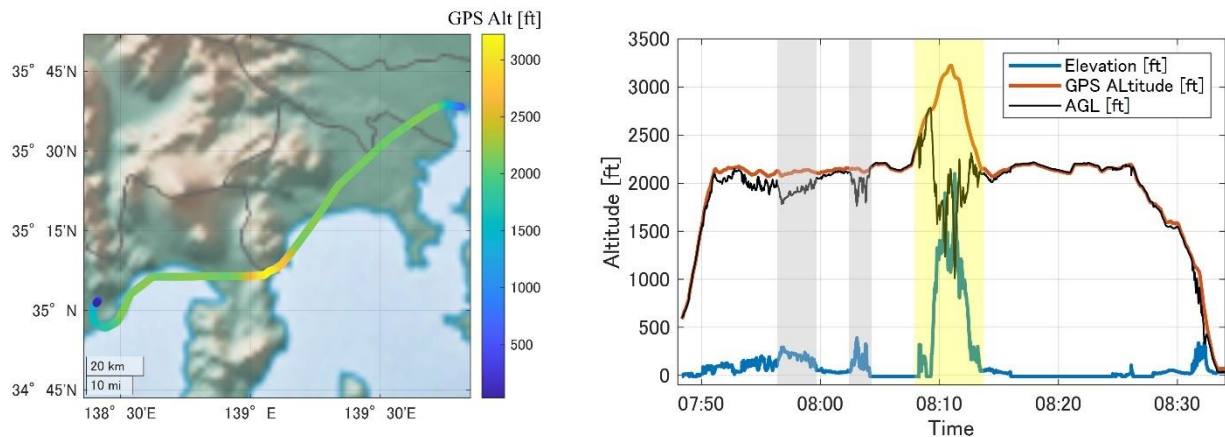


Figure 5 – Terrain effect on AGL.

(5) Weather (clouds, turbulence and visibility, in particular)

Weather can impact the choice of flight altitude in multiple ways. Since maintaining a clear visual field is a requisite for VFR operations, low clouds (ceiling) and/or decrease visibility can lead to the pilot choosing lower than usual altitudes to maintain view of ground references and situation awareness. Turbulence and temperatures can also affect the altitude choice, as the pilot often opts for areas with smoother air to assure safe control and provide the best conditions for the passengers and other crew onboard. Winds impact the altitude as well, but since at low altitudes up to 3000 ft AGL the differences come mainly from the terrain, the response to strong head/tail winds is more complicated than in the case of airliners operating under IFR at high altitudes. Thunderstorms, precipitation and icing are other factors which may affect the altitude selection.

When adjustments to the altitude are not enough to ensure a safe flight, the pilot may choose to cancel the flight or select an alternate route, as seen from the example in Figure 6. In this point-to-point mission, most likely the pilot's plan was to cross the peninsula over the mountains, similar to the track in Figure 5. However, due to the adverse weather in the area [10], the helicopter flew along the coastline.

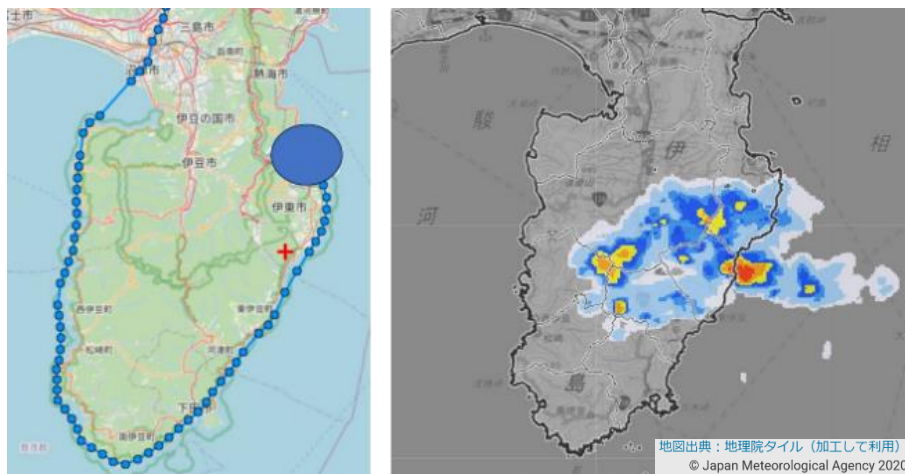


Figure 6 – Sample of a flight affected by adverse weather.

