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Master's degree in Applications and Technologies for Unmanned Aircraft Systems

UAV based GNSS Reflectometry

TITLE: UAV based GNSS Reflectometry

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Abstract

This project combines GNSS-R technology and UAVs in the context of the aerial remote sensing field, from the design of the assembly of the UAVs and GNSS-R to the execution of the different tests, as well as the data collection and analysis. As it will be seen in the document, this analysis has allowed to improve the original design of the system. The remote sensing technology based on GNSS reflected signals is simply called GNSS-R, and the greatest advantage of UAV as a mounting platform is the low cost, high system availability, and fast installation. Thus the main task of this project is to experimentally verify the possibility of CTTC's own developed GNSS-R working with UAVs.

In this report, first I explain some basic principles of GNSS and GNSS-R, as they are important technical backgrounds for the whole project. Secondly, I describe the application of the RTKPOST software, which is an important processing and analyzing tool in the entire project, mainly describing the positioning methods used in the different processing modes in RTKPOST, also the parameter needed for analysis.

Then, the design of the UAV-GNSS-R assembly is discussed, with different options based on the characteristics of the UAV, such as weight, payload space, and so on. The whole experimental process is also explained, and all the test data are analyzed and processed by using the Static mode or Kinematic mode in RTKPOST, and the data results are analyzed and compared in terms of satellite visibility, signal-to-noise ratio, elevation angle, Standard Deviation and Root Mean Square.

The experimental process is roughly divided into three parts. The initial verification test is used to collect signal data as a basis, through which it is found that drone interferes with GNSS-R to a greater extent, and that the reflector antenna cannot receive the signal if the drone is placed too close to the ground. The second part of the experiment is a stationary test, where the UAV is placed on a tripod, and it's found that there is a difference in accuracy when the UAV is working on different land surfaces, which a higher accuracy can be obtained on rock than on grassy field. It is also found that the interference problem can be mitigated when the receiver is placed farther away from the UAV body. In the last part of the flight test, the optimization of the interference problem is further confirmed by the comparison of the two flight tests, and the positioning error is reduced from about 50m to 6m.

At the end of the report, suggestions are given for the future development of this project, as it is clear that the meter-level accuracy does not meet the needs of many applications, and that the integration of the UAS and GNSS-R needs to be further optimized to reduce interference problems and thus achieve higher accuracy positioning.

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Chapter 1. Introduction

1.1 Project background

In addition to the applications of UAV (Unmanned Aerial Vehicle) in various fields such as agriculture, rescue, cartography, logistics and entertainment, the usage of aerial remote sensing should not be ignored, and this work developed tests and results analysis based on this. Aerial remote sensing can be understood as airborne remote sensing, using unique platforms such as drones or manned aircraft as sensor carriers, and remote sensing techniques are carried out in the air to obtain valid ground data and image information. The selection of UAV as the platform has lots of advantages such as long endurance, real-time image transmission, low cost, mobility and flexibility, also fast installation and deployment of load systems, all these make up for the shortcomings of satellite remote sensing and manned aerial remote sensing, which makes UAV aerial remote sensing technology an important means of spatial data acquisition.

The development of UAVs in the field of aerial remote sensing over the years, combined with GNSS-R (Global Navigation Satellite System Reflectometry) technology, has gradually emerged to the fore. When the function of reflecting signals and the advantages of the drone as a platform work together, they open up more applications, such as measuring the thickness of snow and the moisture content in the soil[1].

1.2 Description of project

More specifically, in this project, a new GNSS-R system which has been fully developed at CTTC was combined as a payload with UAV, aiming to develop, test and characterise whether this GNSS-R system can work with UAV, the work includes from the assembly design to the final analysis of test results. First, the GNSS-R system was tested on the ground and the acquired data was processed simply by using RTKLIB which is a GNSS data processing software[2]. After that, the System was designed and installed on board of the UAV according to the characteristics of the UAV. In the next step, different kinds of tests with the system onboard was used to evaluate the antenna´s behaviour. By comparing and analysing the signal quality, stability, and the accuracy of the final positioning of each test, it was concluded that the interference to the GNSS- R system caused by the operation of the UAV would greatly reduce the quality of the satellite signal, It was also found that when the UAV and the GNSS- R system were stationary for signal collection, the positioning accuracy was superior on the stone ground than on the grass. At the end of this work, some optimization suggestions are given for the future development of the project, from the assembly of the UAV itself to the configuration of the RTKPOST files, to reduce interference problems and errors, making the results of the subsequent tests more stable and reliable.

1.3 Motivation and Objective

The first motivation is to see if the GNSS- R system designed by CTTC would work with UAVs and to see if its performance would be affected by UAVs. The second is that we´ve known that different properties of land surfaces affect signal reflection and propagation, so we want to further verify whether the positioning accuracy of the GNSS- R reflector system will be affected by this.

The main purpose of this work is to get a clearer understanding of how GNSS- R works, to learn how to use RTKPOST to process the signal files and to analyse the results. From the initial assembly of the UAV and GNSS- R, designing specific tests, analysing the results of the test data, to as well as thinking about how to optimize the overall system. Verify how well the GNSS- R antenna performs and observing how different land surfaces affect the accuracy.

1.4 Technologies involved

GNSS (Global Navigation Satellite System) refers to a constellation of satellites that provide signals from space to transmit positioning and timing data to GNSS receivers on the ground. GNSS has been widely used in many disciplines such as geodesy, space science and geophysics, and also benefits various industries such as urban mapping, precision agriculture and unmanned vehicles. With the development of GNSS technology, GNSS-R technology has emerged, GNSS reflection signal can detect the characteristics of the earth's surface[3], and this technology, as the current research hotspot in the field of GNSS and remote sensing, has made a lot of research progress and achievements, such as detecting the rise of the coastline, the area of the lake detection, soil moisture, etc., and in these experiments, the GNSS-R system equipped with UAV plays an important role.

In the tests of this project, the GNSS-R system was mounted onboard the drone as payload, it consists of two antennas, one is to receive the direct signals and the other one is to collect the reflected signals from the ground, then drone collected the signal data during the flight that through some simple flight commands, at last RTKPOST was used to process and analysed the observation files to compare the accuracy.

1.5 Project risk analysis

The table below shows the risks and problems that may occur during the project and the corresponding solutions.

Risks	Solutions
Bad effects of extreme weather on tests	Check the weather forecast before the test day to avoid heavy rain and windy weather
Drone damage during flight	Check drone battery before the flight to prevent damage from falling drone
The signal collected by the test is faulty (missing file, corrupted)	Do a pre-testing to verify the raspberry pi in the GNSS-R system is functioning correctly
GNSS-R system and UAV installation failure	Know the characteristics of the UAV and GNSS-R before installation, (size, weight, load) and design several installation plans
Project postponed without completion	Complete each task on time

Table 1. Project risk analyse

1.6 Document Overview

This work is divided into six chapters. Firstly, I provided a brief introduction to the full report, as well as a description of how the work develops. The second chapter presents a background overview of the main technologies and tools used that are covered in the whole work. The third chapter focuses on the design and assembly of the UAV and the GNSS-R system, and also the whole design of test procedure. Chapter four covers data processing and analysing. Chapter five then includes recommendations for subsequent project development, at last is the conclusion of whole work.

The following table shows specific tasks and timelines:

	Tasks to be carried out	**Start date**	**Duratio n**	**Completio n date**
1	Read the literature about GNSSR technology in UAV applications	20/02/2023	2weeks	05/03/2023
2	Write GNSS-R technology in UAV	06/03/2023	1week	12/03/2023
3	Practice using RTKPOST software for signal data analysis and understand different processing modes	13/03/2023	3weeks	02/04/2023
4	Write the characteristics of different processing modes in RTKLIB software	03/04/2023	1week	09/04/2023
5	Write the Introduction chapter	10/04/2023	1.5week	19/04/2023
6	Meeting with Eulalia and Miguel	20/04/2023	1day	
7	Meeting with Eulalia and Esther	25/04/2023	1 day	
8	Design and assembly of payload	26/04/2023	2week	10/05/2023
9	Write Chapter 3	11/05/2023	0.5week	14/05/2023
10	First test and process the data	15/05/2023	1week	21/05/2023
11	Write Chapter 3	22/05/2023	1week	28/05/2023
12	Carry out the text	29/05/2023	1week	04/06/2023
13	Write Chapter 4	05/06/2023	1.5week	14/06/2023
14	Write Chapter 5	15/06/2023	1.5week	25/06/2023
15	Write Chapter 6 Conclusion	26/06/2023	1week	02/07/2023
16	Review all (corrected and formatted)	05/07/2023	1week	16/07/2023
17	Prepare presentation	17/07/2023	1week	24/07/2023

Table 2. Planification of work

Chapter 2. Technological Background

In the previous chapter, I gave a short introduction to the background, goals and plans of this project. In this chapter, I will introduce some of the technical knowledge involved in the project, which are GNSS-R technology and RTKLIB software, as they are the basis for the whole project.

