# [EN-A-050] Simulation Techniques for Small Unmanned Aircraft Systems (sUAS) Trajectories including Signal Propagation

(EIWAC 2017)

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**Abstract: With the dramatic increase in the demand for small unmanned aircraft system (sUAS), simulation techniques for sUAS have become important in assessing the safety of future sUAS operating environments. This study investigates the simulation techniques regarding the trajectory of sUAS and their radio communication. Radio communication is one of the most important factors for safe operation of sUAS. With the increase in the number of sUAS, radio wave interference can possibly occur because sUAS use radio waves for aircraft control, flight data transmission, and surveillance. To study the interference, the trajectory simulation is coupled with the radio signal propagation simulation. The sUAS movement affects the radio signal propagation of communication systems. Simulations are performed regarding the trajectories of sUAS-equipped automatic dependent surveillance broadcast (ADS-B), which is one of the most promising solutions for aircraft localization and situational awareness in future sUAS operations. The simulation results show the effects of the sUAS movement on the signals received by a receiving station in a radio communication system.**

**Keywords: sUAS, trajectory simulation, radio environment simulation, signal propagation, ADS-B**

## 1. INTRODUCTION

The demand for unmanned aircraft system (UAS), especially small UAS (sUAS), also known as drones, has been dramatically increasing in several fields, for example, infrastructure inspection, pesticide application, land survey, and logistics. With the increase in sUAS usage, problems arise regarding the safety of sUAS operations. In fact, several sUAS clashed, and near misses between visual-flight rule (VFR) aircraft and sUAS have been reported [1, 2]. sUAS generally fly in a low-level airspace such as the non-controlled airspace (class G) because of its flight performance and legal constraints. In the low-level airspace, no air traffic control service is available, such as maintaining safety separation, and VFR aircraft occasionally fly and land at a location that is not an airport, for example, rescue and air-ambulance helicopters. In such an environment, frameworks to maintain safe separation and prevent collision between sUAS and VFR aircraft are required following the increase in sUAS operations to ensure safety in low-level airspace.

Several research and development projects regarding safe operations of sUAS have been launched around the world. One of the most active and remarkable projects is the UAS traffic management (UTM), which is a framework designed to enable safe large-scale sUAS operations in the low-level airspace, proposed by the National Aeronautics and Space Administration (NASA) [3]. NASA defined the technical capability level corresponding to the operational risk of the UTM and performed experiments on UTM operations in several UAS experimental fields to demonstrate its capabilities [4]. The simulation environment of the UTM was developed to also perform simulation-based experiments [5]. In addition, in Europe, several demonstration projects are ongoing, which are funded by the Single European Sky ATM Research (SESAR) Joint Undertaking [6]. They focus on the integration of a remotely piloted aircraft system (RPAS) that generally considers UASa that are larger than drones. Joulia et al. proposed to apply the concept of a four-dimensional trajectory-based operation (4D TBO) for the UTM [7]. The 4D TBO was developed for civil aviation. In Japan, Nakamura et al. demonstrated collaborative operations between a helitack and sUAS [8], and the Japan UTM Consortium developed a UTM prototype and performed demonstrations involving multiple sUAS operators in the Fukushima Robot Test Field [9].

To support the research and development of these concepts, one of the key technologies is numerical simulation. Simulation is often performed to review the safety, efficiency, and effectiveness of new concepts before they are implemented in real world. In the rapid development of sUAS, many projects have developed simulation environments for the sUAS trajectory and motion [10, 11]. However, additional component techniques are required to review the safe operating principles of sUAS. For example, NASA investigates the simulation techniques of a sUAS flight under wind conditions. D'Souza proposed a framework for the trajectory prediction of sUAS under wind conditions [12], and Krishnakumar et al. developed computational fluid dynamics simulation techniques to estimate the wind in an urban environment, including several buildings [13]. By combining these simulation techniques and the aerodynamic characteristics estimated using a wind tunnel [14], a sUAS simulator can predict the sUAS trajectory that considers complex wind conditions in such urban areas.