(6) Controlled airspaces/ airspace restrictions/ air traffic control instructions

Controlled airspace can significantly impact the altitudes of VFR flights. There are certain airspaces where VFR flights are generally not allowed, and in others they are allowed, but special ATC permissions, clearances and instructions are required. In uncontrolled airspaces VFR pilots

have more flexibility in choosing their altitudes, but there are cases when restrictions apply, in particular, in proximity to controlled airspaces. In the example in Figure 5, the pilot selected a 2000 ft AGL so as to avoid entering Yokota Approach Airspace, where clearance would have been needed.

(7) Aircraft performance and fuel efficiency

Unlike civil airliners, helicopters are not more fuel-efficient at high altitudes. Due to decreased air density at high altitudes, the lift generated by the rotor blades decreases. Whatever the selected altitude is, the pilot must make sure it is within the operating limitations of the helicopter. Furthermore, the pilot selects altitudes considering the entire flight profile. In the example in Figure 5, the pilot could have flown at 1500 ft AGL in the first part of the flight, but since they knew that they would have to climb to clear the mountains, they selected 2000 ft AGL for the initial flight segment.

3. Altitude Analysis of Disaster Reconnaissance Missions

To manage and integrate traffic in congested airspaces, some restrictions on the current operations are considered. Assigning operation volumes to VFR flights, very similar to how drones are managed in the UTM ConOps [1], or having corridors assigned to VFR operations [11] are just a few airspace structure examples on potential operation concepts. In all of these concepts, both pre-tactical, i.e., pre-flight trajectory prediction used in flight planning, as well as in-flight real-time short-term trajectory prediction used to assure conformance to the flight plan will be essential. In the current research, we focus on altitude predictions and propose two different algorithms for the pre-tactical and in-flight phase. Specific results will be included in the final paper, but this abstract provides an outline of the algorithms based on some of the factors affecting VFR altitude profiles discussed in Section 2.2.

3.1 Flight data analysis considering terrain

The presence of target altitude contributes to more stable and predictable flights in the vertical plane without obstructing the missions, as demonstrated by the initial analysis shown in Section 2.2. Since the target altitude is assigned in AGL, however, and past data indicated that the pilot does not strictly follow the terrain (see Figure 5). To confirm this assumption, a series of flight tests has been conducted from 2020 to 2023. To analyze the effect of topology, this paper focuses on two main areas in the greater Kanto Area in Japan- area KK and a mountainous area in the vicinity of Mount Fuji, called Area A here (see upper left panel of Figure 7). Note that these notations agree with the ones used in the author's past work [12], [13], [14]. The flight test in area KK was conducted in November 2020, and the one in Area A- in August 2022. The flights consisted of two mission types- point-to-point movement, and reconnaissance along landmarks, but this paper discusses only the latter missions. In a briefing prior to each flight, the pilots were given a booklet containing information on each flight segment plan. Each segment was described by a reference landmark, target altitude (ranging 800 ft to 1800 ft) and approximate entry and exit time, only used as a reference. In area KK, a total of five reconnaissance segments were constructed, while area A had only one reconnaissance segment flown along a highway. All reconnaissance segments were flown manually by the same pilot. In the flight test in Area A, the pilot was given advisories on the temporal and lateral deviations from the predicted lateral trajectory [13], but no advisories on the target altitude compliance.

