Flight Test Exploration of Integrated Wildfire Response Operations with Crewed and Uncrewed Air Assets

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Since 2016, Japan Aerospace Exploration Agency (JAXA) and NASA have partnered to investigate the safe and efficient integration of uncrewed aircraft systems (UAS) in disaster relief operations. Current disaster response operations would benefit from the use of UAS but are limited by the need for safe airspace integration technologies and enabling regulations. The work presented in this paper focuses on the safe integration of UAS and helicopters in active wildfire disaster response operations. The authors propose the use of mission planning and traffic management technologies, including onboard pilot situation awareness support technologies, to coordinate airspace operations between crewed and uncrewed aircraft (e.g., UAS). A representative wildfire scenario including a helicopter and UAS was developed. The helicopter mission included a flight path that mimicked the siphoning of water from a natural water reservoir (lake) and a subsequent water drop over vegetation along the progressing edge of a fire perimeter. Simulated UAS were assumed to conduct aerial ignition flights in the vicinity as part of a controlled burn of the vegetation ahead of the fire front to create a natural barrier between the fire and a nearby populated area. A situation awareness tool was developed and used to support the helicopter pilots' task to stay clear of the volume of airspace where the UAS was conducting its operation while efficiently conducting the fire suppression mission. A flight test using JAXA's experimental helicopter was conducted in August 2022 to validate the developed technology. The advantages of the developed technology were demonstrated, and pilot feedback confirmed that real-time awareness of the UAS operation airspace helped the flight planning and execution of a safe mission that minimized the flight time loss due to the potential interference with the UAS. Post-flight interviews with the pilots indicated no sufficient increase in the pilots' workload and provided ideas for future technology development. Future research will provide recommendations to standards development organizations to support considerations for crewed-uncrewed interactions in disaster-response operations.

I. Introduction

The use of Uncrewed Aircraft Systems (UAS), and small UAS (sUAS) in particular, has gained widespread adoption across many applications due to their low cost, versatility, and ability to reduce risk in roles traditionally served by humans. Given the increase in frequency and severity of natural disasters due to climate change, the use of UAS to support disaster response operations has been gaining interest within the emergency response community. As the scale of natural disasters increase, emergency response agencies continue to seek new and innovative solutions to integrate into disaster prevention, mitigation, response, and recovery. For instance, aerial imagery has become a common approach to acquiring situation awareness of the current impact of a natural disaster and UAS are viewed as an

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improvement over crewed aircraft operations due to their affordability, ease of operation, large coverage area, mission versatility, and information storage capacity. Current disaster response operations would benefit from broader use of UAS, but their integration has been limited by regulatory restrictions preventing access to the airspace and a lack of requirements that ensure safe operations when crewed and uncrewed aircraft operate simultaneously. For example, during current wildland fire operations, UAS and crewed aircraft are able operate in the same airspace in certain conditions. However, the respective operators lack situation awareness of each other's operations, which often requires the UAS to be grounded while crewed flights are in the vicinity. Conversely, the crewed aircraft either avoid or delay movement into an area with active UAS due to uncertainty and perceived risk.

