

# **Report ITU-R SM.2486-1**

**(06/2024)**

SM Series: Spectrum management

## **Use of commercial drones for ITU-R spectrum monitoring tasks**



## Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

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P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
<b>SM</b>	<b>Spectrum management</b>
TF	Time signals and frequency standards emissions

*Note: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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## REPORT ITU-R SM.2486-1

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(2021-2024)

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NOTE – In using commercial drones for spectrum monitoring tasks, attention should be drawn by the users to the fact that in case of the likelihood of entering unintentionally or intentionally into another country’s airspace, the explicit authorization of that country is specifically required.

**Scope**

Commercial drones which are similar to legacy airborne monitoring stations can assist in regulatory spectrum monitoring and measurement procedures. Radio monitoring utilizing commercial drones can be appropriate for use in difficult situations where the traditional ground-based measurements and transmissions are unable to overcome geographical barriers or to ensure the safety of operations. The application of commercial drones in this Report is understood to be conducted within visible line of sight by ground operations and is for use within the country of the authorities operating the drone.

This Report details the common elements, considerations on the uncertainty, possible missions as well as use cases of spectrum monitoring and measurement procedures that are assisted by commercial drones.

### Abbreviations

3D	Three-dimensional
DTV	Digital television
EMI	Electromagnetic interference
GNSS	Global navigation satellite system
GPS	Global positioning system
GS	Glide slope
ICAO	International Civil Aviation Organization
ILS	Instrument landing system
INS	Inertial navigation system
LOC	Localizer
RTK	Real-time kinematic
UAS	Unmanned aircraft system
UAV	Unmanned aerial vehicle
VOR	VHF omnidirectional range
VSAT	Very small aperture terminal

## 1 Introduction

The International Civil Aviation Organization (ICAO) defines unmanned aircraft systems (UAS), which is commonly well known as unmanned aerial vehicle (UAV), as an aircraft and its associated elements which are operated with no pilot on board. Commercial drones fall into this general category. As such, they are able to overcome geographical limitations and provide relatively low cost of flight compared to manned aircraft. Commercial drones can perform reception or transmission at locations inaccessible by ground equipment, and at multiple locations in a short time similar to legacy manned airborne stations. Because conventional stationary or mobile radio monitoring systems carry out measurements and transmissions on the ground or at a limited height from the ground, they may experience reduced accuracy due to the site environment such as surrounding urban buildings, mountains, antennas at high elevation, and coastal areas.

Potential measurement and transmission tasks using commercial drones can include:

- radio field strength measurements;
- three-dimensional antenna pattern measurement;
- radio coverage measurements;
- inspection of radio monitoring stations on site;
- inspection of radio stations on site;
- maintenance and calibration of radio monitoring stations and equipment;
- investigating of interference;
- direction finding of an emitter source;

– technical and scientific studies.

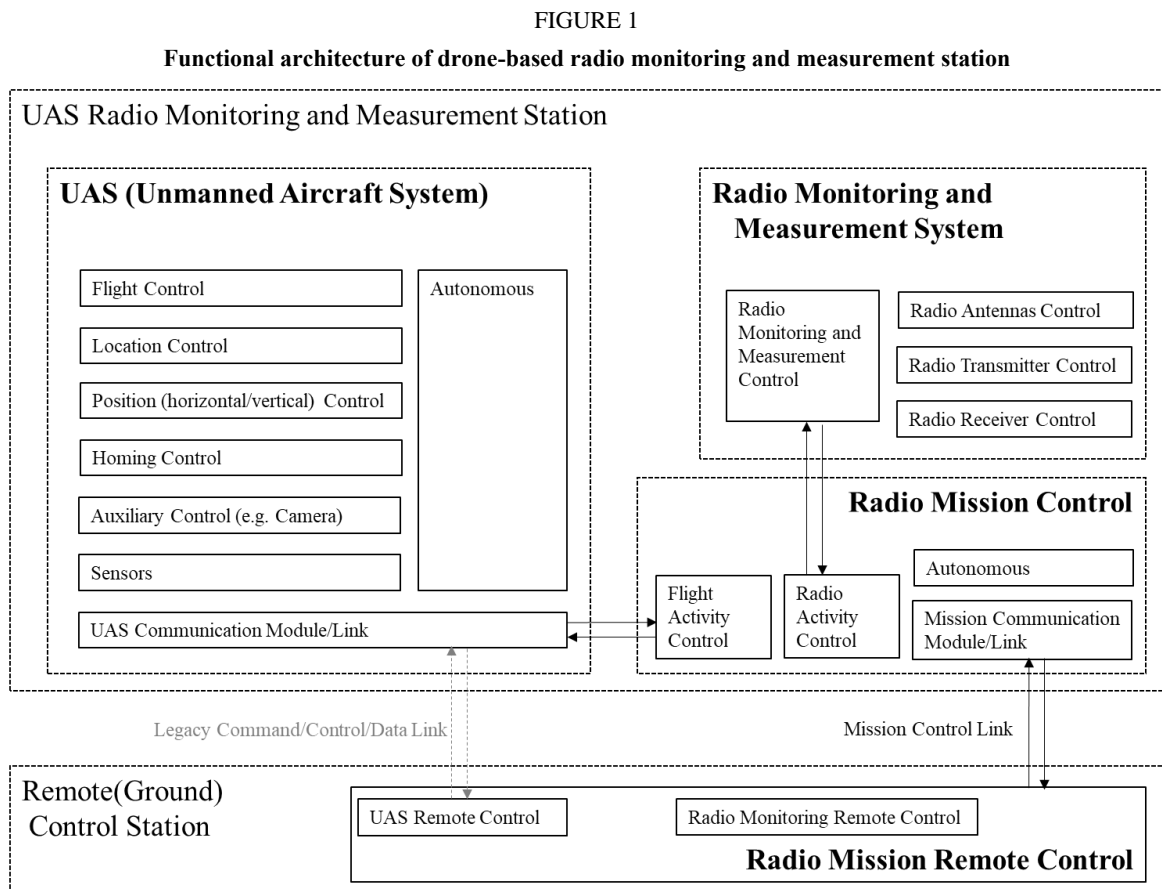
The advantage presented by drone-based spectrum monitoring is the ability to observe the spectrum and make signal specific measurements or recordings at an elevation far above that possible with a ground-based monitoring system. The additional elevation may prove extremely beneficial in any of the applications mentioned above. Additionally, the cost of purchasing a drone platform for spectrum monitoring purposes is far below that of the most basic mobile platform.

## 2 Functional components of commercial drone-based monitoring systems

The functional components of radio monitoring and measurements using commercial drones can be described as having four parts, as shown in Fig. 1:

- the drone flight system,
- radio monitoring and measurement system,
- the radio mission control, and
- radio mission remote control.