2.1 GNSS and GNSS-R

Global Navigation Satellite System is a collective term for several navigation constellations. It uses satellites and ground-based devices to provide global positioning and navigation. The satellites in a GNSS system continuously send L-band radio signals to ground receiving equipment. These signals contain information about the satellite's positions, time, the encoding and frequency of the satellite signals and other relevant navigation data. While ground devices such as mobile devices, GNSS receivers or base stations perform positioning by processing these wireless signals, so that GNSS has the characteristics of working globally, in real-time and with high accuracy[4].

GNSS reflection signals can be received and utilized, and this remote sensing technology based on GNSS reflection signals is referred to as GNSS-R. When a GNSS satellite transmits a signal, part of the signal is scattered from the Earth's surface and received by the GNSS receiver[4]. The GNSS delayed signal reflected from the rough surface can provide different information about the direct and reflected signal paths. This information includes changes in the waveform, amplitude, phase and frequency of the reflected signal. Combined with the receiver antenna position and medium information, the delayed measurement observations are used to determine surface roughness and surface properties, such as snow thickness, soil moisture, etc., also known as GNSS-R reflectometry.

In this project, the accuracy of the navigation data files is critical to achieving accurate positioning, providing the key satellite information and parameters for the GNSS-R system installed on the UAV. The GNSS-R system, as the ground-based device, includes the GNSS-R and GNSS receiver and antennas, it is able to decode the received satellite signals to calculate the distance and time delay between the satellite and the GNSS-R system to determine its position, velocity and time.

GNSS-R technology has a wide range of applications in geological exploration, glacier monitoring, coastline status monitoring, etc. It also works in L-band, so it can monitor all day and all night. It belongs to passive reception and does not need to transmit signals itself, so its device is small and weight and requires little power consumption. It uses the global coverage of the satellite system and high-precision signals to obtain parameters of the surface and water bodies[5], which has the advantages of convenience, flexibility and high real-time, so the technology provides an ideal to monitor the ground and analyse the patterns of changes in the ground. In this project, the advantages of the GNSS-R technology mentioned above are used to detect its accuracy when working on different surfaces.

The resolution of the signal data is related to the type of ground-based receiver, with high-resolution data meaning data with more detail and more accurate spatial information, as well as more dense sampling intervals. In general, ground-based receivers are limited to a very small area within the static antenna beam. In the figure below, when the UAV is combined with GNSS-R, the data resolution increases significantly, adding more utility and flexibility to GNSS-R. The aircraft based GNSS receiver provides approximately 300 m to 1 km of medium spatial resolution, depending on the flight altitude[4].

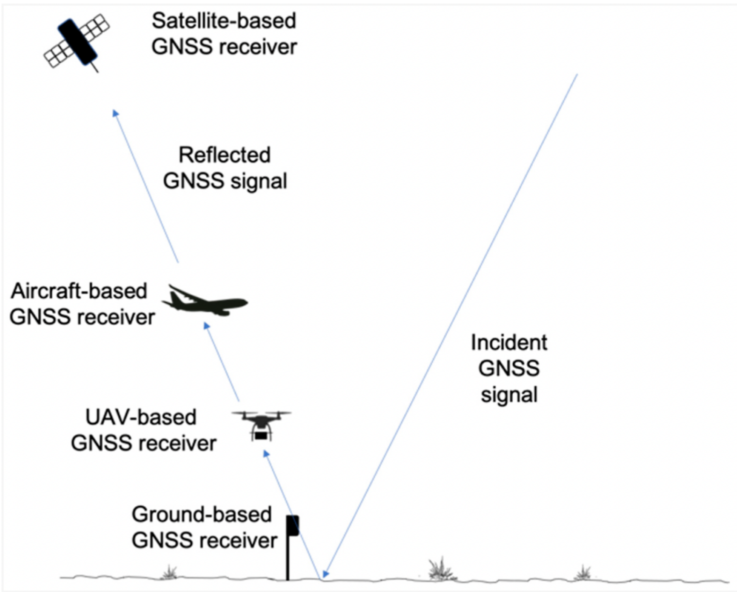


Figure 1. Impact of different platforms on GNSS signals

2.2 GNSS Processing Tool

RTKLIB is a GNSS data processing open-source software dedicated to RTK (Real-Time Kinematic) and precision navigation applications. It provides a set of algorithms and tools for processing data from GNSS receivers to achieve high-precision positioning and navigation functions.

RTKLIB supports multiple GNSS systems, including GPS, GLONASS, Galileo, Bei Dou and other satellite navigation systems. It is capable of processing raw observation data from these systems and using techniques such as differential positioning and carrier phase measurement to achieve highly accurate position calculations.

There are many different types of tools included in RTKLIB, and I will list a few of them below that I used in the project:

- **rtkconv**: It provides data format conversion. For example, it can change the raw data of the receiver to rinex.obs (observation file), or it can change the version of the rinex file.

- **rtkpost**: This post-processing software is used to process the data from the receiver and contains different processing modes, such as static mode and kinematic mode. These algorithms are enabled to achieve centimetre or sub-meter positioning accuracy levels using multiple satellite observations and high-precision navigation data. Different processing modes provide different positioning accuracy, and each mode has its degree of complexity, precision and accuracy.

- **rtkplot:** This is a data visualization tool that allows to plot map traces and get important data analysis results such as signal-to-noise ratio, position, signal convergence time, etc.

- **teqc**: Teqc is designed to handle mixed satellite constellations, in this project, I mainly used it to stick the GNSS observation data in different periods[6].

2.2.1 RTKPOST

In RTKPOST, there are different processing modes depending on the measurement method and the state of the base station. In the following paragraphs, I will briefly describe RTK positioning and traditional positioning, the characteristics of the different processing modes in RTKPOST and the two main measurements used in them.

2.2.1.1 Different positioning methods

- **Traditional positioning**

Only one GNSS receiver is used in the traditional single-point positioning method, which calculates its position directly from the navigation signals emitted by satellites, but the signal transmission is often unstable or uncertain, resulting in low positioning accuracy, which can only be achieved at the meter level.

- **Differential positioning**

Differential positioning, which uses two or more receivers to eliminate signal errors, with one receiver being used as the base station, whose position is known and able to communicate with the other receivers. Usually When the base station receives the satellite signal, it sends the measured data and its known position information to the mobile station, which can perform real-time calculations to eliminate the error of the satellite signal and calculate the high-precision position information through the difference between the two data, also called differential correction data.

- **Summary**

In this project, two stations are used, UAV as a rover and the base station should be near it because the shorter distance provides more stable data transmission. Generally, it is recommended not to use stations that are beyond 20km far away in case the results are too noisy.

2.2.1.2 GNSS Processing measurements

- **Pseudorange measurements**

The pseudorange is the time delay measured by the receiver after receiving the electromagnetic signal from the satellite, multiplied by the speed of light to obtain an estimate of the distance[7]. There are some errors in the pseudorange measurement, such as atmospheric delay in signal propagation, receiver clock aberration, etc. These errors are the reasons for the lack of accuracy of single-point positioning.

- **Carrier phase measurements**

Carrier phase measurements are more accurate and stable compared to pseudorange measurements, but they are also more complex. The carrier phase is the phase information of the satellite signal received by the receiver. The phase information is the count of the oscillation period of the satellite signal, and in GPS receivers, the distance between the receiver and the satellite is calculated by measuring the phase difference of the signal. However, it has an integer ambiguity problem, it can be seen the integer multiple of the phase cannot be determined directly. To solve this ambiguity problem, it is necessary to use differential techniques to calculate the ambiguity degree and apply it to the processing of carrier phase observations. For instance, In Kinematic positioning, the receiver continuously tracks and measures the carrier phase changes of the satellite signal. These carrier phase measurements, after differential correction and processing, can be used to calculate the receiver's position and velocity information for accurate motion positioning.

- **Summary**

The accuracy and reliability of GNSS positioning can be improved by using both carrier phase and pseudorange, and by combining techniques such as differential correction and ambiguity resolution.