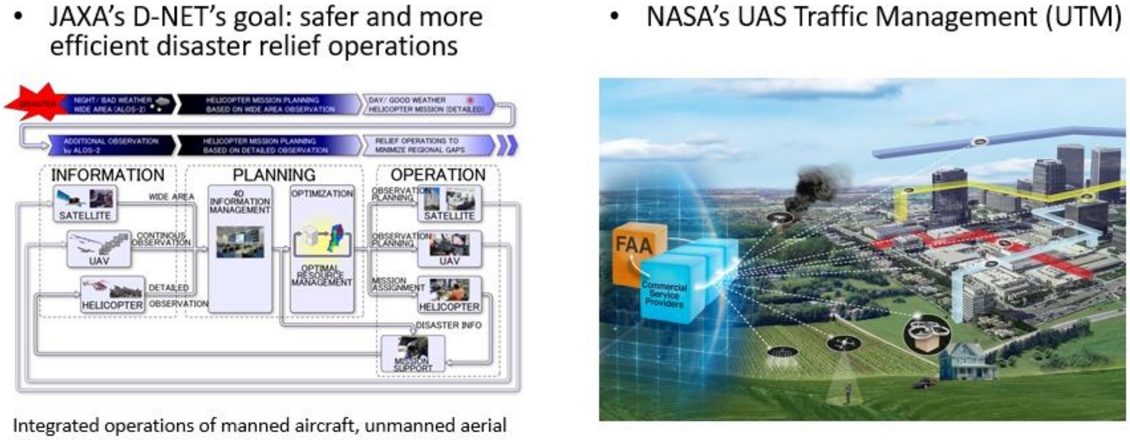
Many researchers propose the use of sUAS for wildfire monitoring and reconnaissance, focusing on the low-cost, ease of operation, and potential for early deployment. Since sUAS have limited range and coverage, the use of UAS formations or coalitions have been explored [1], [2], [3]. Multiple vehicles can expedite response operations by monitoring the progression of a wildfire, locate people in danger or those who need rescue, and/or aid communications by providing network access from areas impacted by a disaster. However, the current limitations preventing the expanded use of UAS in concurrent operations results in UAS or crewed aircraft needing to operate independently and separately rather than in coordination [4]. Optimizing firefighting resources is key for efficient disaster response, and the safe airspace integration of both crewed and uncrewed vehicles can provide a substantial improvement to current operational efficiency.

Since 2016, JAXA and NASA have been collaborating on research, development, and testing of the integration of crewed and uncrewed air assets for disaster response operations. This collaboration has sought to leverage the capabilities provided by JAXA's Disaster Relief Aircraft Information Sharing Network D-NET system with NASA's UAS Traffic Management (UTM) [5] system for mission planning, common situation awareness of the airspace, and deconfliction of operations within the airspace over an incident. Since 2016, this collaboration has conducted concept development, simulation, and flight testing to inform requirements for both crewed and uncrewed operations when sharing the airspace. Current research under this collaboration is focused on how conventional aircraft and UAS can safely integrate into wildfire response operations, particularly considering tools and technologies that can enable better situation awareness for the pilot. The goal of this effort is to ultimately provide recommendations to standards development organizations towards the development of new standards that can better support crewed-uncrewed interactions for disaster response operations.

II. Past Research and Initial Collaboration

A. D-NET and UTM: two complementary systems

Over the years, JAXA and NASA have independently worked on approaches to the management of multiple air assets with different systems in place to provide the necessary capabilities. As shown in Fig. 1, JAXA's D-NET system [6] was developed to support the planning, execution, and awareness of disaster response operations. However, there was a desire to improve the integration of small UAS (sUAS) [7] in the suite of capabilities. At the same time, NASA had been developing its UTM concept and associated technologies for the management of sUAS to help coordinate and deconflict operations within the airspace. The D-NET and UTM systems are uniquely complementary, particularly in the context of disaster response support. Thus, the initial collaboration between the two organizations was focused on the integration of the two respective systems and their testing across multiple testing events.



- JAXA's D-NET's goal: safer and more efficient disaster relief operations

Integrated operations of manned aircraft, unmanned aerial vehicles, and satellites with optimized allocation of available resources.

- NASA's UAS Traffic Management (UTM)

Collaborative, automated, and federated airspace management approach that enables safe, efficient, and equitable small UAS operations at scale.

Fig. 1 JAXA and NASA technology contributions

B. Initial D-NET and UTM accomplishments

To drive the innovation in improved response, JAXA and NASA successfully connected their respective D-NET and UTM systems and conducted a series of live flight tests first as part of a large-scale disaster drill and later in dedicated research flights. In each case, the D-NET and UTM systems exchanged data in real-time, which supported the planning, tasking, tracking, and deconfliction of crewed and uncrewed operations. In October 2018, JAXA and NASA participated in a large-scale disaster drill held in Ehime Prefecture, Japan where the integration of systems was successfully demonstrated through coordinated airspace management of a helicopter operating under Visual Flight Rules (VFR) and an uncrewed sUAS that were both operating in common areas [8] (Fig. 2). In December 2019, a follow-up flight test was conducted in Tokyo, Japan, which focused on the evaluation of pilots operating under VFR communicating through D-NET and sharing intent and position information within UTM [9]. Through these test events, several key findings were derived through data analysis and stakeholder interviews with respect to the improvements offered by the integrated systems as well as considerations for situation awareness of pilots regarding other operations in the airspace and flight path management.