Figure 2 shows the example of a drone-based radio monitoring station.



### 2.1 The drone flight system

Commercial drones have control components similar to manned aircraft, and the major functions required for radio monitoring in either autonomous or manual mode are as follows:

- flight control with/without collision avoidance;
- location and altitude control;

- horizontal and vertical position control (hovering);
- homing (origin) control.

Commercial drones are typically able to be remotely and fully controlled from a distant location, or pre-programmed to conduct its flight autonomously without intervention. The accuracy of each method of control depends on the flight performance of the drone.

## **2.2 Radio monitoring and measurement systems**

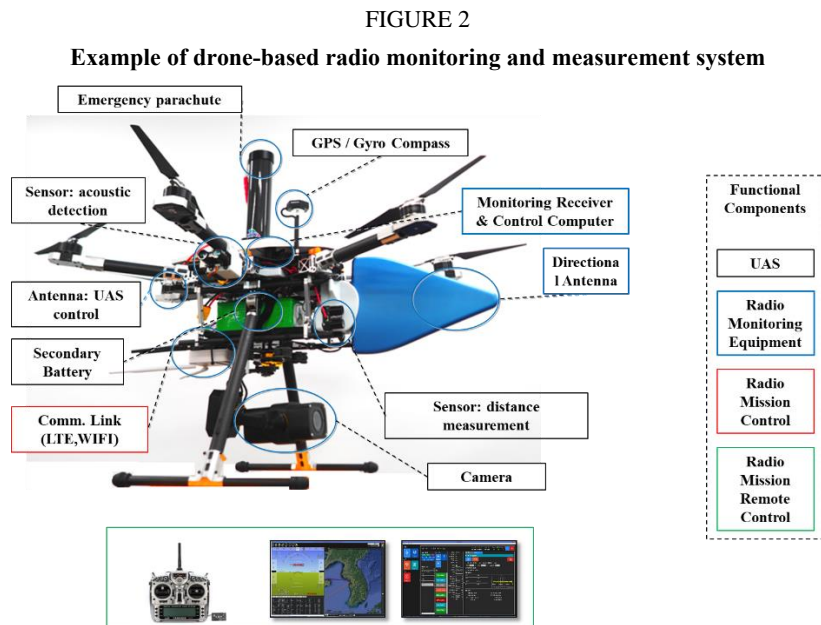
The radio monitoring and measurement system can include both equipment for receiving and measuring radio waves and equipment capable of transmitting signals. It is conceptually identical to existing radio monitoring and test equipment, but the type, size and weight are limited by the drone capacity (e.g. maximum payload, power consumption, dimensions and shape). For example, the size of the antenna or antenna array that determines the frequency range is affected by the drone size, and the size and weight of the receiver, signal generator, or power amplifier is directly limited by the payload capability. In addition, the possible radio monitoring and measurement tasks depend on the precision of position control. For instance, if the drone is used to measure a near-field three-dimensional antenna pattern, the location accuracy and precision of position-keeping control must be ensured.

## **2.3 Radio mission control**

Radio mission control coordinates the drone as well as the radio monitoring and measurement system to perform one or more tasks. The radio mission control can move the drone to a precise location, perform radio measurements or transmissions, collect and transfer the results. The radio mission control has a communication link for transferring telemetry and other data to the remote (ground) control station and uses some or all the links depending on the mode of flight and the measurement tasking. Depending on the situation, the drone can use dedicated legacy communication links, and radio monitoring-related missions can be operated through the mission control link.

## **2.4 Radio mission remote control**

Commercial drone radio monitoring and measurement stations can be fully controlled by the radio mission remote control during the process of radio monitoring. The radio mission remote control communicates with the radio mission control via the mission control link. The use of the link depends on the level of automation of the radio monitoring and measurement procedures and the drone flight control mode.



### 3 Other considerations

#### 3.1 Prerequisites to operation

##### 3.1.1 Size, weight and power impacts on performance

Since a relatively small drone body limits the installation space, it is necessary to select components based on their size, weight, and power consumption. They must be installed in a very space-efficient, but functional configuration that enables both flight and measurement operations. Unlike traditional radio measurement systems, RF components able to fit on a drone (antennas, receivers, and transmitters) may exhibit poor performance, and narrow operating bandwidth, or range characteristics. Therefore, when deploying a monitoring system on a drone, it is recommended to measure, calibrate, and verify the overall system performance with all monitoring equipment installed.

##### 3.1.2 Antenna patterns

Commercial drones use a relatively small amount of metal to make it light, but there are many structures around the antenna that may interfere with signal reception. Landing legs, propellers as well as their arms, and mounts for attachment of peripheral equipment such as cameras, may interfere with signal reception from certain directions. The pattern of an antenna mounted on a UAV will affect the measurement results. During flight, while the UAV is in continuous motion, some systems may use a laser reflector to obtain accurate three-dimensional position data to point the antenna in the correct direction. To make accurate antenna pattern of UAV, the pattern is typically measured in an anechoic chamber. During the chamber measurements, all the equipment needed for the operation should be mounted (such as laser reflector) to accurately determine the pattern.

##### 3.1.3 Noise floor

Commercial drones have a number of radio frequency devices on board for:

- legacy remote control and data transmission,
- communication links for the radio monitoring mission, and
- components that can be sources of EMI, such as electric motors and power supplies.

Therefore, noise levels may be abnormally high in certain frequency bands. Some of these may need to be turned off to create a better measurement environment.

#### **3.1.4 National flight regulations**

Because there are national regulations limiting flight regions, time of day, flight controls for each type of drone (including total weight and size), it is necessary to assure compliance and contact the appropriate civil aviation authority in advance as required.

### **3.2 Measurement uncertainty factors**

Since drones are not firmly attached to the ground, it is trying to keep at a target position using various sensors and algorithms. Therefore, any volatility or sudden movement during the signal acquisition time can result in measurement uncertainty, and variation of the results. For example, if a measurement is performed at the same location and a different time, the measurement results for a single tone signal may be different. While drones are controlled to maintain the same position, in actual measurements it can be assumed that volatility in the operating environment will impact the measurement.

The main sources of uncertainty that contribute to measurement volatility include the following.

#### **3.2.1 Flight control by single operator**

When the drone is remotely controlled by an operator, flying to the target coordinates and performing measurements or transmissions at the same time is a very difficult task. If the position of the drone is suddenly changed due to weather conditions, wind, or inaccurate position readings, it is almost impossible for a single operator to visually confirm and maintain the fixed position.