2.2.1.3 Processing modes

a. Single

Single point is a simple positioning method because only one station is used. In this mode, the receiver uses only its own received GPS signal, it offers an absolute solution using only pseudorange, without differential correction or communication with other reference stations, which may be less accurate compared to differential positioning, usually it can achieve meter-level accuracy.

b. DGPS/DGNSS (Differential Global Positioning System)

This mode also uses the pseudorange ranging method, aka code-based differential GPS. Unlike single point positioning, in this mode two receivers are required, a rover (in this case acted by the drone) and a receiver with a known position as a reference station to determine the drone's position[8]. When a reference station is added to the measurement system, the receiver on the UAV will correct the satellite signal based on the pseudorange error information broadcast by the base station, and some of the errors mentioned in the single point positioning will be eliminated, normally it can reach to centimetre-level accuracy.

c. Kinematic

By using RTKPOST's Kinematic mode, GPS data in motion scenes can be processed and the corresponding position and velocity information will be obtained. It also requires two receivers to calculate the rover´s position by using differential positioning techniques, differential correction is performed by reference data from the base station. Unlike DGPS, this processing mode uses carrier phase technology.

d. Static

The static processing mode is similar to the Kinematic processing mode and is also based on carrier phase ranging, the only difference is that in static mode rover is relatively stationary, for instance, a measuring station fixed in one position. Static positioning generally uses long-time observations to obtain higher positioning accuracy and does not require a high frequency of position updates. So in Static processing mode, the coordinates are adjusted for the entire observation interval, while in the Kinematic mode the adjustment is by season[9].

e. Moving base

This mode also uses a combination of carrier phase measurement and differential techniques for positioning. In the aforementioned processing mode, the base station is in a static state, in this mode both the base station and the rover can be in movement[10]. This is a relative positioning mode, where the relative distance between the base station and the rover station is calculated independently of the base station location.

Moving base positioning is typically used in applications such as vehicle tracking or the positioning of a fleet of drones, enabling high-precision positioning and relative position monitoring of mobile base stations, usually to centimetre-level accuracy.

f. Fixed

This mode also uses carrier phase measurements, meanwhile it uses differential positioning techniques to process the observation files from the receiver and calculate the receiver's position. The goal of this model is to obtain a fixed solution, i.e., a positioning result with high accuracy and reliability, which is usually higher than other solution types (e.g., floating-point solutions). The fixed solution usually needs to satisfy certain conditions and requirements, such as the stability of communication between the receiver and the base station, the quality of the observed data, etc.

The fixed processing mode is very useful in the fields of precision measurement, geodesy, and precision navigation. It can provide sub-meter or even sub-centimetre level positioning accuracy with high accuracy and reliability.

g. PPP (Precise Point Positioning)

PPP (Precise Point Positioning) is an evolution of the single point positioning mode, unlike conventional differential positioning, PPP does not require observations from the base station. It is a method to determine the receiver position using precise orbit files or clocks from the IGS, which can achieve centimetre-level positioning accuracy, but only one single station is processed at a time. Determine position using pseudo-range and carrier phase of the individual GNSS receiver. In the PPP processing, the receiver observations are compared and calculated with a precision ephemeris and an atmospheric delay model to eliminate errors and delays.

There are three types of PPP positioning as follows:

- Static PPP: It is applicable when the receiver remains relatively stationary for a longer period.
- Kinematic PPP: It suits for moving receivers, such as vehicles, ships or aircraft.
- Fast PPP: This is a special type of positioning that can be achieved in a short time to calculate the position. It is usually used for applications that require fast position information, such as emergency measurement of the position of a moving vehicle.

2.2.2 Processing mode for GNSS-R

Selecting the appropriate processing mode according to the needs of different scenes can obtain more accurate positioning results. Among the different processing modes in RTKPOST, the single processing mode does not suit this project because it uses the traditional single-point positioning method. The final processing result will be noisy. The moving base processing mode is not selected because the base station in this project is stationary and its position is known. The antenna receiver used in the project is single frequency, I don´t choose the PPP processing mode because it cannot process with the single frequency. The Fixed doesn´t work because the base station can´t be guaranteed stability, maybe sometimes occurs the rams. After comparing the processing results of different modes, I finally focus on the Kinematic and Static processing modes.

2.2.2.1 Ancillary files in RTKPOST

- **Data sources**

To process data with RTKLIB, theses processing modes need additional information beyond the one provided by the receiver, the flowing parts show the data sources of the files used.

<u>Base station file and Navigation file</u>：

The rinex data for most of the stations in Catalonia are available on this website. In addition to the observation files, the navigation files for the day are also available in the downloadable package. The time is expressed in the UTM frame, if I want the data file for 10 am, I need to download the data file for 12 am.

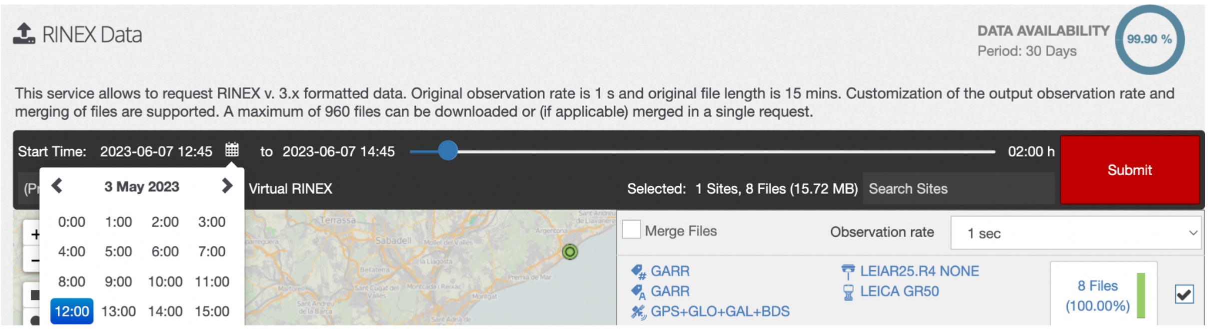


Figure 2. ICGC reference stations
(https://catnet-ip.icgc.cat/sbc/User/Xpos/RinexDataRequest)

Precise orbits file:

This file is used to provide precise orbital information of the satellite, only for correction. The first thing to do to obtain the precise orbits file is to calculate the GPS week.

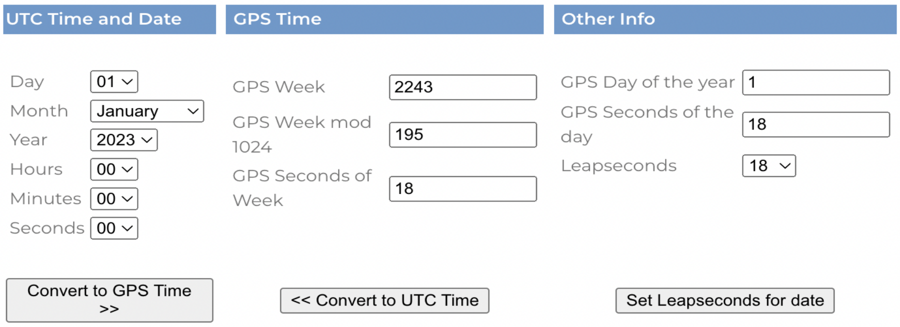


Figure 3. Calculator of the GPS week
(https://www.labsat.co.uk/index.php/en/gps-time-calculator)

Then in CDDIS the related precise orbits file will be found:

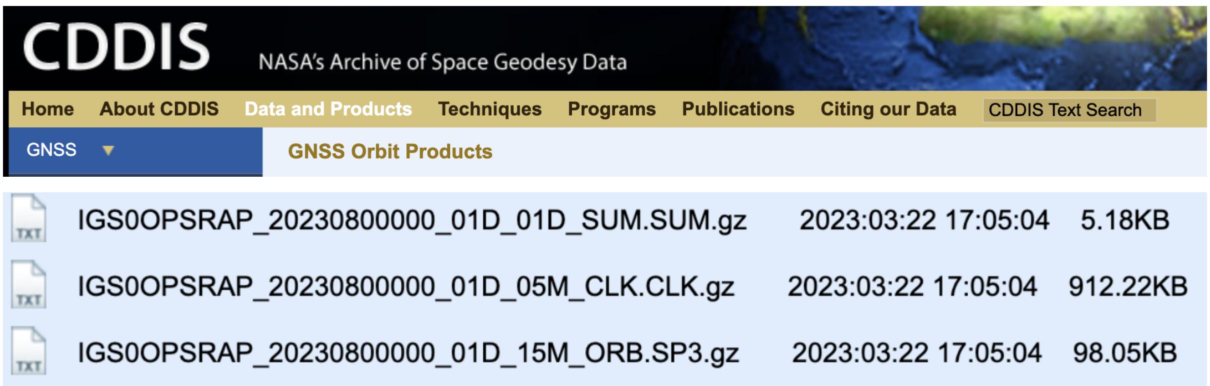


Figure 4. NASA´s Archive of Space Geodesy Data
(https://cddis.nasa.gov/archive/gnss/products/2254/)