Fig. 2 Disaster drill Ehime, Japan. Upper panel: operation center in Ehime. Lower left panel: operation support at NASA Ames. Lower right panel: sUAS mission and operation volumes on D-NET

III. Active Disaster: Wildfire Test Scenario

Building upon the prior JAXA-NASA testing, the current collaborative research focuses on active response during a wildfire scenario and the situation awareness requirements of the crewed operation's pilots when sharing the airspace over an incident with sUAS. A representative wildfire scenario was developed to exercise crewed-uncrewed interactions and investigate the crewed pilots' perspective during a flight test. During the scenario, qualitative and quantitative metrics were taken to better understand the pilot's awareness of the sUAS operations. The objectives of the flight tests were to:

- Assess how technology can support improved situation awareness for pilots during their flight planning and mission execution tasks
- Use JAXA's experimental helicopter with D-NET's technology and NASA-provided sUAS trajectory data for assessment of pilot response time to identify and address potential conflicts between sUAS and helicopter operations

To provide a representative test environment, a scenario was developed that considered input from stakeholders in the emergency response community and introduced interactions between crewed and uncrewed operations to test the research objectives. The scenario consists of a wildfire urban interface in which active wildfire aerial suppression operations, provided by a crewed helicopter, is conducting water drops over the wildfire front while aerial ignition operations, provided by sUAS, is conducting a prescribed burn ahead of the fire front to reduce the ground fuels (e.g. shrubbery, grass, etc.) and prevent the spread of the fire to the nearby populated area. The intent of these missions is to reduce the intensity and spread of the wildfire, and aid ground firefighting crews in the establishment of a containment boundary (e.g., control line) between the fire and nearby populated area. During the operation, the sUAS was limited by a volumetric area, denoted as the UAS Volume, that was shared and visible on the D-NET interface onboard the helicopter for awareness of the pilot. There were three conditions that were considered during the assessment: 1) the UAS Volume was inactive (e.g., volume not displayed), 2) the UAS Volume was active but unoccupied (e.g., volume displayed), and 3) the UAS Volume was active and occupied (e.g., both volume and relative helicopter position information displayed).

IV. Flight Test

Flight tests were conducted with experienced disaster response helicopter pilots. The main flight test took place on August 23, 2022. JAXA, using its research helicopter BK117C-2 [10] (Fig. 3), operated from the Chofu Aerodrome, Tokyo and conducted its mock firefighting mission in the Mt. Fuji area of Japan.

Fig. 3 JAXA helicopter used in flight test

A. Test Setup

The flight test's goal was to test the effectiveness and potential issues with situation awareness technology supporting crewed and uncrewed vehicle integration. The crewed vehicle conducted actual flight on the test day, but the uncrewed vehicle (i.e., the sUAS) flight paths were simulated based on prior sUAS flight data from prescribed burn training operations in the United States and the flight paths were adjusted to be coincident with the location of the flight test in Japan. The prior flight test data was used to construct the UAS operation volume, and the pilots of the crewed aircraft were instructed that a UAS was in the vicinity and to avoid the UAS during its water drop passes. Figure 4 presents the sUAS operations translated to the test location bounded by the larger UAS Volume (represented by the 2D orange polygon) that served as a reference for the helicopter pilots to operate relative to. The resulting polygon measured an area of 0.66 km^2 with the outer edge located approximately 210 m from the simulated fire to its south-west. According to the test scenario, the UAS conducting prescribed burns within the volume were assumed to be in flight according to their recorded flight paths (denoted by blue paths in Fig. 4) at different points in time while the response helicopter was in the vicinity making its water dropping passes.