#### **3.2.2 Location control by global navigation satellite system (GNSS)**

Drones typically use GNSS for navigation, including GPS, GLONASS, Galileo, Beidou, and uses an inertial navigation system (INS) for short-term accuracy. These signals are also susceptible to interference or jamming and can suddenly weaken or disappear in some environments during drone flight. The performance of GNSS reception can be degraded by EMI from various peripherals of the drone itself, and by weather conditions such as strong winds or thick clouds. This can cause unstable hovering, which is a problem for measurement or transmission accuracy. Multiple GNSS receivers or multi-frequency receivers, EMI enhancements, etc. can be used to improve reception performance of the navigation signals and therefore, the stability of the drone platform.

GPS has horizontal plane errors of metres under normal conditions, and vertical plane errors are 1~2 times that of the horizontal. In order to increase the position accuracy, real-time kinematic (RTK) GPS technology like that used in surveying etc. can be used, and as a result, position error range of several centimetres can be obtained.

#### **3.2.3 Horizontal and vertical position control (hovering) and homing**

Drones remain at the target position with high accuracy but can still be tilted and rotated, which can cause large errors in near field measurements.

#### **3.2.4 Measurement and transmission antenna characteristics**

Drones can be equipped with directional, omnidirectional antennas, or antenna arrays depending on the mission. Even if an antenna with a known radiation pattern is installed, it is necessary to check the radiation pattern in the mounted condition considering the influence with the drone body or peripheral devices. The altitude and attitude/tilt of the drone can also be changed during measurement or transmission, so it may be necessary to measure the 3D antenna pattern of the target frequency band. When using a directional antenna, the drone homing status and antenna pattern have a bigger



effect on the measurement results. In general, it is more important to know the antenna pattern in near-field missions, where calibration becomes more important in the case of source reconstruction using near-field measurements and converting them to far-field measurements.

### **3.2.5 Influence of wind**

Even if the location accuracy is improved using RTK or the like, wind can constantly disturb the drone to suddenly move from its position. Most of the recreational drones sold in the real world do not guarantee safe or stable operation in windy environments, and there have been many accidents reported due to wind in wireless monitoring tests using drones. In order to have a successful monitoring mission, it may be necessary to monitor, and record the speed of wind on every flight, or every measurement. This may help to better understand measurement results.

## **3.3 Current limitations of commercial drones**

Despite its many advantages, the drones have many of the limitations of conventional aircraft.

### **3.3.1 Location positioning, homing**

There are limits to controlling attitudes where exist both/either the inaccuracy of the sensors' detection and/or atmospheric flow. For example, the drone may not be reporting the direction of the actual origin at the same moment the motion sensor of the drone detects the pointing to the origin. If the drone is used without additional compensation for rotation and tilt, such as laser equipment, the measurement angle can easily vary by several degrees resulting in measurement error.

### **3.3.2 Dependency on weather condition**

Mission planning relies on weather forecasts but is a factor that must be verified in-situ and is the biggest influence on drone activities. High or low temperatures can also have an adverse effect on batteries, sensors, motors and radio monitoring equipment. Drones are also difficult to operate in high humidity, on foggy, rainy, or snowy days, and their use can be limited by local climate in the measurement area. In addition, high winds make drones difficult to fly, and can adversely affect the measurement results.

### **3.3.3 Short operating time**

With limited power supplies, drone flight times are typically less than a few tens of minutes in duration, and spare batteries and charging stations are required for repeated use.

### **3.3.4 Size, weight, and power**

Commercial drones, which can be easily purchased, are relatively small and lightweight, so there is a great limitation on the payload weight including power supply, mountable peripherals, antennas and radio monitoring receivers.

### **3.3.5 Risk of accident**

The systems have many constraints, and present certain risks of accident. Drones, when in flight, always present risk of accident that can include injury to people, damage to property and damage to on-board systems during operation.

### **3.3.6 Cost and regulations**

Since there are many limitations in the operating environment and method, and the risk of accidents, it is necessary to evaluate the cost effectiveness when using drone-based spectrum monitoring for special purposes.

### **3.4 Safety factors**

Commercial drones travel through the air like any aircraft, so the UAV operator must operate the UAV in a manner that ensures the safety of other airspace users and the safety of persons and property on the ground. In addition, a drone equipped with a radio monitoring system is an expensive asset for an agency but can be prone to crashing and the subsequent costly repairs. Therefore, it may be necessary to install an acoustic detection sensor capable of detecting and avoiding a collision during a flight, a parachute in case of an emergency drop, a backup communication link, and a backup location tracking system.

In addition, during operation of the UAV, the following should be considered:

- for spectrum monitoring missions to have one pilot, one operator for monitoring, and optionally, one to observe surrounding conditions;
- airspace management (operations near airports/other airspace users);
- equipment consideration (securing the payload on the UAV);
- site selection for the UAV operator;
- environmental considerations (Weather, wind speed);
- data redundancy (back up channels);
- crash prevention and safety of persons on the ground.

#### **3.4.1 Airspace considerations**

To ensure airspace safety during flight, many countries have published flight laws and regulations according to their own national conditions.

#### **3.4.2 Equipment payload considerations**

In order to attach the monitoring equipment to the UAV, modification of the UAV from the OEM may be required. Additional considerations will be required in these cases as described here. Unmodified commercial UAVs have structural integrity and known flight behaviours. After adding the radio monitoring equipment, the flight behaviours of the UAV may be changed. It is necessary to consider measures to protect the equipment and the corresponding environment where the drone is operating. Some commercial UAVs are rated for heavy payloads. If the monitoring equipment is within the payload capacity specified by the UAV manufacturer, the structural integrity of the UAV system is unchanged.

FIGURE 3  
Monitoring system structure based by UAV



### 3.4.3 UAV operator site selection

In order to achieve efficient monitoring and emitter localization, operators need to find a UAV launch and control site that is advantageous to achieve the monitoring tasks, maintain line of sight to the drone (if required), and safe for the operations and others that may be close by. Additionally, site selection may require coordination with national/local authorities, for example, in the case of restricted zones.

### 3.4.4 Communications redundancy

UAV uplink and downlink transceivers typically use one of the ISM bands. These unlicensed bands are often subject to interference. For that reason, it is important for the UAV to have adaptive communication controls to, for example, switch frequency channels in the case of interference. Many commercial UAV control units apply frequency hopping in the uplink to alleviate the interference that is inherent in the ISM bands which are most commonly used for drone command and control. Of course, frequency bands allocated to ISM vary in different regions and countries; however, 2.4 GHz and 5.8 GHz bands are most often used.