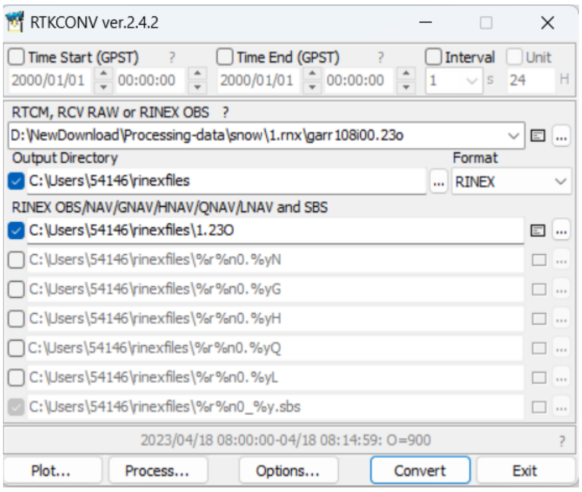
2.2.2.2 Data File Pre-Processing

When the observation time is longer than 15 minutes, the acquired files will be segmented (one every 15 minutes), so to be able to process the files in RTKPOST, I tried teqc to stick them into one file. First I used RTKCONVER to convert the file version from 3.04 to 2.1, because teqc did not support the processing of the 3.04 rinex version.

The origin version of the Navigation file and Observation file:

```
     3.04           OBSERVATION DATA    M: MIXED            RINEX VERSION / TYPE
```

RTKCONVERT:



Data file merging by using teqc:

```
C:\Users\54146>cd rinexfiles

C:\Users\54146\rinexfiles>teqc file*.23O> garr.23O
```

- **Options of RTK-Post**

In the following chapters, the parameters for all tests were unchanged except for different processing modes. This is to reduce uncertainty in the final results and control the parameter variables to obtain more accurate analysis results. The parameters are set as shown below.

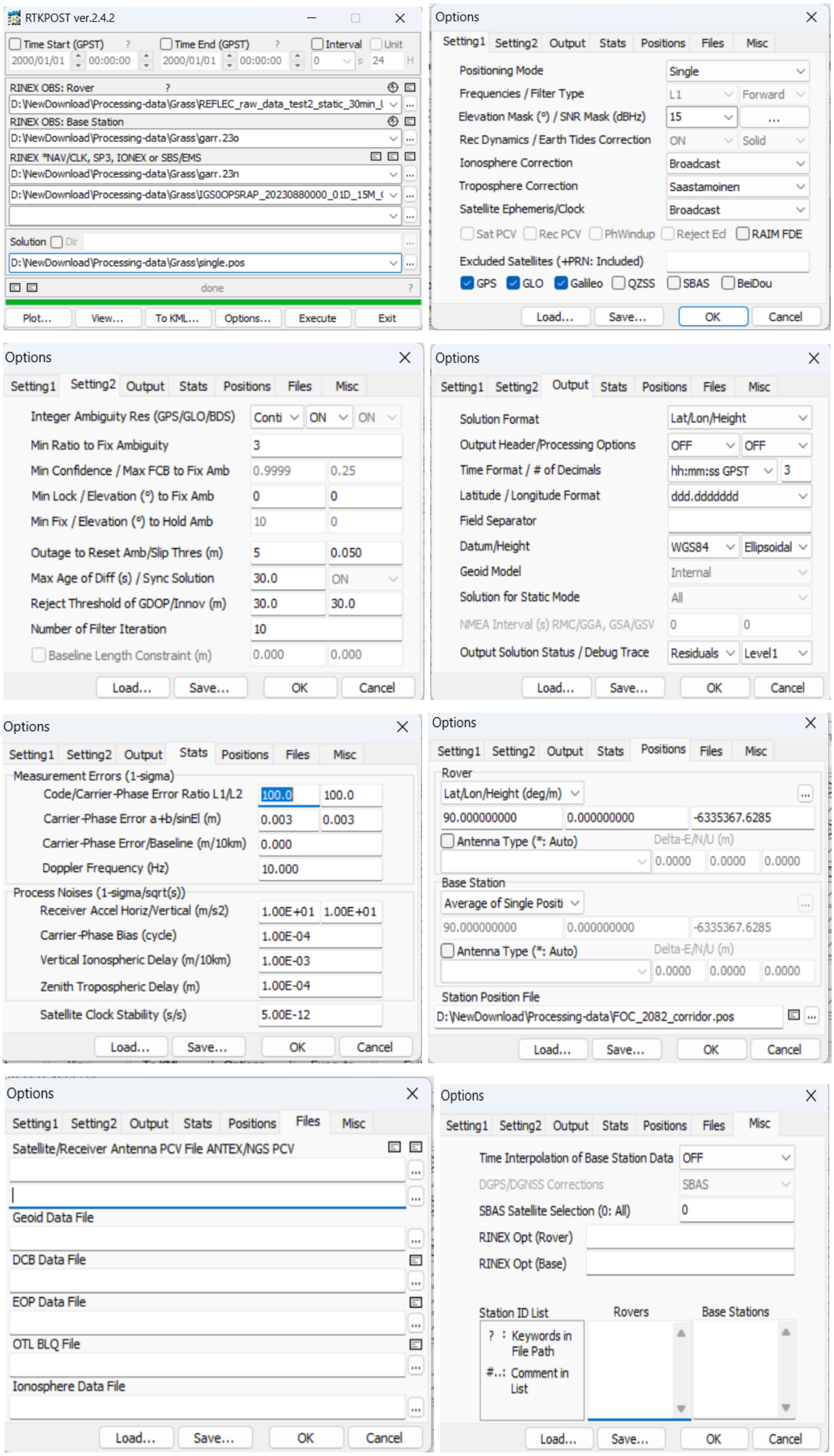


Figure 5. Options setting in RTKPOST

Chapter 3 Design of System Integration and Test

In the previous chapter, I described the preparation before the experiment, from the technical principles of GNSS-R to the use of RTKLIB software, as well as analysing the different processing modes and file preparation in RTKPOST.

In this chapter, I will present the design details of the project. Firstly, I will detail the features and components of the GNSS-R system used in the project, as well as provide the scheme of the ensemble installation of the GNSS-R system and the UAV. Secondly, I´m going to design the specific test procedure for the project in order to achieve the best performance of the system after the installation is completed, the method of analyzing the results will also be mentioned here.

3.1 Payload Integration Design

3.1.1 System characterization

a. GNSS reflectometry system

This system consists of two receivers and their corresponding antennas, raspberry pi, as well as the battery and data cable. The total weight is 640g. The antennas are used to receive satellite signals, and the receivers analyze the received information and convert it into understandable measurements such as longitude and latitude. One of the receivers and antennas is oriented towards the sky to receive the direct navigation signals from the satellites, and the other is oriented towards the ground and is used to receive the reflected signals from the ground. The raspberry pi contains a variety of applications related to the collection of data files.

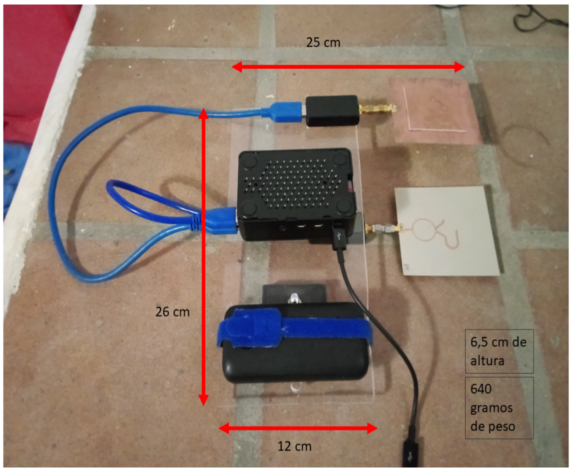


Figure 6. GNSS-R system

b. The UAV

The drone used in the project is a quadcopter drone with raspberry pi, IMU, camera and battery installed as it is the drone I was using in another group project. The raspberry pi of the drone is not removable because the other project has not yet been completed. The battery is attached to the bottom of the drone by Velcro and can be removed and replaced.

The drone's maximum payload is 250g (excluding the battery), and the battery weighs about 400g, the maximum flight time is not more than 10 minutes.