Flight data was available from the aircraft measurement system. The positioning data consisted of latitude, longitude, and altitude references in the World Geodetic System (WGS84). The analysis presented uses the data recorded every second only, without applying any filters, and corrects for the geoid height. Detailed elevation data [9] is obtained for the test area and together with the GPS data recorded by the helicopter's data recording system, is used to calculate the altitude AGL. The data is then used to calculate the altitude deviation, i.e., the difference between the actual AGL and the target altitude. The deviations for Areas KK and A are shown in the upper panels of Figure 7. The altitude deviations in Area KK are between -85 and 130 ft and are relatively uniformly distributed for all segments. The deviations in Area A are much larger, ranging from -650 ft to 215 ft. One of the main reasons for these differences in the overall altitude deviations is the terrain of both areas. Area KK is a flat area with little elevation variations (see the upper left and center panels of Figure 7), whereas area A is a mountainous area with complex terrain (see the upper left and right panels of Figure 7). The views from the aircraft window confirm this- in Area KK the pilot has a clear view over a wide area with few terrain obstacles to consider, whereas in Area A the pilot follows a highway surrounded by mountains which increases the workload and calls for more attention to the surroundings. Note that

there are three regions in Area A where the altitude deviations are significantly more severe. A detailed analysis of these regions is presented below.

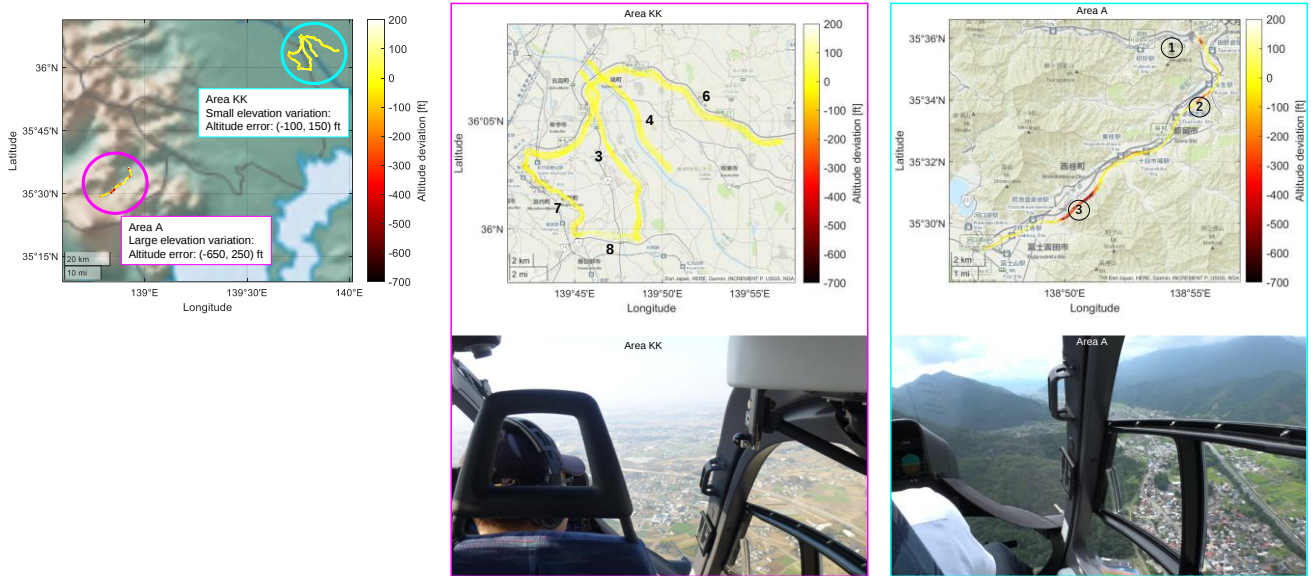


Figure 7 – Terrain in two flight areas affecting the altitude profile.