Real-time transmission of monitoring data in the UAV downlink may be essential for some monitoring tasks. Additionally, monitoring tasks often need to live stream video and telemetry data in the downlink. Based on this, high data rates between the UAV and the ground control station may need to be sustained for the duration of the flight. To ensure the integrity of the mission data, the flight range of UAV monitoring platform should be limited to the range specified by the UAV controls manufacturer. The UAV monitoring system should also have the ability to automatically retransmit data that has not been acknowledged by the UAV ground control unit, backup data, and home back to the launch point in the event of a communications link failure.

### 3.4.5 Crash-prevention

There are many factors that can lead to a UAV crash. External factors include weather (high winds), birds, RF interference and other obstructions. Other factors may be avoidable such as a distracted pilot or low battery conditions. When a UAV carrying a heavy monitoring payload is in flight, it is necessary to perform all checks necessary pre-flight to ensure the safety of the UAV, the monitoring

payload, and the personnel who may be in the UAV operating area. Including sound and light alarms (often found on large UAVs) to alert people on the ground that the UAV is in danger of crashing will provide some basic protection. Commercial UAVs have safety features that cause emergency landing based on certain conditions (i.e. low battery). Some drone platforms include parachutes that can deploy manually or when a certain vertical drop is detected to safeguard those on the ground and the drone. Such features are also useful to prevent crash landings.

### 3.4.6 Environmental considerations

UAV flights can be affected by environmental conditions such as strong wind, rain and sandstorm. These conditions can also put more strain on the positional control systems which result in a faster drain on the batteries than under calm conditions. The environmental conditions and effects should be carefully considered by operators prior to conducting monitoring missions with UAVs.

## 4 Experiment and use cases

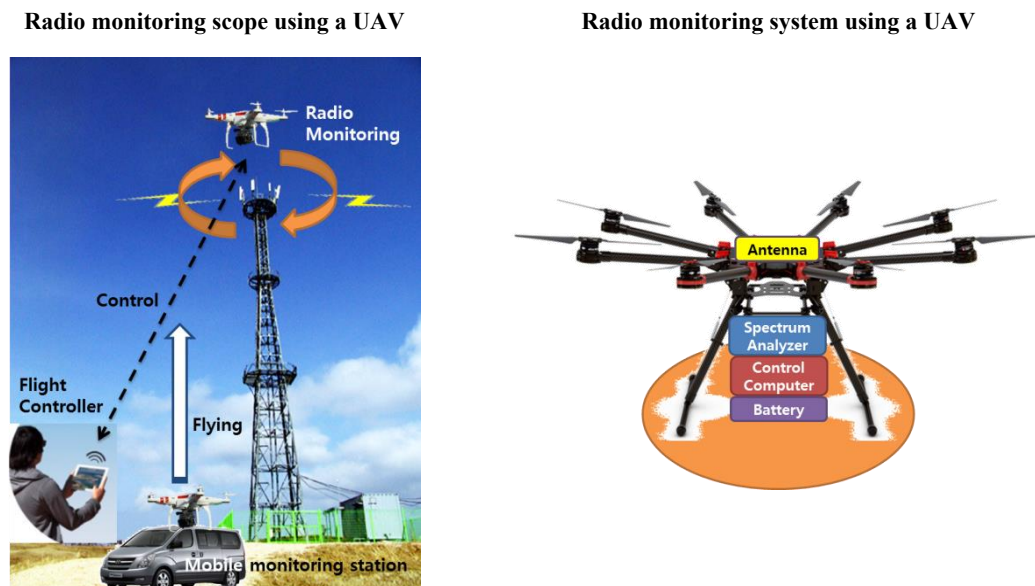
### 4.1 Radio field strength measurement: DTV broadcasting signal

This subsection describes the measurement of radio signals for terrestrial broadcasting from a UAV platform and compares the results with measurements made with a traditional fixed monitoring system.

Figure 4 shows the UAV remote radio monitoring system.

FIGURE 4

#### UAV remote radio monitoring system



#### 4.1.1 Technical considerations

Handheld three-axis gimbals are used in stabilization systems designed to give the camera operator the independence of handheld shooting without camera vibration or shake in order to remove measurement errors due to blurring while flying.

Consideration should be given to visual cognition technology for correct landing position. The programmed landing point of the UAV may have a three-metre variance. To overcome this potential offset, the UAV should be visually monitored during the landing process.

In case of measurements in the HF band, the potential radio noise caused by the UAV motors should be documented and measured.

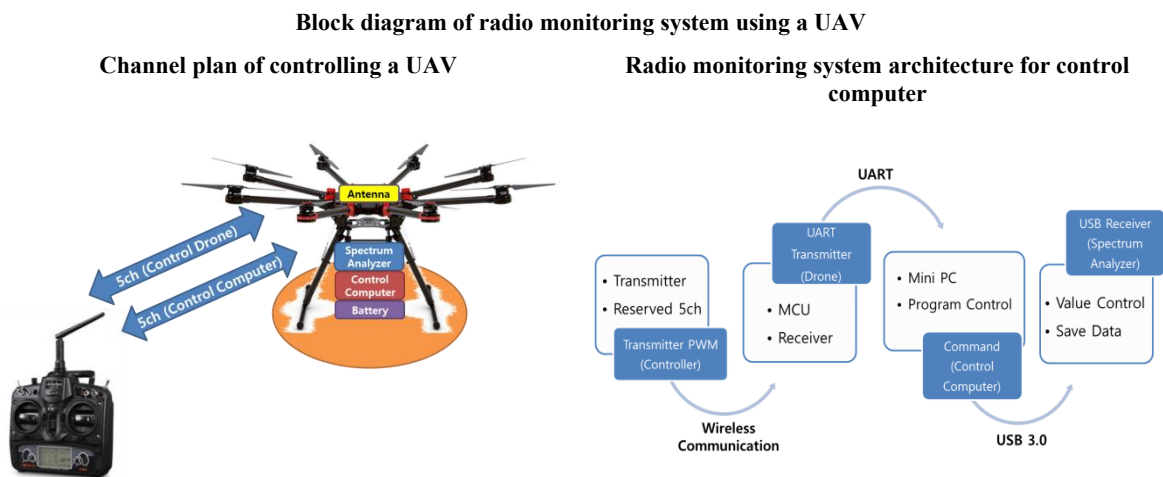
Operators must consider the size, weight, payload, and operating time of the UAV since measurement equipment will be carried on the UAV.

Factors to consider in the selection of the monitoring equipment for use with the UAV should include the size, weight, power supply, and performance.

When selecting a control computer, relevant specifications (OS, CPU, memory size, etc.) are needed dependent on requirements of the monitoring equipment.