Figure 7. UAV and Battery use in test

3.1.2 Payload integration design

In order to maximize the performance of the GNSS-R system, the following different installation options have been designed:

- **Option A**

Install all accessories of the GNSS-R system as payload on the UAV.
- Pros: Easy to install.
- Cons: Payload overload, and too much weight may affect the flight time and reduce the working performance of the drone.

- **Option B**

Remove the battery from the GNSS-R system and mount the remaining accessories (raspberry-pi, receivers and antennas) on the drone.

- Pros: payload weight reduction, more convenient to install only the receivers and antennas.
- Cons: The battery equipped with the drone must supply both sets of equipment, the UAV's own raspberry pi and GNSS_R system, and insufficient battery supply will greatly reduce flight time and performance.

- **Option C**

Remove the raspberry pi and battery from the GNSS-R system and mount the remaining accessories (receivers and antennas) on the drone.

- Pros: Greatly reduced load weight for the drone.
- Cons: Downloading the GNSS-R system-related software on the raspberry pi that comes with the UAV will be more complicated to operate, and the GNSS-R system software needs real-time to handle different tasks, which will degrade the performance of the whole system.

- **Option D**

This option has some similarities to option C， which also remove the raspberry pi and battery from the GNSS-R system, however the receiver and antenna are mounted differently. Not directly on the drone, but by adding plastic plates that extend out from the drone to fix the receiver and antenna on it.

- Pros: Greatly reduced load weight for the drone. Also considering the interference problem of the drone itself, the receiver is installed at a location slightly away from the drone body to help the reception of the signal.
- Cons：In addition to adding some complexity and weight to the installation of plastic plates, it may also affect the balance of the drone.

- **Final Option**

By analyzing and comparing the above four options, I finally chose Option C and D to realize the tests.

Firstly I use option C, which is to install only the antennas and receivers of the GNSS-R system as payload. Since raspberry pi can change the memory card, so to carry out the flight test of this project, just use the memory card of raspberry pi in this GNSS-R system. The battery used is the one that comes with the UAV. For other projects, the antenna can be removed and the raspberry pi memory card can be changed. This allows for maximum ease of installation operations while minimizing the UAV payload and also ensuring a certain degree of UAV performance and operating time.

Use stickers to fix two signal receivers on the top and bottom of the drone respectively. The upper receiver is used to receive direct signals, and the lower receiver receives signals reflected from the ground.

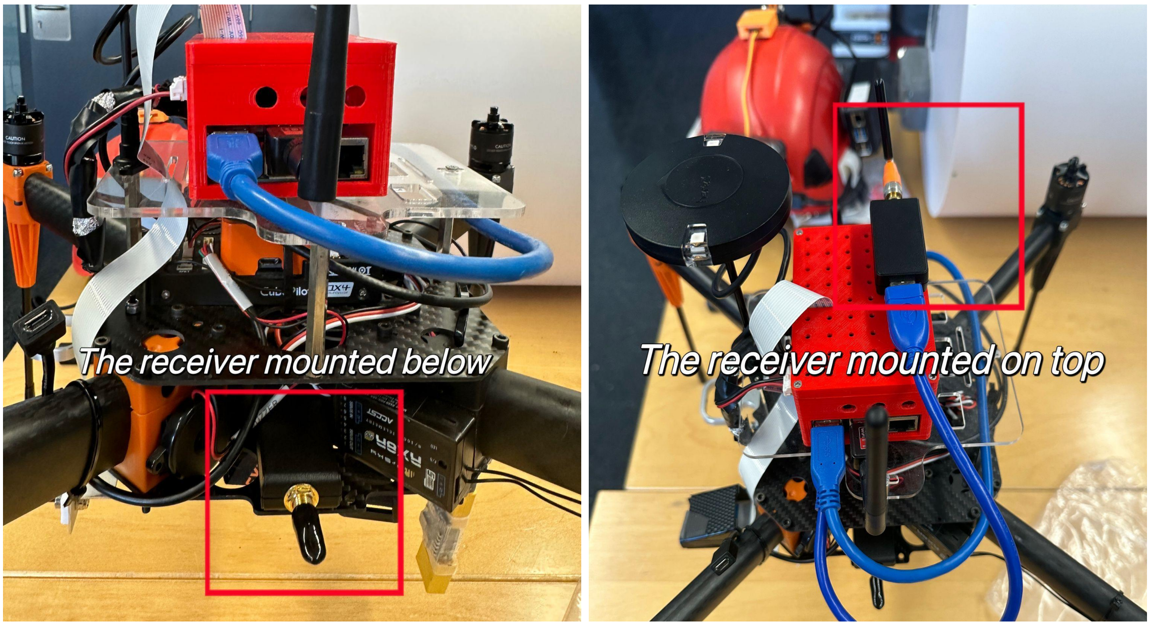


Figure 8. Receiver Installation

For Raspberry Pi, just remove the memory card with a clip for replacement.

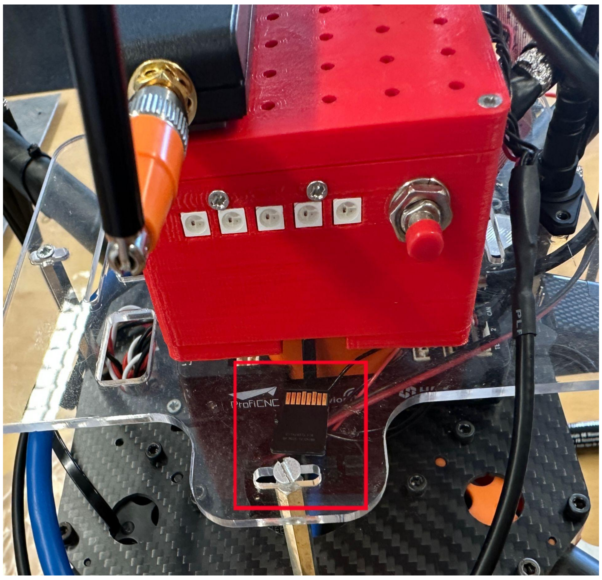


Figure 9. Rasberry pi installation

Secondly, for the other part of the test, I need to use Option D. The only difference from the one described above was the installation of an extension plate on the drone to fix the receiver. As shown in the figure below, the position of the receiver above remains the same. The plastic plate is fixed under the drone, the receiver and antenna for receiving reflected signals are fixed on it, away from the drone body.

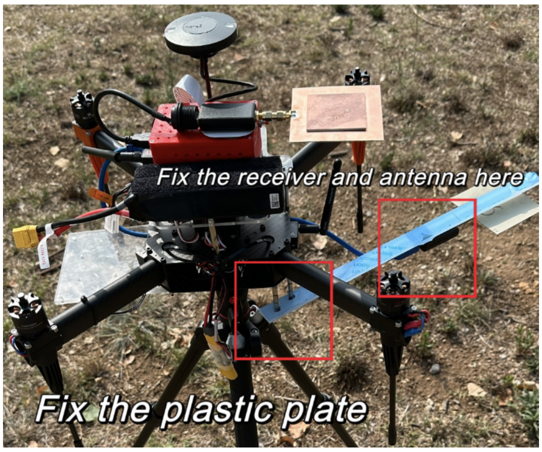


Figure 10. Option D installation

3.2 Test Design

3.2.1 Test Procedure

The experiment is divided into three parts in total. First is the initial verification experiment, which is to test whether the integration of UAV and GNSS-R system is successful and whether the two can work perfectly together, for instance, how the flight altitude of the UAV affects the reception of satellite signals by the GNSS-R system, or whether the site where the UAV flies has an impact on the accuracy of the final signal processing results. Meanwhile, the different verification tests provide a good implementation basis for the continuous tests, and to be able to adjust the later experiments based on these verification tests´ results. The second part of the experiment is conducted on a tripod, and the third part of the experiment is performed in flight. The purpose of both experiments is to confirm whether the installation position of the receiver in the GNSS-R system influences the final collected signals and whether different ground surfaces have an effect on the accuracy of the final processing results. In addition, by comparing the overall second and third part of the collected signals, more sources of interference can be determined.

	Verification				**Stationary**			**Flight**	
Test name	Verification 1		Verification 2		Stationary 1		Stationary 2	Flight 1	Flight 2
Status	Fly	Fly	On Tripod	Fly	On Tripod			Fly	
Receiver Position	1				1		2	1	2
Ground Surface	Sandy	Grass	Grass	Grass	Grass	Stone	Stone	Grass	Grass
Altitude	5 m	8 m	1m	1m	1m	1m	1m	1m	1m

Table 3. Test procedure design

(In the line of receiver position, it refers to the different position of reflective signal receivers, 1 means the receiver is mounted directly on the bottom of the drone in **Option C**, 2 means the receiver is mounted on the extended plastic plate in **Option D**.)