The altitude profiles of the flights in Area A are shown in Figure . The horizontal axis shows the latitude, which decreases with time. The black solid line in the figure shows the predicted lateral trajectory. The pilot is flying from north to south, tracking the highway on the west side of the predicted trajectory and shown in dark grey. In region 1, the pilot crosses over a hill without increasing the AGL and maintaining somewhat stable GPS altitude (see the left panel of Figure). This cross over lasts between 15 to 20 seconds. The deviations in regions 2 and 3 are of similar nature- they were both caused by a hill on the left of the landmark, which the pilot flew over. These hills are visible from the elevation data in Figure as well.

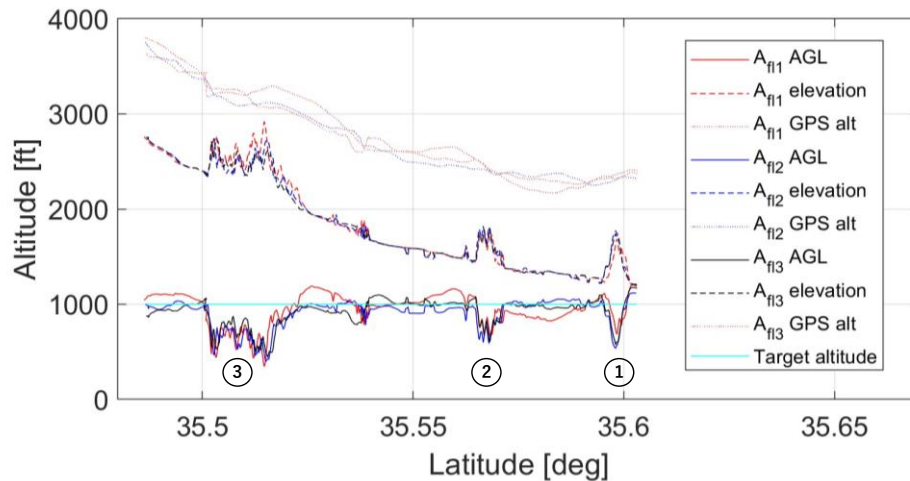


Figure 8 – Altitude profiles of Area A flights (flight data from August 22, 2022).

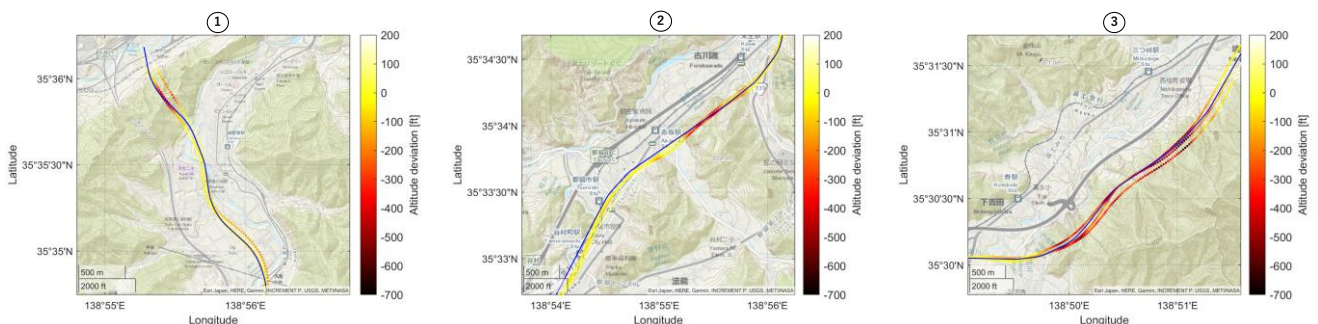


Figure 9 – Large altitude deviation regions in Area A (flight data from August 22, 2022).