The ultimate goal of the present study is to simulate a future sUAS operating environment to assess its safety, efficiency, and effectiveness. This goal is required to develop several component techniques to simulate future operating environments. This study addresses trajectory simulation and includes radio signal propagation to review radio communication systems. Radio communication is an essential component for the safe operation of sUAS. The next section describes the reasons to simulate the sUAS trajectory, including radio signal propagation. An overview about the automatic dependent surveillance-broadcast (ADS-B) for sUAS is also provided. Section 3 explains the simulation techniques regarding the trajectory and signal propagation. Section 4 shows the simulation results to demonstrate the abilities of the simulation coupling of the trajectory and signal propagation. Section 5 concludes this paper and presents a summary of our future works.

## 2. RESEARCH OUTLINE

### 2.1 Radio Communication for sUAS

One of the most important factors for safe flights of sUAS is radio communication. Radio communication is used not only in controlling sUAS but also downlinking live movies and flight data from sUAS as well as communication among sUAS. These functions, namely, communication, command, and control, are often referred to as a C3 link. If a sUAS loses the C3 link during flight, the risk of a clash dramatically increases. With the increase in sUAS flights in the future, equipment that emits radio waves in the low-level airspace will increase. In such an environment, radio waves will interfere with one another. However, various radio techniques, including sUAS localization and monitoring, will be important for UTM systems as well for communication. Thus, radio environment simulation techniques that can assess a comprehensive sUAS operating environment are required to support the UTM system.

### 2.2 Trajectory Simulation and Radio Signal

The interference of radio waves mainly depends on the radio power and sUAS traffic density [15]. Recently, many companies have proposed radio communication equipment for sUAS with various power, frequency, and communication systems. In the future, sUAS will be loaded with various types of radio communication equipment depending on the mission targets in the sUAS operating environment. To simulate such a mixed-equipage environment, each sUAS radio communication system should be modeled and simulated. Furthermore, the sUAS traffic density depends on the sUAS movement. One of the features of sUAS is their different aircraft types such as fixed wing, multicopter, and helicopter with various sizes and motor power. Another feature is that sUAS can fly from almost anywhere and anytime, in contrast to commercial aircraft that must take off and land at an airport on a certain schedule. The trajectories of sUAS have many variations owing to these features and affect radio signal propagation. Accordingly, the radio signal propagation should be calculated, together with the sUAS trajectories, to accurately simulate the interference of radio waves.

### 2.3 ADS-B for sUAS

As a radio communication device for sUAS, this study focuses on ADS-B. ADS-B is one of the most promising solutions for situational awareness and for further detect and avoid (DAA) operation in future sUAS operations, even though many technological and regulatory problems must be overcome to implement the ADS-B for sUAS operations [16]. Several choices are available to implement the ADS-B, such as air-to-air and air-to-ground configurations. Figure 1 shows an air-to-ground configuration. In this configuration, the sUAS is equipped only with ADS-B Out which can only transmits aircraft information without receiving, and the receiving station can obtain information on the other sUAS by receiving an ADS-B Out signal. The operator can maintain safe separation between its own sUAS and the others based on the information obtained from the ADS-B. A possibility exists that the receiving station will not be able to decode the ADS-B signal owing

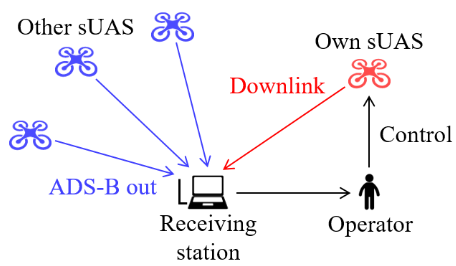


Fig. 1 Implementing configuration of ADS-B.

to interference in the radio waves when many sUAS simultaneously fly. A coupling simulation between the trajectory and radio signal propagation is performed to review the effect of the sUAS flight on the ADS-B radio communication.