- **The first part: Verification**

The first part consists of two verification experiments, each consisting of two sets of simple flight tests. The first v verification experiment performs two missions at different altitudes and on different terrain types (grass and sand). The second verification experiment maintains the same altitude and surface type, with the first UAV stationary on a tripod and the second remaining hovering in the air.

The purpose of the verification experiment is to test the overall performance of the UAS and GNSS-R, and to observe the behaviour of the two antennas in the GNSS-R system through data comparison. At the same time, the verification experiment is also the basis for the later two parts of the experiment, which can give them a clearer development direction, and with the data results of the verification experiment, adjustments can be made to the later experiment, to continuously optimize the whole experimental procedure as well as the final results.

- **The second part: Stationary experiment**

The second part is two sets of stationary experiments, in which the UAV is stationary on a tripod to receive signals without performing a flight mission. In the experiments, the GNSS-R reflective signal receiver is placed in different positions of the UAV, that is, option C and option D mentioned in the assembly part above. In the first set of stationary experiments, the reflective signal receiver of the GNSS-R system is mounted on the bottom of the UAV, and tested on the stones and grass at the same height. In the second set of stationary experiments, the position of the receiver is changed to a plastic plate and the experiments is conducted on a stone ground.

The purpose of the stationary experiment is to detect the effect of different antenna positions on the final positioning accuracy, the second is to detect the effect of different ground surfaces on the final positioning accuracy.

- **The third part: Flight experiments**

The third part is two flight experiments, again with the antenna and receiver placed in different positions. In the first flight test the receiver is mounted on the bottom of the drone and hovered on the grass. In the second test the receiver is on an extended plastic plate and hovers over the grass at the same height.

The purpose of the experiment is to confirm further whether changing the antenna position can reduce interference effects when the UAV is in flight.

3.2.2 Experimental sites and tools for analysis

- **Experimental sites**

The tests in the flying part were carried out in the drone lab, following the rules for the safe flight of drones.

Figure 11. Dronelab scenario

The ground controller is a laptop and radar, which communicates simple flight commands to the drone via mission plan software.

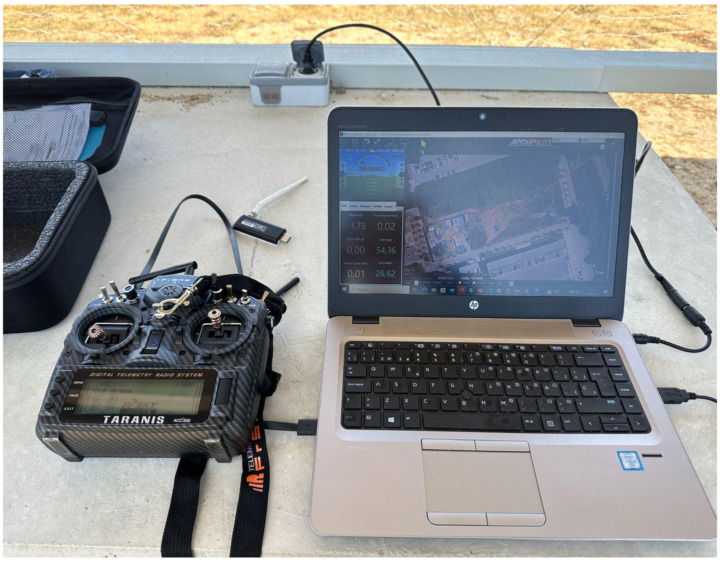


Figure 12. The ground station of UAS

The stationary part of the experiment consisted of two different types of ground surfaces, the stone part was conducted on the roof of the CTTC, and the grass part was conducted in a grassy area near the CTTC, as shown in the figure below.

Figure 13. Experimental site for stationary tests

- **Tools and parameters used for the system performance analysis**

RTKPLOT and RTKPOST are the two tools used to process the signal files in the GNSS-R system. RTKPLOT is used to process the raw files collected to obtain satellite visibility images, SNR (Signal to Noise Ratio) and Elevation images. RTKPOST uses different processing modes for the original file to achieve positioning, I mainly used Kinematic and Static modes, I used Static mode when the drone remained stationary most of the time during the test, and I used Kinematic processing mode when the drone was in motion. Below I will briefly introduce some concepts to help in the analysis of the test results that follow.

a. Satellite visibility

It allows to know all satellites received by the receiver and to see the positioning quality of different satellites at different time periods.

b. SNR

The SNR is usually the ratio of useful signal power to noise power, and in RTKPLOT it is the ratio between the received satellite signal strength and background noise, through which the quality and reliability of the signal can be seen. A higher SNR means that the signal can be detected and decoded more easily, thus improving better communication quality, while the opposite means that the signal is interfered with too much by noise and the signal quality is weaker.

c. Elevation

The elevation angle in RTKPLOT can be understood as the angle of the satellite to the position of the receiver antenna in the GNSS-R system. When the elevation angle of the satellite is higher, it means that the satellite is positioned higher to the receiver, i.e., closer to vertical in the sky, which means that the satellite has a shorter signal propagation path and can provide stronger signal quality. Conversely, a low elevation angle means that the satellite position is low to the receiver and the signal has a longer propagation path, which also means that when the signal is transmitted it is more affected by obscurants such as buildings, ultimately resulting in a less stable, lower quality signal.

d. STD and RMS

STD (Standard Deviation) demonstrate the largest deviation from the averaged coordinate origin, STD reflects the degree of dispersion or precision of the data.

RMS (Root Mean Square) demonstrate the largest deviation from the real coordinate origin, it reflects the accuracy of coordinates, the smaller the RMS, the higher the accuracy.

In the final RTKPOST results image, the STD and RMS of three paths will be given, and the change in the position of the UAV can be seen during that period. Respectively, East-West demonstrates the deviation of the calculated mean position in the east-west direction, North-South shows the deviation of the ORI in the north-south direction, and the Up-Down path indicates the altitude change of the UAV.

Chapter 4 Data Processing and Analysis

In the previous Chapter, I described the design of the entire experiment, including the assembly of the UAV and GNSS-R system, the specific test procedure, the test site and tools used, as well as the relevant metrics concepts that will be involved when analyzing the results.

In this chapter, there are three sections, each documenting the three parts of the tests mentioned in the previous chapter, the verification test, the stationary test and the flight test. In each section I will describe in detail the results of the signal processing and analyze the statistics presented by RTKPLOT and RTKPOST.

4.1 Verification Test

Before doing the verification test, a simple signal reception test was performed with the purpose of testing whether the raspberry pi and GNSS-R systems are working correctly and can receive signals and eventually be read on the computer. The UAV was placed on a grass surface for about five minutes, and then the data file was read by using the card reader. At the end of this test, the computer failed to read because it did not receive the data file from the receiver. With the help of the professor, the problem was found to be a bad cable of one receptor, after we replaced the cable with a new one, the data files were successfully collected. This means that verification experiments can be started.

4.1.1 Verification 1

- **Test description and objectives**

After the above simple test, the first flight was performed at Dronelab. The first verification consisted of two flights with different flight altitudes and changes to the surface. Except for checking the performance of the overall GNSS- R system, also aims to examine how the altitude and the type of ground surface affect the signals received by the GNSS-R system.

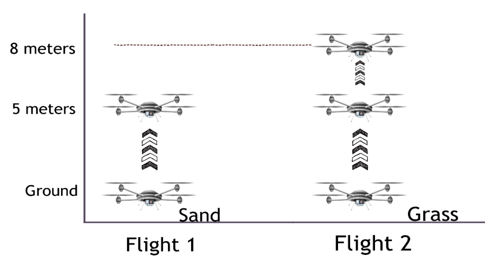


Figure 14. Verification 1 test procedure

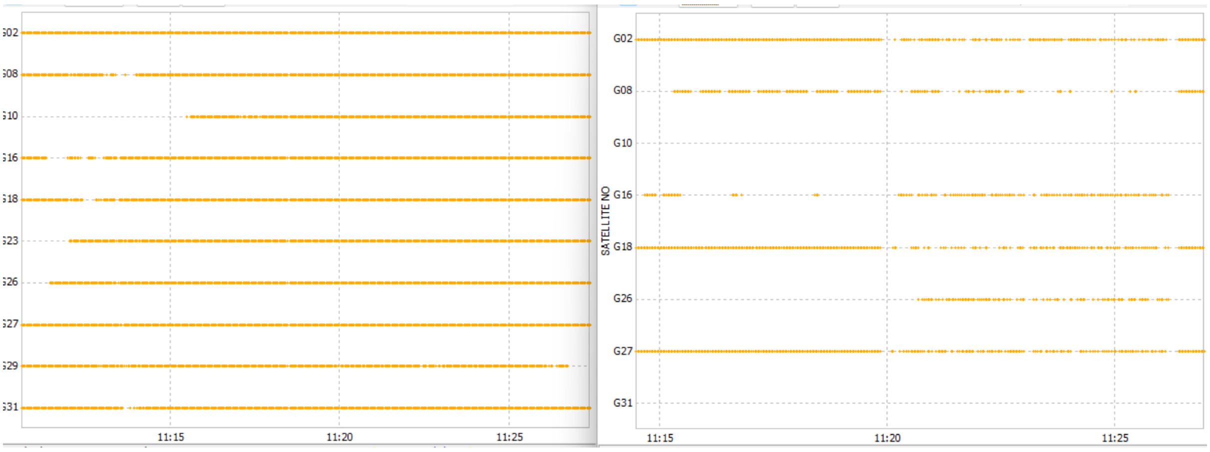
- **The first flight**

The first flight was on sandy ground, where the drone first remained stationary on the ground for ten minutes, then flew to a height of five meters and hovered for about seven minutes.