The monitoring equipment is controlled by the remote controller’s ten available communication channels. Five of the channels are used for controlling the UAV and the remaining five channels are for controlling the computer programme and operation of the on-board equipment.

FIGURE 5



#### 4.1.2 Experiment of DTV terrestrial broadcasting signal measurement by UAV

The comparison of measurement results for DTV broadcasting is described between fixed radio monitoring and drone remote radio monitoring.

FIGURE 6

**Radio monitoring DTV transmission station**



For DTV broadcasting signals, the antenna height for measurement is 9 metres above the ground. The existing method (fixed radio monitoring) requires installation of an antenna mast to the vehicle and takes more time, and more budget for measurements and results in a limited number of measurement sites. However, if a drone is used in the monitoring process, it could monitor at a height of 9 metres with stable position and monitor from locations hard for vehicles to access.

Measurements were taken using both methods on five DTV channels transmitting from Mt. Moak in Jeonju City. The comparison of results between the two methods ranges from 1 to 2 dB, which is negligible since it corresponds to the measurement error that occurs in the existing method. The left side of Fig. 7 shows the measurement spectrum from the fixed radio wave measurement method using the antenna mast, and the right side shows the remote radio measurement spectrum using drones. Table 1 shows the measurement results of all broadcast channels transmitted from Mt. Moak. This Report shows the feasibility of using a drone as a remote radio monitoring system, since the measurement result of the conventional fixed radio monitoring using the antenna mast is comparable to the result using UAVs.

FIGURE 7

Spectrum monitoring result of DTV terrestrial broadcasting station

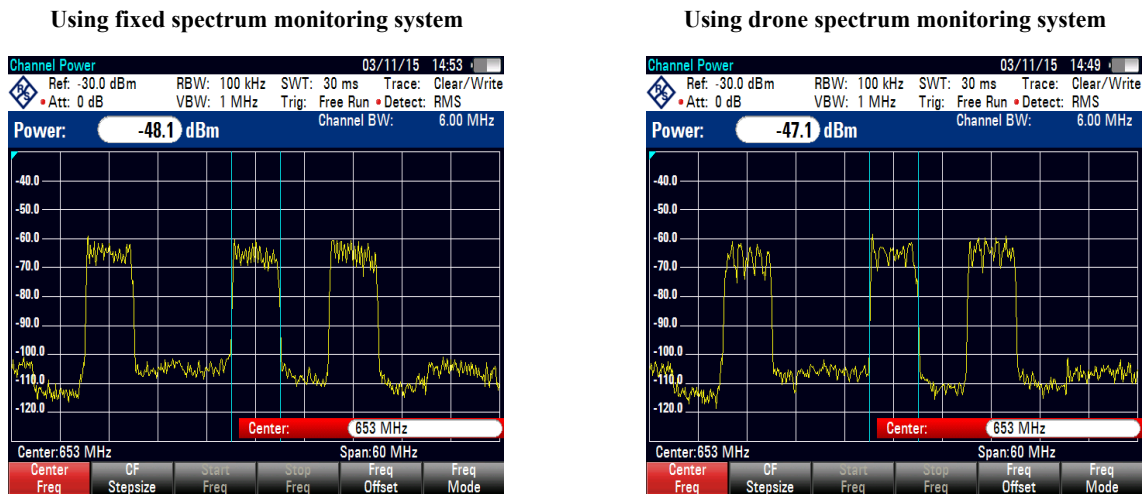


TABLE 1

Spectrum monitoring details of DTV terrestrial broadcasting station

DTV Ch. (Mt. Moak)	Frequency (MHz)	Fixed station (dBm)	Using drone (dBm)	Difference (dB)
27	551	-46	-48	2
33	587	-51	-49	2
41	635	-48	-49	1
44	653	-48	-47	1
46	665	-47	-46	1

## 4.2 Locating VSAT uplink satellite signal

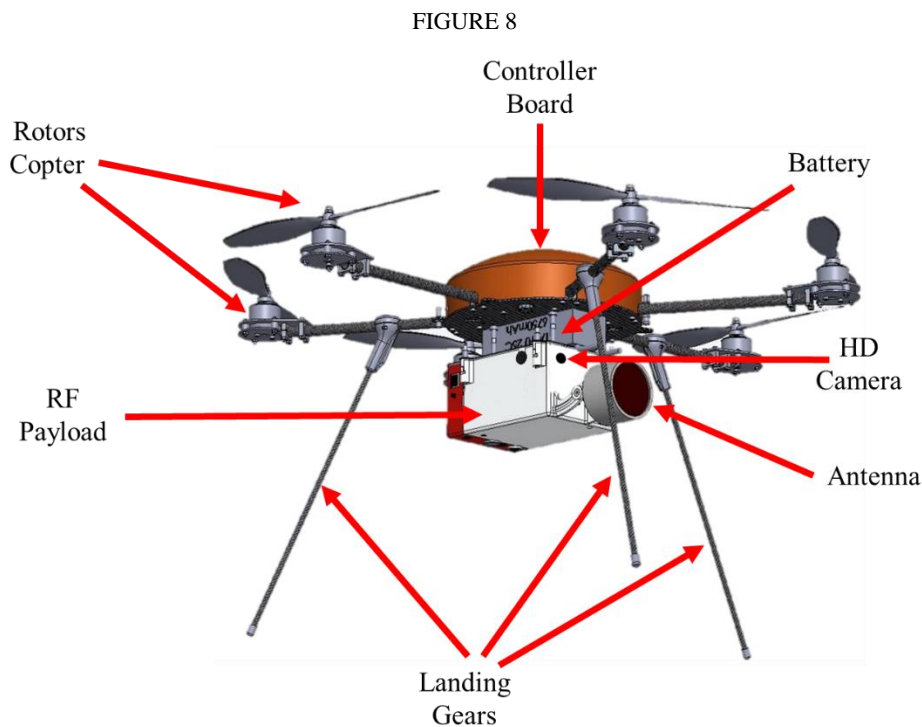
### 4.2.1 Introduction

This section provides an example of using UAV platform to detect and locate VSAT uplink satellite signal.

### 4.2.2 System information

#### 4.2.2.1 UAV

The UAV platform includes 6 Rotors copter and support vertical take-off and landing. It is equipped with high definition (HD) camera and two payloads covering the frequency band 2-40 GHz. Figure 8 shows the components of the UAV.



The ground station of the UAV includes Gamepad, laptop, telemetry module and anemometer.

#### 4.2.2.2 Radio monitoring system (RF payload)

The UAV platform can monitor the frequency band from 2 to 40 GHz using two payloads as mentioned below:

Parameters	L, C, X, Ku bands payload	Ka band payload
Frequency band	2-18 GHz receive antenna	18-40 GHz receive antenna
Polarization	LCHP and RCHP	LCHP and RCHP

The communication between the ground station and UAV is done via wireless link in the 2.4 GHz frequency band.