## 3. SIMULATION TECHNIQUES

### 3.1 Trajectory Simulation

This section presents the simulation method for the sUAS trajectory. A quadrotor is used as a sUAS model. The trajectory is calculated by integration using the fourth-order Runge–Kutta method. The equations of motion of the sUAS are formulated as a three-degree-of-freedom model (that is, point-mass model), as expressed in Eq. (1).

$$\frac{d^2}{dt^2}\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} (f_x + D_x)/m \\ (f_y + D_y)/m \\ -g + (f_z + D_z)/m \end{pmatrix} \quad (1)$$

where $f_x$, $f_y$, and $f_z$ are the forces acting on the sUAS. $D_x$, $D_y$, and $D_z$ represent the aerodynamic drag. $m$ and $g$ are the mass and gravitational acceleration, respectively. Eq. (1) does not include rigid-body dynamics such as the sUAS attitude, but the attitude can be calculated if required. For a controlled quadcopter without a yaw control, the attitude can be derived using the following equation:

$$\begin{aligned} \phi &= -\tan^{-1}(f_y/f_z) \\ \theta &= -\tan^{-1}(f_x/f_z) \end{aligned} \quad (2)$$

where $\phi$ and $\theta$ denote the roll and pitch angles, respectively, of the quadrotor.

Table 1 Mission plan for sUAS.

| | Position | Velocity | Holding time |
|---|---|---|---|
| Take off | $(x_{tko}, y_{tko}, z_{tko})$ | $(0, V_{z,tko})$ | $t_{tko}$ |
| WP$_1$ | $(x_1, y_1, z_1)$ | $(V_{h,1}, V_{z,1})$ | $t_1$ |
| WP$_2$ | $(x_2, y_2, z_2)$ | $(V_{h,2}, V_{z,2})$ | $t_2$ |
| ⋮ | ⋮ | ⋮ | ⋮ |
| WP$_f$ | $(x_f, y_f, z_f)$ | $(V_{h,f}, V_{z,f})$ | $t_f$ |
| Land | $(x_f, y_f, z_{lnd})$ | $(0, V_{z,lnd})$ | - |

The mission plan is given in Table 1, and the sUAS sequentially cruises through the waypoints after taking off. $V_h$ and $V_z$ denote the horizontal and vertical velocity, respectively, and subscripts $_{tko}$ and $_{lnd}$ denote takeoff and landing, respectively. After reaching the final waypoint, the sUAS lands at the final waypoint. To track the sequential waypoints, a standard guidance system of the quadrotor is simulated. As an example, Fig. 2 shows the schematic image of the horizontal control. When a distance is established between the quadrotor and target waypoint, the quadrotor is controlled using velocity control to maintain target velocity $V_h$. The azimuth angle is also controlled to cancel the deviation from the line of sight (LOS) between the waypoints. When the quadrotor approaches the target waypoint within a predefined threshold, the horizontal control is changed to position control. After reaching the target waypoint, the quadrotor hovers at the waypoint for a holding time and commences to cruise to the next waypoint.

### 3.2 Signal Propagation Simulation

A simulated sUAS trajectory provides reality to a radio wave environment simulation. Here, we assume an environment where many sUAS fly while emitting ADS-B signals. Each signal arrives at the receiving station on the ground with a certain attenuation and time delay, according to its propagation environment. At the receiving station, superposition of all signals is detected. This study aims to estimate the arriving signal at the receiving station.

In this estimation, the signal attenuation *loss* follows the free-space propagation model, namely, Eq. (3), because very few radio obstacles are present, such as metallic structures and buildings, in the sUAS flying environment. This assumption also means that the fading and Doppler effects are not considered in this study. The signal phase delay is inversely proportional to the speed of light.

$$loss(t) = \left(\frac{4\pi R(t)}{\lambda}\right)^2 \quad (3)$$

In Eq. (3), $R$ is the distance between a sUAS and the receiving station, which is obtained from the trajectory simulation mentioned in Section 3.1, and $\lambda$ is the wavelength defined by the frequency. In other words, the propagation loss and delay basically depends on the distance and frequency. Thus, the propagation loss and delay in flight time *t* are obtained by substituting the sUAS position with time in Eq. (3).

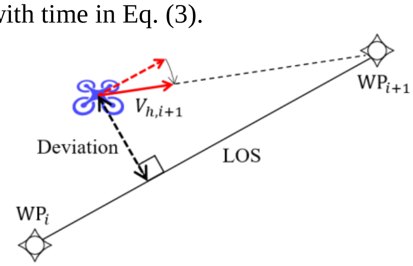


Fig. 2 Schematic image of horizontal control.