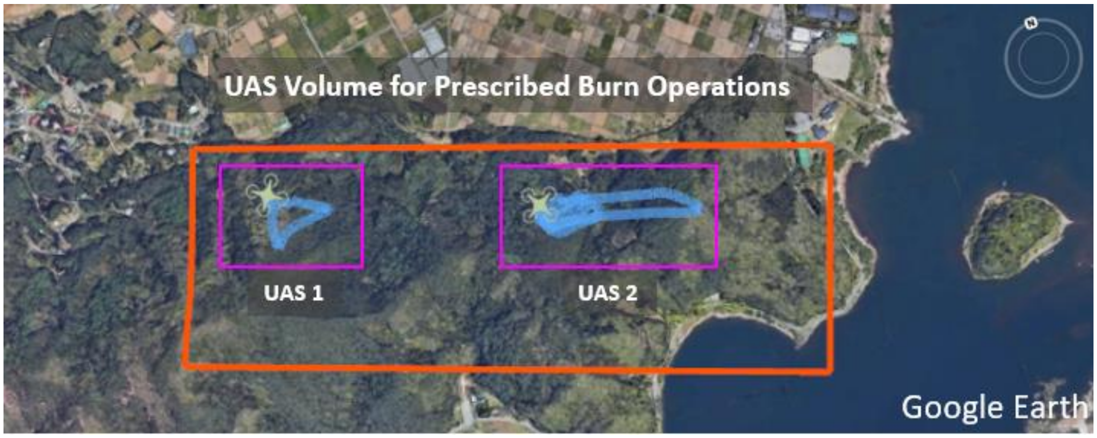


Fig. 4 UAS operating area where simulated prescribed burns were performed

The flow of the flight test is described below. A fire was assumed to be in the location shown by the flames icons in Fig. 5. A zone to refill water (e.g., dip site) located in the nearby lake was identified where the pilot simulated siphoning water from the lake before heading towards the fire front where they would release the water and head back for another round towards the water fill zone. sUAS was assumed to conduct their aerial ignition missions in the vicinity within a volume defined by the orange polygon referenced in Fig. 4 and shown across the panels in Fig. 5.


UAS Volume Established in Airspace

Helicopter dropping water in proximity to active UAS prescribed burn

Helicopter maintaining well clear of active UAS Volume

Fig. 5 Flight test scenario overview

B. Pre-flight (flight-planning) Phase

The approximate fire location and UAS Volume were known prior to helicopter departure and this information was conveyed to the pilots during the pre-flight briefing. Additionally, pilots were given a booklet containing relevant information regarding their mission and the UAS mission that could be used as a reference during the flight as well. The UAS Volume data was also imported into D-NET's portable mission support tool, D-PAS, which enabled the pilots to actively display and reference from the flight deck.

Two pilots conducted operations in the helicopter during the flight testing, and four researchers were onboard as well to: track the flight test progress on the mission support tool D-PAS, provide oral advisories to the pilot, and record data of the flight test. The main pilot was a veteran with more than 3500 hours flight experience in disaster response and flight testing and the co-pilot had multiple years supporting disaster response experience as well. Throughout the flight test, the pilot in command (sitting in the right seat) was given oral advisories and assistance on landmarks and general situational awareness by the pilot in the left seat and the researcher in the back of the vehicle.

Prior to flight, three cases within the overall scenario were selected, each with varying levels of information and activity in the area:

1. Inactive sUAS operation volume
2. Active sUAS operation volume, oral advisory from the researcher based on D-PAS on the volume location only.
3. Active sUAS operation volume, oral advisory from the researcher based on D-PAS on the volume location and relative helicopter position.

C. In-flight Phase

The weather conditions on the flight day consisted of clear visibility and low winds (less than 5-10 knots). One flight was conducted for each of the three test conditions resulting in a total of three flights. Oral advisories were provided by the researcher sitting in the back of the helicopter based on the UAS volume (purple polygon in Fig. 6 and Fig. 7) shown on D-PAS and the current position of the vehicle (red arrow).