3.2 In-flight altitude deviation alert concept

While in flight, situation awareness support tools such as JAXA's D-PAS, originally developed as part of JAXA's D-NET research [15] [16], can help the pilot comply with the target altitude. D-PAS is a fully portable system consisting of three main components: a satellite transmission component, a digital antenna, and a touch-screen display (see the right panel of Figure 8). The system has a built-in map and combined with the GPS data obtained real-time, position awareness can be achieved easily. Additions to the software can be used to issue alerts to the pilot when the helicopter deviates or is about to deviate from the planned altitude. Past research focused on the lateral component mainly, but it can be tailored to the vertical plane. In the past, two types of alerts were tested- an alert algorithm based on the predicted position in both the temporary and spatial dimensions (Figure 9, right panel), and another one based on the vertical uncertainties (volume) around the predicted trajectory (Figure 9, left panel). Coordination in both the spatial and temporal dimensions increases the pilot workload [12], so pilots the altitude volume alert approach is being implemented in the current development. To determine the optimal vertical buffer, both the predicted altitude and nominal deviations should be calculated.

Work is ongoing to develop the altitude prediction model and implement it in D-PAS, similar to the lateral volume shown in Figure 8. The pilot can get voice advisories from the researcher/staff who can issue those based on the D-PAS alerts.



Figure 8 - D-PAS display with operation volume and predicted lateral trajectory.

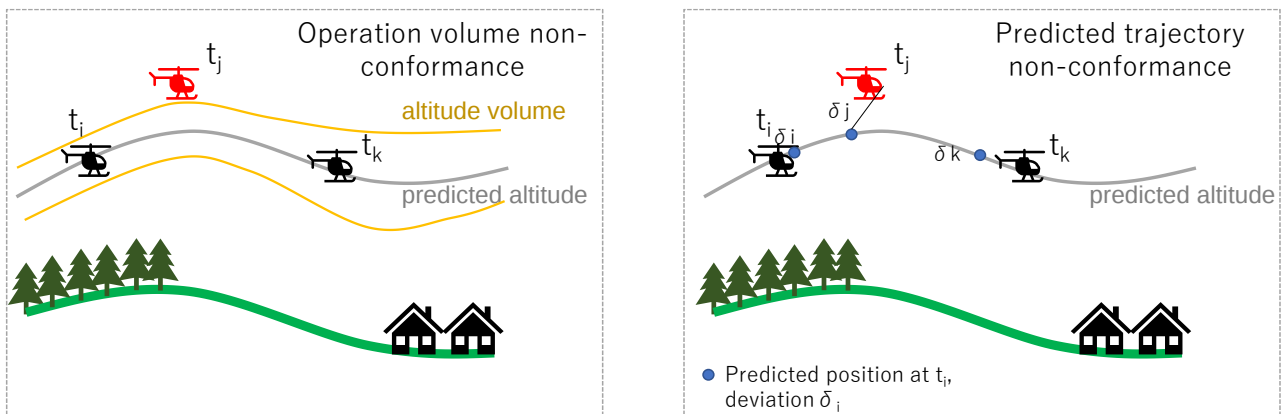


Figure 9 - Two vertical deviation alert algorithms.

4. Concluding Remarks: Contributions to the Field

The use of sUAS and other new entrant vehicles will require safe and efficient airspace integration. Helicopters, sUAS and eVTOLs are going to share low altitude airspace, and are most likely to be separated vertically, so accurate altitude prediction is essential. The altitude profile, however, should allow for the mission of each vehicle to be performed safely and efficiently. Since there are few details in the VFR flight plan, the prediction of altitudes is very challenging. Besides, due to the low altitudes and airspaces in which VFR helicopters usually operate, there is very limited track data available for post-operational analysis. The authors were able to obtain real flight data for the purposes of this study. Furthermore, a major part of the decisions on trajectory and control are pilot-dependent, so track data by itself is not sufficient to model operations well. The current research team, however,

includes a pilot as well, so their input and expertise are reflected in the analysis. The authors have already conducted a detailed lateral trajectory modeling in their past work and will use their experience to model the altitude profile as well. The preliminary analysis presented in this paper discussed the input parameters for the altitude prediction algorithm and proposed an in-flight alert concept to help the pilot maintain conformance. The results can be applied to advanced air mobility concepts and enable sUAS, helicopter and new entrant (eVTOL) low-altitude airspace integration.

5. Contact Author Email Address

The contact author email address is andreevamori.adriana@jaxa.jp.

6. Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS proceedings or as individual off-prints from the proceedings.

References

- [1] FAA, "UTM Concept of Operations ver.2," 2 3 2020. [Online]. Available: https://www.faa.gov/uas/research_development/traffic_management/media/UTM_ConOps_v2.pdf. [Accessed 4 3 2021].
- [2] J. Homola, M. Johnson, P. Kopardekar, A. Andreeva-Mori, D. Kubo, K. Kobayashi and Y. Okuno, "UTM and D-NET: NASA and JAXA's collaborative research on integrating small uas with disaster response efforts," in *2018 Aviation Technology, Integration, and Operations Conference*, 2018.
- [3] O. Nunes, "A Geometric Challenge- No pressure," in *ATM Seminar*, Savannah, GA, 2023.
- [4] "ICARUS Integrated Common Altitude Reference system for U-space," 2022. [Online]. Available: <https://www.u-spaceicarus.eu/>. [Accessed 13 11 2023].
- [5] J. O. Entzinger and D. Kubo, "Modeling Low Level Flight Patterns of Manned Aircraft from Actual Flight Tracking Data," in *Asia-Pacific International Symposium on Aerospace Technology (APISAT2021)*, Jeju, Korea, 2021.
- [6] D. P. e. a. Thippavong, "Urban air mobility airspace integration concepts and considerations," in *Aviation Technology, Integration, and Operations Conference*, 2018.
- [7] International Forum for Aviation Research (IFAR), "Scientific Assessment for Urban Air Mobility (UAM)," 1 3 2023. [Online]. Available: <https://ifar.aero/attachments/article/57/ifar-scientific-assessment-for-uam.pdf>. [Accessed 22 12 2023].
- [8] JAXA, "JAXA's Research Helicopter," [Online]. Available: <http://www.aero.jaxa.jp/publication/pamphlets/pdf/heli.pdf>. [Accessed 21 02 2020].
- [9] Geospatial Information Authority of Japan, [Online]. Available: https://maps.gsi.go.jp/development/elevation_s.html.
- [10] Japan Meteorological Agency, "Nowcast," [Online]. Available: <https://www.jma.go.jp/bosai/nowc/>.
- [11] Airbus, "Blueprint for the Sky: The roadmap for the safe integration of autonomous aircraft," 2018. [Online]. Available: https://storage.googleapis.com/blueprint/Airbus_UTM_Blueprint.pdf. [Accessed 28 12 2023].
- [12] A. Andreeva-Mori, K. Ohga and K. Kobayashi, "Reconnaissance Mission Flight Modeling for Strategic Planning of Manned and Unmanned Vehicle Integrated Disaster Response," in *The 40th Digital Avionics Systems Conference*, San Antonio, Texas, 2021.
- [13] A. Andreeva-Mori, K. Ohga, K. Kobayashi, A. Yoshida and N. Takeichi, "Feasibility Study of Operation Volume Design Concept for Integration of Aircraft Flying under Visual Flight Rules Based on Actual Flights," *IEEE Aerospace and Electronic Systems Magazine*, vol. 38, no. 6, pp. 14-26, 2023.
- [14] A. Yoshida, A. Andreeva-Mori and N. Takeichi, "Modeling and Evaluation of Disaster Response Operations under Visual Flight Rules Using Helicopter Flight Data," in *APISAT*, Niigata, 2022.
- [15] A. Andreeva-Mori, D. Kubo, K. Kobayashi, Y. Okuno, J. Homola, M. Johnson and P. Kopardekar, "Operational Testing of Unmanned Aircraft System Traffic Management in Disaster Response," *Journal of Air Transportation*, pp. 1-11, 2021.
- [16] Y. Okuno, K. Kobayashi and H. Ishii, "Development of a helicopter operations management system for disaster relief missions," 2016.
- [17] D. Opitz and R. Maclin, "Popular Ensemble Methods: An Empirical Study," vol. 11, pp. 169-198, 1999.