# 4. SIMULATION RESULTS

## 4.1 Simulation Example

As an example, Figs. 3 and 4 show the simulation results of a single sUAS trajectory. In this simulation, the sUAS is designed as a quadrotor type. The sUAS takes off, climbs to 120 m, and cruises along a 300 m square grid, which is a well-used route for land survey and pesticide application. After completing the grid route, the sUAS returns to the launch site and lands. The target velocity is horizontally and vertically set as 2 and 1 m/s, respectively. Figure 4 shows that the sUAS can follow the target velocity during cruising. The sUAS decelerates to change direction at each waypoint.

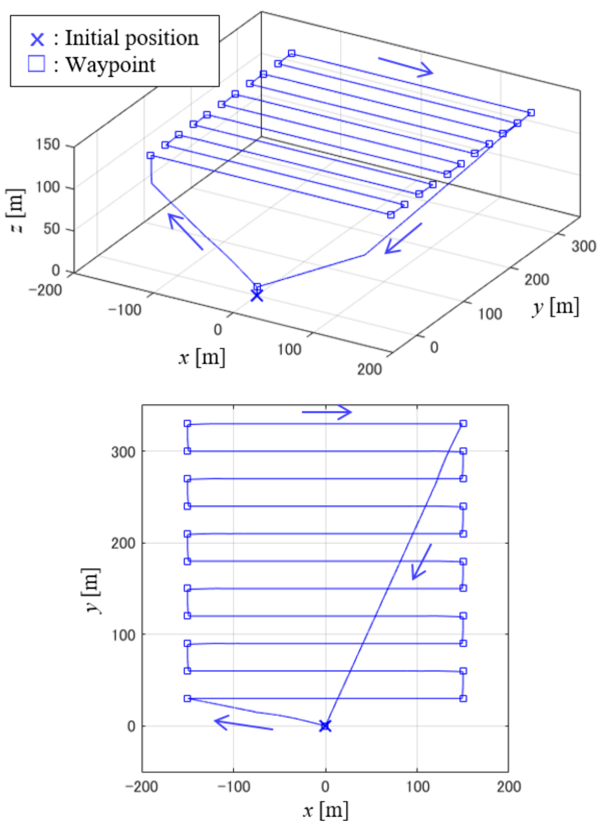


Fig. 3 Flight path of the single sUAS.
(top: in 3D; bottom: in 2D)

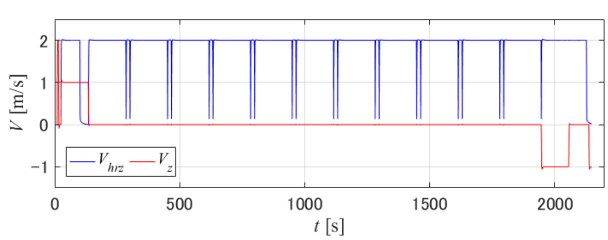


Fig. 4 Velocity of the single sUAS.

## 4.2 Simulation Conditions

Five sUAS are used as objects in the simulations. All sUAS are designed as a quadrotor type with the same parameters. The mission plans are set in a grid similar to that shown in Fig. 3 except for the takeoff time and initial position. All sUAS have different takeoff times and initial positions, as listed in Table 2. The receiving station is located at $(x, y, z) = (0, 0, 2)$, expressed in meters. The sUAS are assumed to emit ADS-B signals in the same manner as a manned aircraft (1090-MHz extended squitter). Therefore, the frequency is 1090 MHz, and a pulse position modulation signal with 112 μs length is emitted every 0.5 s [17]. The transmitted power is set to 20 W, which is smaller than the general standard for manned aircraft. In reality, a small ADS-B transmitter for sUAS is already available in the market, and its transmitted power is reduced to 20 W [18]. As an example, Fig. 5 shows the directory-measured time domain ADS-B signal by an ADS-B transceiver "ping2020". The top figure shows that extended squitter signals are emitted every 0.05 s. The bottom figure shows the details of the single extended squitter signal.