### 4.2.2.3 Control and operations

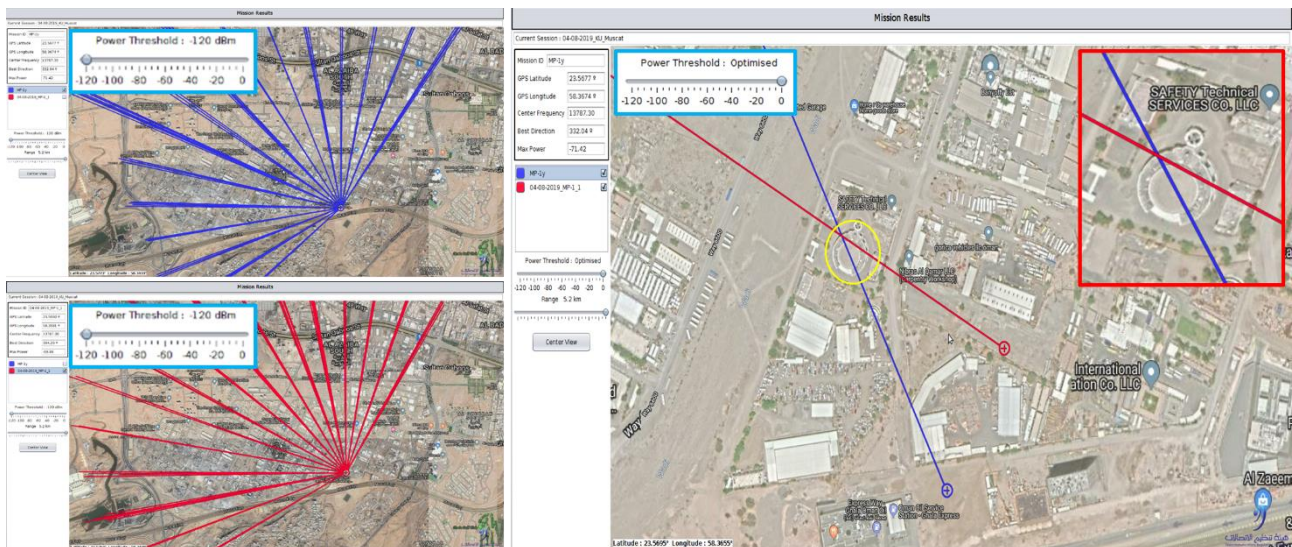
The UAV supports two modes of operation: manual and automatic. It can be manually controlled via Gamepad by an operator to fly in any desired direction. Alternatively, the flight route can be decided and programmed ahead of flight via using the software to load a flight plan into the UAV. For the sake of safety, UAV is equipped with safety landing feature to home position in case of battery drainage.

### 4.2.3 Measurements and results

To carry out such measurement, consideration needs to be taken before performing the mission in a specified large area, such as identifying the measurement location and flying points to locate the target antenna, besides the direction of the suspected target location.

Figure 9 shows the measurement results of UAV mission. During the mission, the UAV measured the target frequency from two measurement points and at different specified degrees. With the use of power threshold metre, the result of the measurements can be filtered on the map to view only the direction with high power received (left-side picture). The UAV system can then provide an optimized result that shows the best direction of measurement calculated based on all received power from all directions. The intersection of optimized results circled in yellow from two measurement flying points shows the location of VSAT transmitter (right-side picture).

FIGURE 9  
UAV measurement results and analysis



Based on the above measurement, the UAV built-in camera helps in identifying any antenna placed on high altitude, where photos are taken in each degree to check if there is an antenna that can be seen in the direction of maximum received power. Figure 10 shows the captured photo of VSAT transmitter.



FIGURE 10  
UAV camera photos



### 4.3 Use of commercial drones for time difference of arrival emitter location

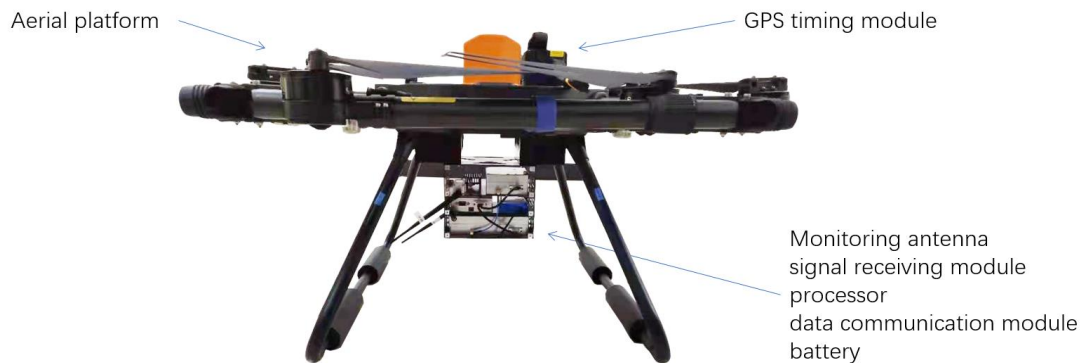
#### 4.3.1 Overview

Spectrum monitoring may include tasks such as spectrum scanning, detection, and location of unknown or interfering signals. Time Difference of Arrival (TDOA) is a passive location technology and offers some advantages for emitter location under the right circumstances. At present, commercial drone technology is mature and widely used, with the advantages of rapid launch, accurate positioning control, high mobility and safety. By combining the advantages of these two technologies (TDOA and UAVs), accurate determinations of emitter location could be obtained. Of course, the advantages and limitations of TDOA as a method of determination of emitter location do not change when implemented from UAV platforms but could overcome geographic barriers and improve line-of-sight (LOS) signal observation.

#### 4.3.2 Implementation

In this case, the TDOA monitoring system includes a minimum of three UAV monitoring platforms and a ground control center. Each UAV monitoring platform includes a 6-rotor UAV equipped with a GPS timing module, monitoring antenna, signal receiving module, processor, data communication module and battery. The GPS timing module enables synchronous acquisition of signals across multiple UAV monitoring platforms. The signal receiving module covers 100 MHz to 6 GHz with the exception of frequencies for control and communications with UAV monitoring platform (typically 2.4 GHz and 5.8 GHz ISM bands). For TDOA measurements, either omnidirectional or directional antenna can be used. However, the impact of size and weight of the antenna element on the UAV monitoring platform must be considered. If a directional antenna is used, rotational movements of the UAV can be used to determine the azimuth producing the best signal to noise ratio. The weight of the spectrum monitoring payload is 2.8 kg, and the maximum flight time under this payload is 30 minutes. The UAV monitoring platform is shown in Fig. 11.