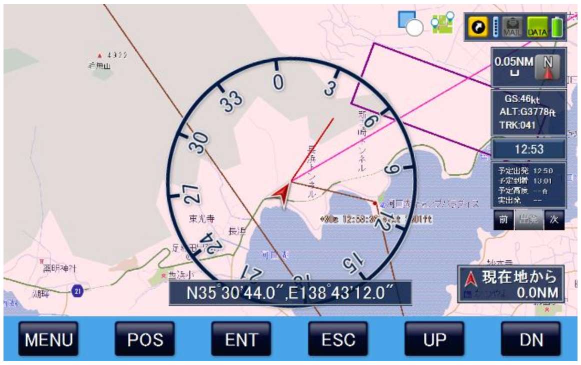


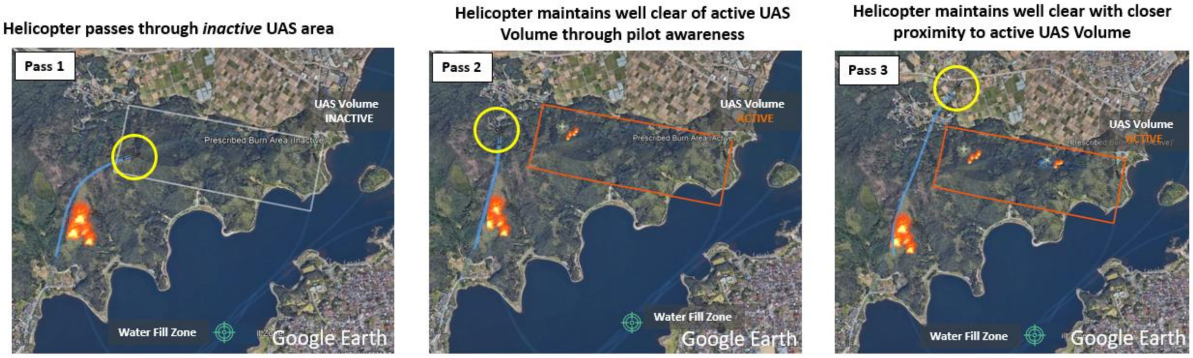
Fig. 6 D-PAS screenshot

Fig. 7 Researcher confirmation of D-PAS

V. Flight Test Results and Analysis

A. Lateral Analysis

Each of the three cases of the scenario were successfully flown and data was collected. The helicopter flight path relative to the UAS Volume and general environment for each case is shown in Fig. 8. The tracks obtained at each run are further detailed in Fig. 9. In scenario 1 when the sUAS volume was inactive, the helicopter passed through the sUAS area on its way from the water drop point to the water refill point, which indicates the shortest and most efficient route the pilot would take had there been no other airspace users. On the second run, when oral advisories of the sUAS volume were provided to the pilot, the vehicle was conservative in remaining clear of the UAS Volume. In case 3, when information on both the sUAS volume and relative position of the helicopter was provided to the pilot, the vehicle stayed clear of the UAS Volume but with a smaller margin, which increased the flight efficiency. This is visible by the overlayed lateral tracks shown in Fig. 9 as well. Note the helicopter flew in from the southeast to approach the water source for refilling. On Pass 1, when the sUAS operation volume was inactive, the pilot’s preferred route entered the area (see the blue track in Fig. 9). On Pass 2, the track prior to the sUAS operation volume was very similar to the track on Pass 1. However, due to the advisories, the pilots avoided the sUAS operation volume by maintaining constant heading for longer, thus stretching the lateral path of the helicopter after the water drop. As a result, the lateral trajectory length measured between two water refills increased by almost 50% from 5.60 km (Pass 1) to 8.25 km (Pass 2). Note that the climb from the water refill point to the drop point on Pass 3 was steeper than the previous two passes. In actual operation, as the vehicle uses fuel and becomes lighter, its maneuverability increases, which allows them to climb faster, shortening the time to complete the mission. Alternatively, the pilot might opt to load more water if it can be contained onboard. Had there been any additional constraints, the pilot would follow a similar climb profile to those of Pass 1 and 2. After Pass 3, the helicopter did not return to the water refill point, so the distance cannot be quantitatively compared, but the flight tracks showed that awareness of operation volumes aids in flight planning prior to and during flight.