Table 2 Takeoff time and initial position.

| | Takeoff time [s] | Initial position [m] |
|---|---|---|
| sUAS1 | 10 | (0, 0, 0) |
| sUAS2 | 10 | (-5000, 5000, 0) |
| sUAS3 | 10 | (2000, 2000, 0) |
| sUAS4 | 10 | (-8000, -8000, 0) |
| sUAS5 | 20.2 | (5000, -5000, 0) |

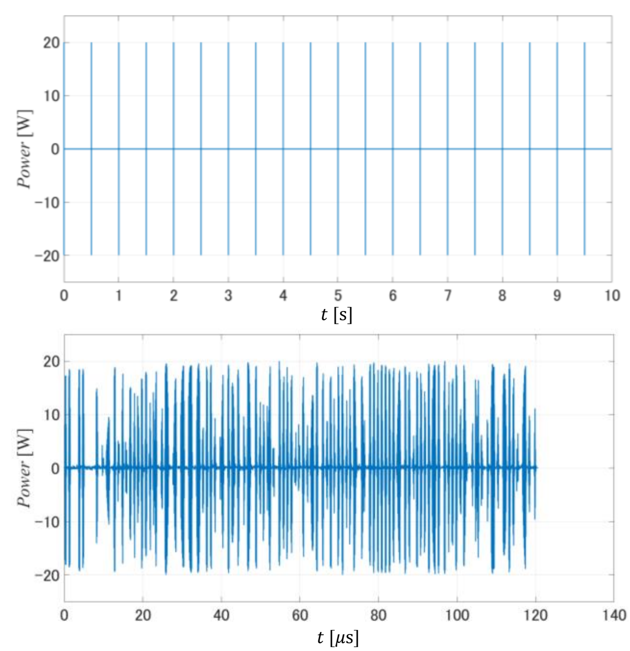


Fig. 5 Actual ADS-B signal used in the simulation.
(bottom: magnified one extended squitter signal)

### 4.3 Simulation Results

Figure 6 shows the simulation results in 2D flight paths. All the sUAS fly along the grid according to the mission plans listed in Table 2. Figure 7 shows the estimated ADS-B signals received by the receiving station. Hereinafter, the signals emitted by sUAS1 to sUAS5 are denoted as signal1 to signal5, respectively. The target signals at the receiving station are calculated as a composition of the original signal modified with the propagation status, as shown in Fig. 5.

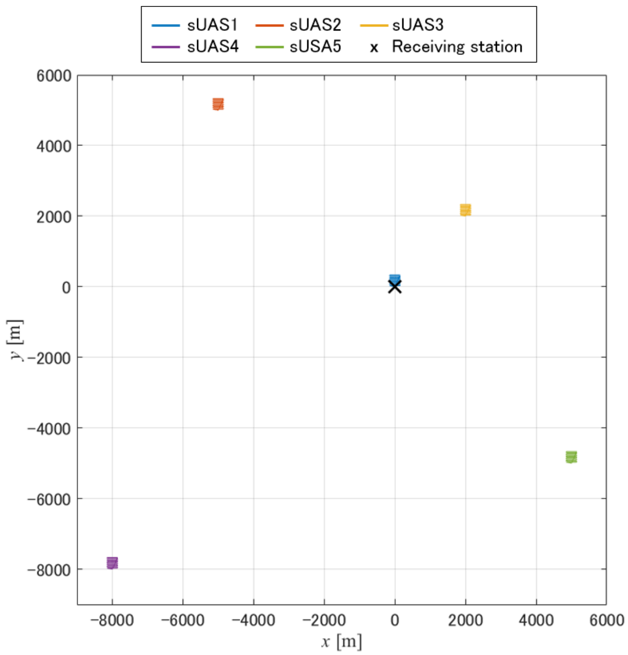


Fig. 6 Flight paths of the five sUASs.

Fig. 7 shows that signal1 is the largest among the five signals because sUAS1 flies nearest the receiving station. The distance between sUAS3 and the receiving station is shorter than that between sUAS2 and the receiving station. Thus, signal3 is larger than signal2 and occurs earlier in the time domain than signal2. In a similar manner, signal4 is smaller and occurs later in the time domain than signal2. The reason is that sUAS4 flies farther from the receiving station than sUAS2. The flight path of sUAS5 is located at almost the same distance as that of sUAS2. The level of signal5 is the same as that of signal2, but the signal phase is different from signal2 because of the difference in the takeoff time.