FIGURE 11  
Composition diagram of UAV monitoring platform



The ground control centre includes a control handle, notebook PC, and data communication module. The control handle works in the 2.4 GHz ISM band for controlling the take-off, landing, hovering and flight of UAV. The UAV monitoring platform could transfer data with control centre in 5.8 GHz ISM band. The notebook PC runs the TDOA software. The TDOA software receives the acquired time-series data and spectrum data and computes the location result. The UAV monitoring platforms perform signal acquisition and data transmission through the data communication module.

#### 4.3.3 Example workflow and application case

During the signal detection process, the UAV monitoring platforms are elevated and positioned to form an appropriate 3D spatial condition for TDOA monitoring. The control center is responsible for processing the data and running the TDOA software to calculate the location of the target transmitter and display the geolocation result. The workflow is shown in Fig. 12 with description of four steps.

Step 1: At least three UAV monitoring platforms are launched and deployed at different locations for monitoring where they can receive the radio signal. In order to improve positioning accuracy, position the UAV monitoring platforms being deployed in a triangle or polygon surrounding the area of interest. In all cases, deploying the monitoring platforms in a straight line should be avoided.

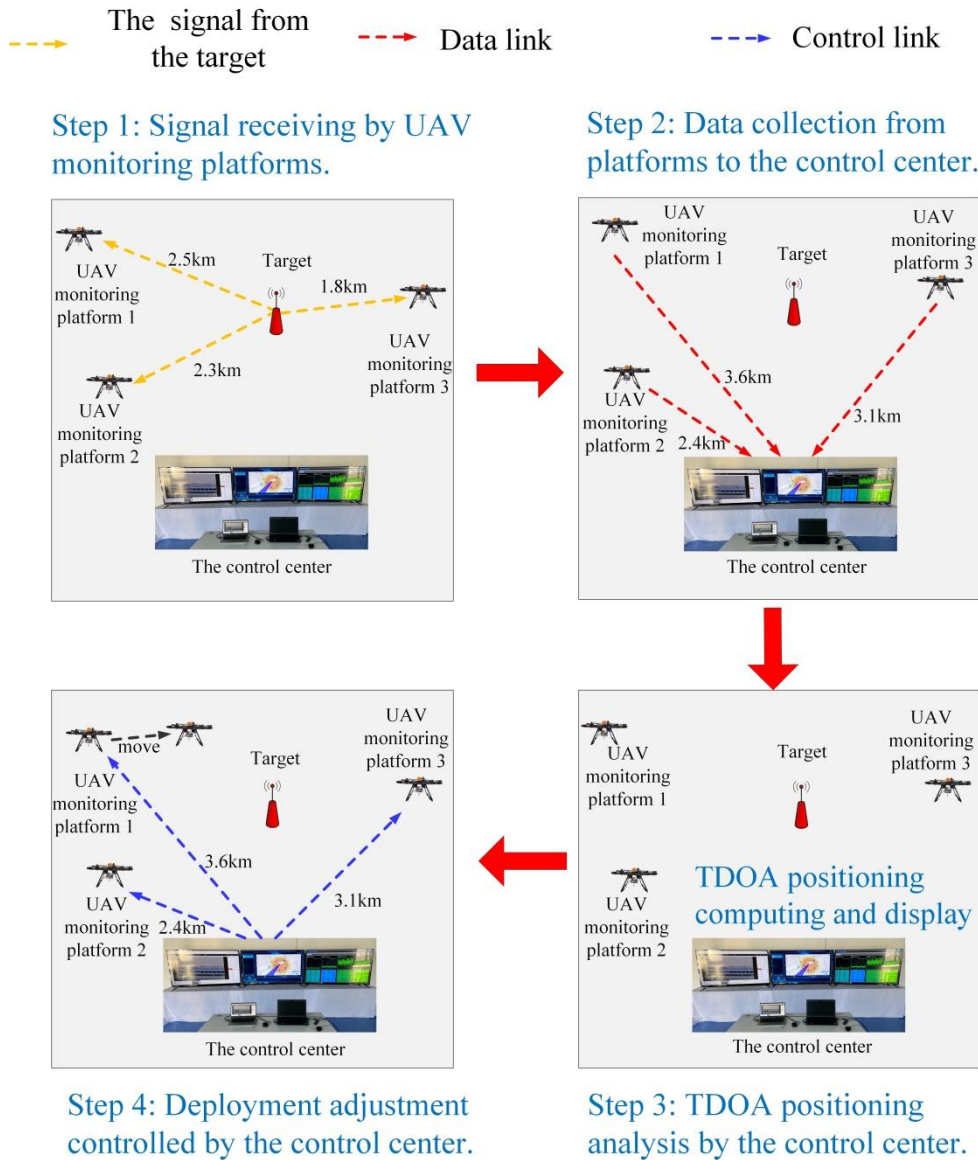
Step 2: The UAV monitoring platforms upload the received data to the control centre through the data link, including the precise time of arrival of the signal and the current position of the UAV monitoring platforms.

Step 3: The control centre collects the data from at least three UAV monitoring platforms, and the TDOA software determines the position of the target transmitter and shows the estimated position on the map.

Step 4: After the initial TDOA measurements, it may be necessary to adjust the relative position of the UAV monitoring platforms to improve geometry, signal to noise, fading or multipath effects. In this case, the control centre will send new deployment locations to each UAV monitoring platform through the data link. After UAV monitoring platforms receive the new deployment command, they move to the specified position and return to workflow Step 1.

FIGURE 12

Working diagram of UAV monitoring platforms




#### 4.4 Flight testing of the ground-based airport radio navigation facilities

This section provides information on UAV radio monitoring systems to inspect and maintain ground-based aviation safety facilities like Instrument landing system (ILS)/VHF omnidirectional range (VOR) at the airport.

##### 4.4.1 System information

###### 4.4.1.1 UAV

The UAV aircraft is a commercial product and is equipped with the measurement devices such as RTK positioning and precision altimeter to obtain precise location information during operations. Some key specifications are given below.