Figure 15. The first flight scenario of Verification 1

The figures below show the processing results using RTKPLOT of signals received by the receiver, the left one is from the antenna looking upward, and the right one is from the antenna looking downward. To obtain more detailed positioning data information, I used the Kinematic processing mode in RTKPOST to process the two antenna files separately. The processing results are as follows.

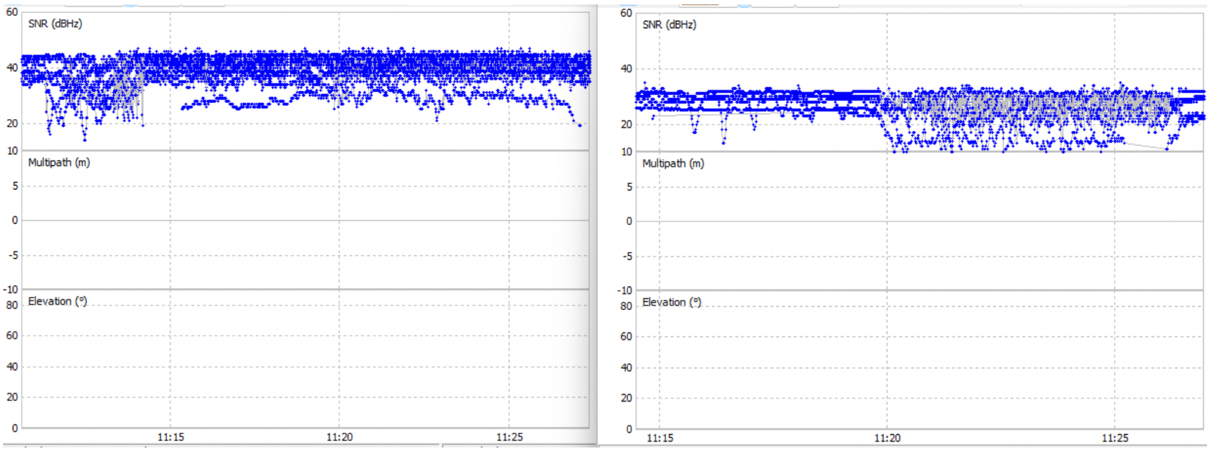
- **Sat-Vis results**



Up antenna Down antenna

Figure 16. Sat-Vis Results of the first flight in Verification 1

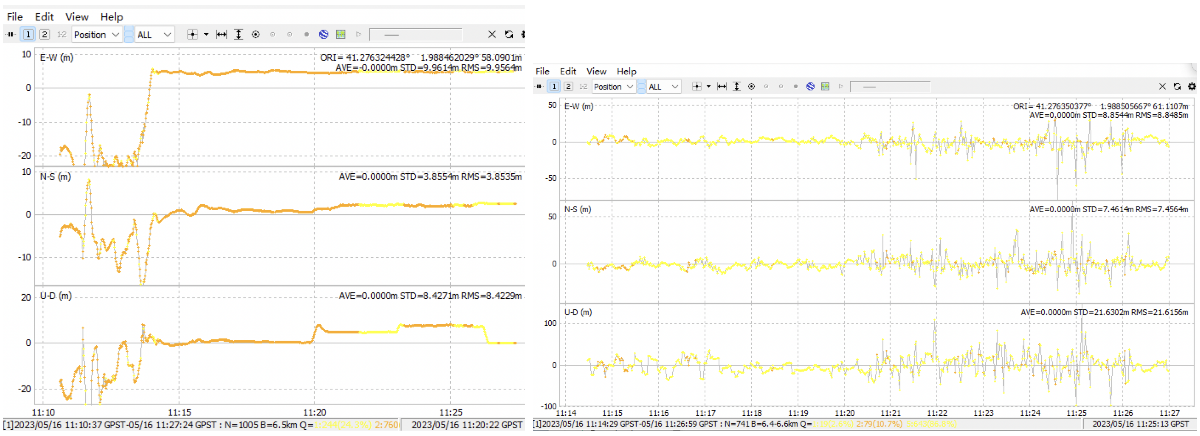
- **SNR/MP/EL results**



Up antenna Down antenna

Figure 17. SNR/MP/EL Results of the first flight in Verification 1

- **Processing results in Kinematic mode**



Up antenna Down antenna

Figure 18. – Kinematic mode Results of the first flight in Verification 1

- **Summary of the processing results**

	Sat-Vis (n)	SNR (dbHZ)	RMS (U-D m)	STD (U-D m)
Up antenna	10	25-40	8.429	8.427
Down antenna	6	10-30	21.6156	21.6302

Table 4. Statistics Results of the first flight in Verification 1

From the Sat-Vis and SNR/MP/EL results, 11:10 to 11:20 the UAV was stationary on the ground, at this time the signal received by the antenna receiving the direct signal is not stable, because the straight line in the sat-vis is not coherent and the SNR is about 20-40dbHZ, which indicates a lot of noise. The antenna facing the ground that received the reflected signal performed even worse, only three satellite signal was received during this period. From 11:20 to 11:27, the UAV took off and hovered 5 meters in the air, and the signal received by the sky-facing antenna was more stable, with the SNR at about 40dbHZ, indicating a reduction in noise. At this time, the antenna facing the ground began to receive more reflected signals, but the low SNR and incoherent satellite visibility lines show that the quality and stability of the received signals are not enough.

From the Kinematic processing results, the behavior of both antennas is not good enough, statistics indicate the final accuracy and precision are low. Despite this, it is still possible to see the processing result of the antenna up to the sky is more stable, the convergence time is faster and the accuracy is higher than the down antenna.

The analysis results of the up antenna show that the curve fluctuates a lot when the signal converges in the early stage, indicating that the received signal is not stable enough, which affects the overall positioning accuracy. The RMS shows that the average error is about 8m, and the STD shows that the dispersion of the solved position with respect to the reference solution is about 8m, which fluctuates a lot.

The analysis result of the down antenna shows that there are fluctuations in the whole curve, especially after the aircraft took off at 11:20, indicating that the signal was more disturbed at this time. The RMS indicates that the average error is about 21m, and the STD shows that the dispersion of the solved position with respect to the reference solution is about 21m, which fluctuates a lot.

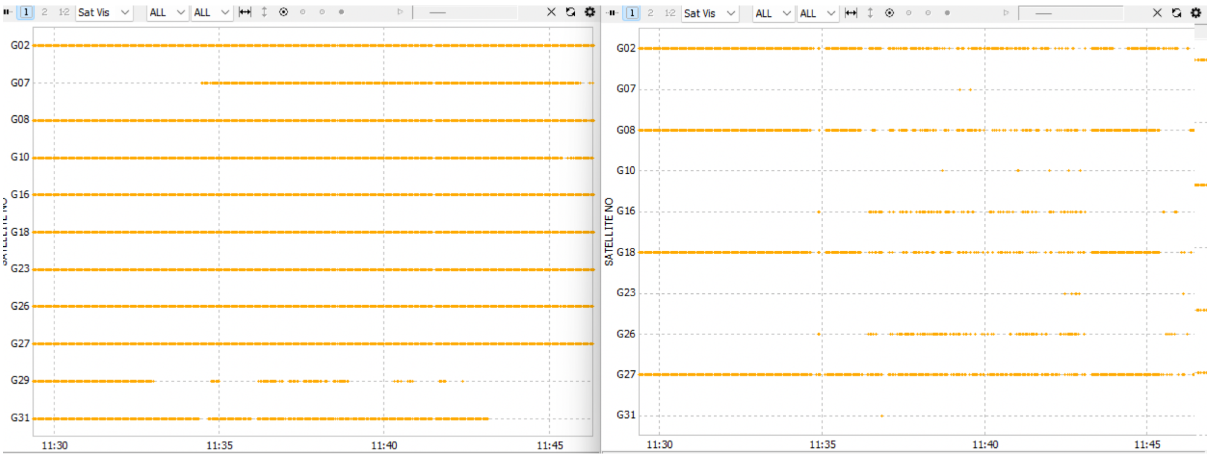
- **The second flight**

The second flight was conducted on the grass with green leaves, also firstly at ground rest for about eight minutes, then flew to an altitude of five meters to remain for around six minutes, next flew to an altitude of eight meters to hover for about ten minutes, and finally returned to the ground.