The simulation results show that each signal has a different shape in the time domain despite all sUAS having the same transmitted power. This result indicates that the difference in the sUAS trajectory affects the radio wave. In particular, the distance between a sUAS and the receiving station has large effects on the signal level and phase. The signal phase also varies because of the takeoff time. The signals have different shapes at the receiving station even though only the takeoff time and initial positions are different among the sUAS under this simulation condition. In future practical operations, sUAS will have more diverse mission plans and different aircraft types. Accordingly, the ADS-B signal at the receiving station will have more diverse shapes with more diverse sUAS trajectories. The simulation results indicate that the radio signal simulation coupled with the trajectory simulation is necessary to assess the radio wave environment in future sUAS operating environments.

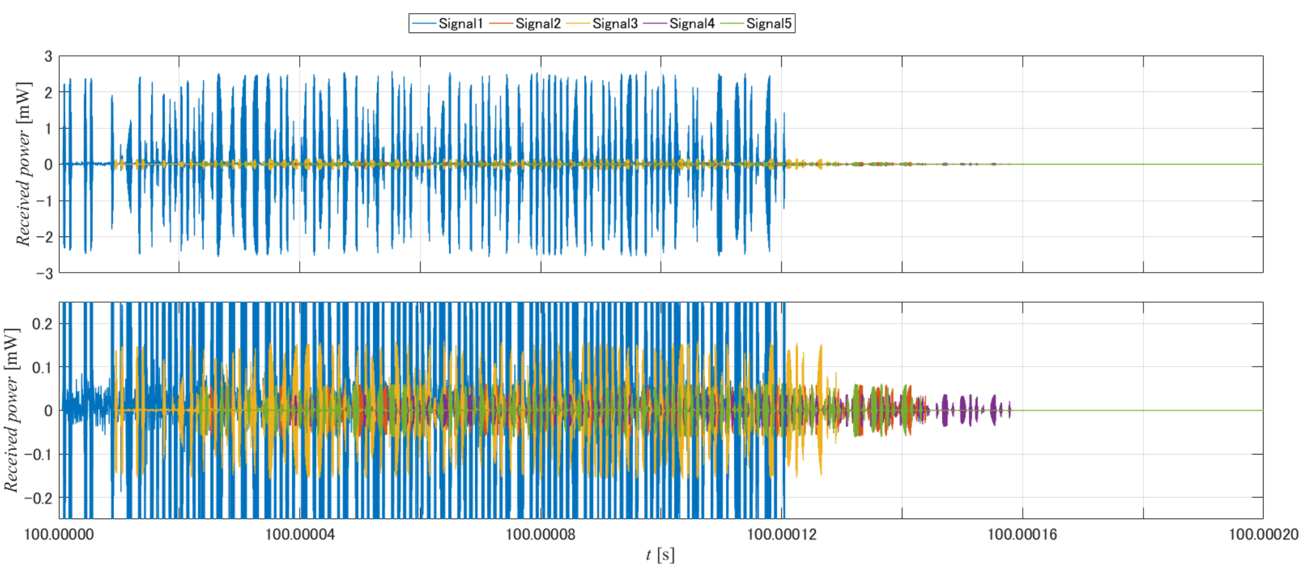


Fig. 7 Estimated ADS-B signals at the receiving station. (bottom: magnified figure)

## 5. CONCLUSION

This study presented a technique for sUAS trajectory simulation that includes radio signal propagation. To estimate the radio wave environment, the trajectory simulation was coupled with the signal propagation simulation. The coupled simulation revealed that the ADS-B signals at the receiving station had different shapes under different sUAS trajectories. The ADS-B signal mainly depended on the distance between the sUAS and receiving station. The takeoff time also affected the ADS-B signal. From the simulations, we have demonstrated that the simulation that coupled the sUAS trajectory and radio signal propagation could accurately simulate the radio wave environment for sUAS.

This paper has presented only the superposition of the ADS-B signals at the receiving station. As a future work, interference of the radio waves will be studied, and the signal decodability will be clarified using a hardware-in-the-loop test. Further, the attitude angle of sUAS will be considered in calculating the ADS-B signal. In particular, a multirotor-type sUAS dynamically changes its attitude, and the emitted radio wave by the sUAS is affected by the sUAS attitude change because of the directivity of the antenna. By including these factors, the sUAS simulation will be more accurate and practical.

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## 7. COPYRIGHT

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