	Overall dimensions	883.0 × 427.0 × 886.0 mm (unfolded)
	Weight/max. payload capacity	4.91 kg (including battery)/1.23 kg
	Maximum operating distance	8 km
	Operating frequency	Control: 2.4 GHz (2.400-2.483) Video: 5.8 GHz (5.725-5.850)
	Hovering accuracy	0.10 m vertical (w/ RTK) 0.10 m horizontal (w/ RTK)
	Maximum wind resistance	12 m/s
	Maximum horizontal speed	81 km/h
	Flight ceiling	3 km
	Operating temperature	−20 to 50° C
	Maximum flight time	< 30 min (w/ payload)
	IMU (Inertial Measurement Unit)	Equipped.
	Anti-collision systems	Vision (frontwards, downwards) IR (Infra-Red, upwards/downwards) Ultrasound (downwards)

#### 4.4.1.2 Radio monitoring system

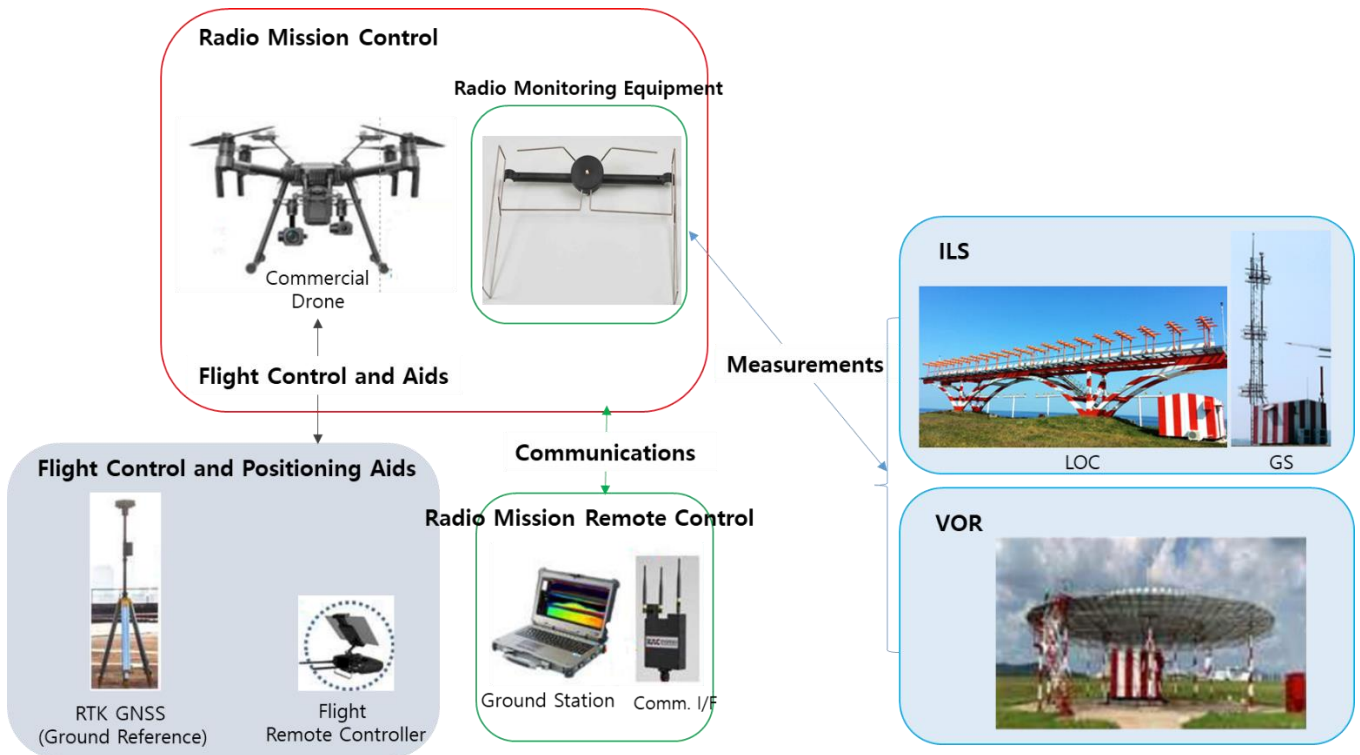
The UAV radio monitoring platform is configured to receive ILS/VOR signals, and in detail, consists of an antenna and single receiver for 108~118 MHz band signals (for VOR and ILS) and 329~335 MHz (for GS) band signals. It is important to test the antenna while mounted on the UAV platform to understand the overall antenna pattern.

	<p>Operating frequency 108~118 MHz (VOR/LOC) 329~335 MHz (GS)</p>
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#### 4.4.1.3 Control and operations

The UAV platform uses the installed devices to measure the ILS/VOR signal at various spatial locations and transmits the data to the ground control station. Since many measurements should be made in consideration of the various horizontal and vertical approach angles in the landing process of the aircraft, it is designed to enable automated measurements by inputting a predetermined spatial path. The ground control station controls UAV flight and position and performs measurements according to the programmed radio mission information. Figure 13 briefly shows the components needed to control the UAV, measure the signal and transmit the measurement results back to the ground control station.

FIGURE 13  
System configuration and operation

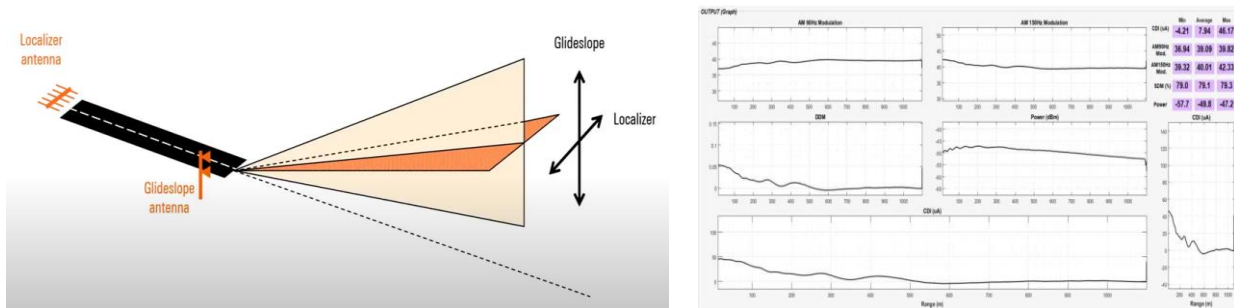


4.4.2 Measurements and results

4.4.2.1 ILS

The primary purpose of ILS measurements is to verify that the signals received at certain horizontal (by LOC) and vertical (by GS) angles meet the references, and the measurement data is provided through analysis. The test results are shown below.

FIGURE 14  
ILS test result



4.4.2.2 VOR

VOR is a system that transmits omnidirectional reference signals allowing VOR equipment mounted on an aircraft to display the direction to the VOR transmitter location during the flight. The test of VOR is conducted in the form of a circular orbit around the VOR transmitter, and the actual and measured azimuth error distribution (relative to the VOR transmitter) and the power of the received signals are logged and evaluated.



FIGURE 15  
VOR test results