Helicopter passes through *inactive* UAS area

Helicopter maintains well clear of active UAS Volume through pilot awareness

Helicopter maintains well clear with closer proximity to active UAS Volume

Fig. 8 Flight test results for the three cases considered.

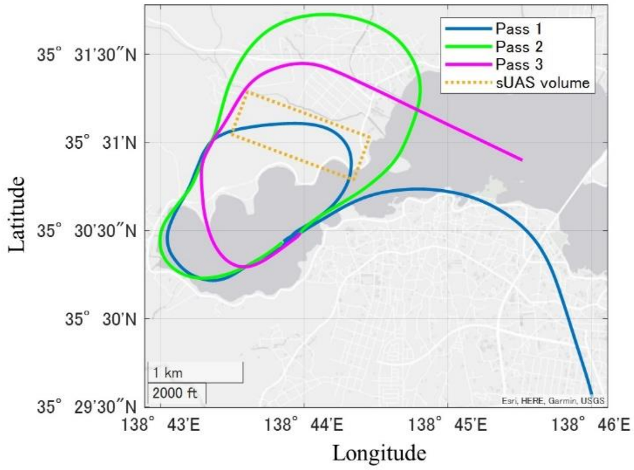


Fig. 9 Lateral trajectories for the three passes relative to the sUAS operation volume

B. Vertical and Temporal Analysis

Firefighting aircraft operations are characterized by very frequent and dynamic altitude changes. Altitude data available from the experimental system onboard the helicopter was used to obtain the GPS altitude profile of the mission. To investigate the effect of topology on the flight trajectory, detailed elevation data was obtained [11] for the test area. The elevation data, together with the GPS data, was used to calculate the altitude above ground level (AGL). The relative values are presented in Fig. 10. Note that the elevation of the water source is about 830 m, but the areas around are very mountainous, so the elevation exceeds 1000 m at the highest point of the area where the missions were flown. While mimicking the firefighting mission, the pilot provided verbal explanation to aid the situation awareness and understanding of the co-pilot and researchers onboard. These were used to identify each phase of the mission: water fill (shown in light blue), water release (shown in pink), and movement between the fill and release zone (shown in grey). Note that refilling was mimicked without an actual bucket being dropped, so the AGL is relatively high (190-200 m AGL). Similarly, the water release was executed at approximately 120 m AGL. These values, and refilling in particular, are going to be lower in actual operations. Note, however, that between the water refill and release points, the pilot climbed to a higher altitude to increase the clearance from the ground. The AGL increases by almost 200 m from 193 m to 382 m in less than 90 seconds, as seen from the data between 12:47:00 and 12:28:30 in Fig. 10. Furthermore, altitude data analysis indicates that pilots did not maintain constant AGL during the movement phase and they were only roughly tracking the elevation. Note the elevation of the terrain between 12:50 and 12:51, for example, when terrain changed from a hill to a valley and then again to a smaller hill, the GPS altitude did not fluctuate in the same manner. As a result, the AGL seemed to vary significantly throughout this short interval. Interviews with pilots indicated that they would maintain a somewhat stable altitude without unnecessary thrust adjustments to increase the flight's efficiency and passenger comfort. Similar strategies have been observed in other missions as described in more detail in the authors' past work as well [12].

Depending on the location of the water source and burn area, the movement segment (enroute phase) might be longer, but firefighting missions try to use the nearest location to safety and expedite operations; so, a cycle of several minutes is common. In this case, the cycles were 04:16 min between the first and second water refill, and 05:24 min between the second and the third refill. Note, however, that the first pass violated the sUAS operation volume (allowable given its inactive status at the time).

Due to the high dynamics of such firefighting missions, pilots suggested that vertical airspace segregation between helicopters and sUAS might be challenging, and practical only during the movement (enroute) phase when the water source and fire location are further from each other.

While the helicopter was conducting its simulated water drops, the sUAS were assumed to be conducting their prescribed burns in the nearby UAS Volume according to the test scenario. The first sUAS conducted a relatively short flight at 04:12 min with an along track flight distance of 541 m while conducting its aerial ignition. The second sUAS flew slightly longer at 9:30 min with an along track flight distance of 1.47 km. The maximum altitude above ground level that the sUAS reached was 75 m and 76 m respectively. A further analysis of the relative altitudes and the helicopter while in proximity will be included in a planned forthcoming publication.

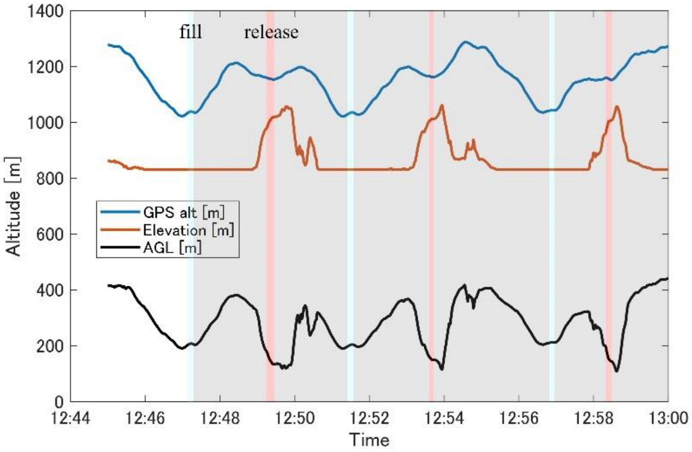


Fig. 10 Altitude data analysis

C. Pilot's Feedback

After the flight test, the pilots and researchers took part in a debriefing where initial results and feedback were discussed. Pilots noted that having awareness of the sUAS flight area, i.e., their operation volume, improved their overall situation awareness. Shared information on the sUAS operation volume contributes to the development of a shared common operating picture among sUAS operators and helicopter pilots as well. Helicopter pilots confirmed that they would not enter the sUAS operation volume when they are aware of the airspace assignments. Pilots said, however, that they would try to visually confirm the presence of the sUAS in their operation volume and verify the number of sUAS they see is the same as what they are expecting. The information on planned operations is to be obtained prior to flight and by the aid of the portable mission support device onboard the vehicle, in this case JAXA's D-PAS. This highlights the need for higher trust in technology to support operations in dynamic environments such as disaster response. Pilots also commented on situations in which there is a limited amount of information. Given the choice between sUAS real-time position information only and operation volume only, pilots stated a preference for the latter if the helicopter mission is in the vicinity of the sUAS mission; but if the sUAS is just passing through the airspace, the pilots stated a preference for being able to view the position information.

VI. Concluding remarks

The flight test demonstrated the advantages of the developed situation awareness technology and confirmed that real-time awareness of the sUAS operation airspace helped the helicopter pilot plan and execute a safe mission and minimize the flight time loss due to potential interference of the sUAS. The key enabling elements for successfully building the pilots' situation awareness were the ability to construct and digitally share the operational airspace data, and view that data on the flight deck in real time. The ability to gain situation awareness during disaster response operations using real-time displays in the flight deck warrants further exploration to identify the most appropriate method to convey that information to the pilots (e.g., heads up vs heads down). The information described is not, however, exclusive to the helicopter: any response stakeholder whether on the ground, in an incident command center, or managing another aircraft operation, can consume and visualize this data and have it tailored to their unique needs to support situation awareness and decision making based on a shared operational picture. The information sharing and availability demonstrated in this test also captures the framework through which additional aspects of integrated operations can be applied and tested in a disaster response environment such as cross-platform or cross-mission priority handling, mission element and phase characterization for awareness and prioritization, as well as a host of other areas in need of further research.

The activities described in this paper are part of an ongoing collaboration between JAXA and NASA towards the broader benefit of integrating technologies to improve safety and efficiency of disaster response aviation operations. One particular area of the current work underway is in support of the development of international standards through collaboration with relevant organizations. Technology standards is a particularly important area as there are not only challenges in different agencies from the same country working together on a disaster response incident, but those challenges may be compounded when working across borders internationally as is becoming more prevalent as wildfires and disasters become greater in frequency and severity. Future JAXA-NASA testing and simulations to support standards and inform requirements for crewed and uncrewed disaster response operations are also being considered.

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