Figure 19. The second flight scenario of Verification 1

The figures below show the processing results using RTKPLOT and RTKPOST. The Kinematic processing mode also is applied. The processing results are as follows.

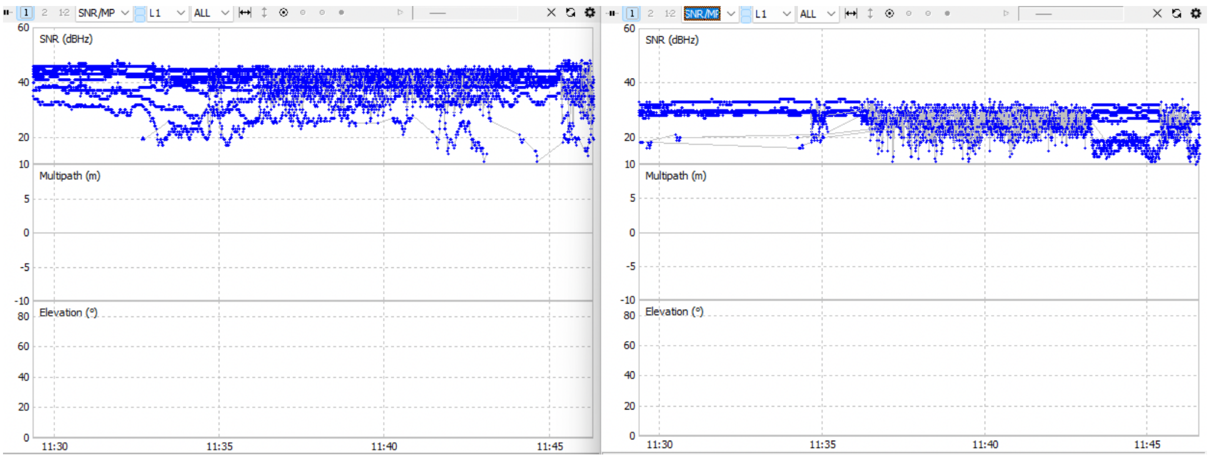
- **Sat-Vis results**



Up antenna Down antenna

Figure 20. Sat-Vis Results of the second flight in Verification 1

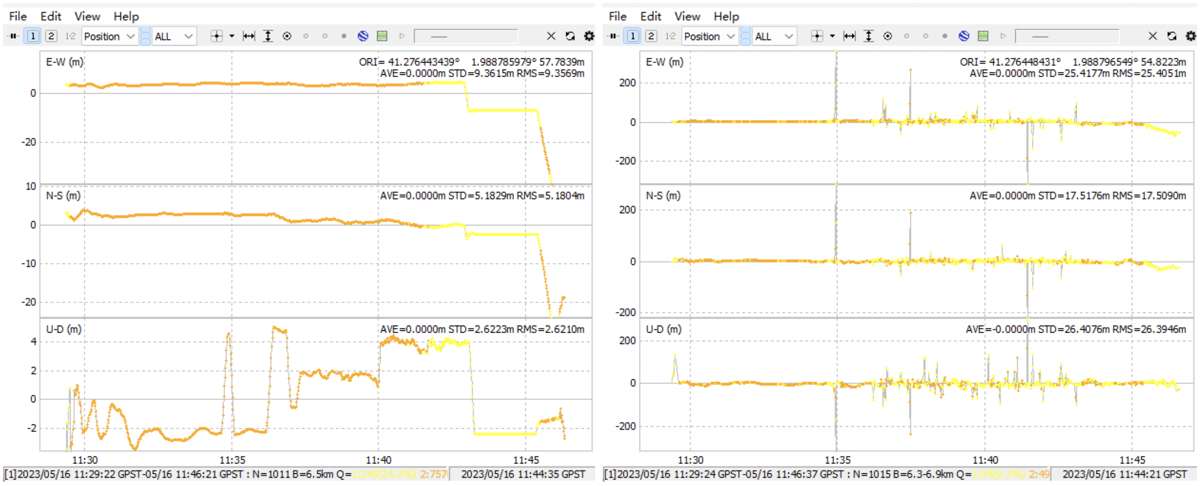
- **SNR/MP/EL results**



Up antenna Down antenna

Figure 21. SNR/MP/EL Results of the second flight in Verification 1

- **Results in Kinematic processing mode**



Up antenna Down antenna

Figure 22. Kinematic mode Results of the second flight in Verification 1

- **Summary of the processing results**

	Sat-Vis (n)	SNR (dbHZ)	RMS (U-D m)	STD (U-D m)
Up antenna	11	20-45	2.6210	2.6223
Down antenna	6	10-30	26.3946	26.4076

Table 5. Statistics Results of the second flight in Verification 1

From the images of SNR/MP/EL and satellite visibility, at 11:30-11:38 when the UAV was stationary on the ground, the downward antenna received signals from only four satellites, at 11:38-11:44 the UAV took off and hovered five meters in the air, it can be seen that at this time the reflective antenna received two more satellite signals, but through the incoherent lines of sat-vis it can be seen that the signals from these four satellites are not stable, meanwhile upward antenna also received an additional satellite signal, through the SNR image can be seen at this time significantly increased noise. After 11:44, the UAV increased its altitude by three meters and can be seen in the sat-vis image that the up antenna and down antenna lost signals from two satellites. The SNR of the signals received by the up antenna was 20-45 throughout the test, while that of the down antenna was only 10-30, indicating that the down antenna collected more signal noise.

From Kinematic processing results, both the upward and downward antennas fluctuate more when the UAV takes off, indicating that the signal is more unstable currently and the instability of the solution results is higher. The figures illustrate that both the STD value and RMS value are large, indicating that the positioning accuracy of both antennas is low. The STD and RMS of the upward antenna are about 2.6m, which means the error is about 2.6m, and the performance of the downward antenna is worse, the error is about 26m.

- **Conclusion**

The processing results of the two tests are similar, neither achieves a high level of accuracy and the GNSS down antenna always performs less well than the GNSS up antenna.

In terms of the results of two flights in different surface types, when the drone hovered at 5m in the air in both tests, the overall result of the second test on the grass was a little better, because the two antennas received more satellite signals at this time, while the upward antenna had a higher signal-to-noise ratio in the second flight, exceeding 40dbHZ. In addition, the error of the upward antenna in the second test was reduced to 2.6m, while the error of the first test was up to 8.4m. However, the error of the downward antenna did not improve, instead it increased from 21m to 26m, so it is not possible to conclude that GNSS-R will obtain more accurate positioning results on the grass surface, plus the difference between grass and sand is not particularly large, so more tests are needed to verify this.

In terms of the flight height of the UAV, when the UAV rose from 5m to 8m in the second test, both the upward and downward antennas lost two satellite signals, and the other signals began to be more unstable, but this still can’t conclude that the higher the flight height of the UAV, the worse the processing results of GNSS-R, because in the test process, due to weather factors, when the UAV rose in height, it was more affected by wind, and the UAV itself did not have enough horsepower to maintain the UAV in a completely stationary state in the air, all of which would affect the quality of the received signals.

Through the first verification test, the following problems were found, which need to be gradually verified and solved in later experiments further:

1. It can be found in both tests that it is difficult to receive the reflected signal when the drone is stationary on the ground. Because the drone is too close to the ground, it is difficult to make the downward antenna receive the reflected signal at 10cm. The only solution is to increase the stationary height of the drone, i.e., to place the drone on a tripod so that there is some space between the drone and the ground, which will give the opportunity to reflect signals.

2. In both tests, SNR showed more noise when the UAV took off, indicating that the operation of the UAV causes some interference to the GNSS-R system, especially to the downward antenna.

3. Through the comparative analysis in the previous part, when the UAV flew on grass and sand respectively, conclusions could not be obtained at present, probably because the difference between sand and grass in the test was not

obvious enough, and in the later test, the sand could be replaced with a more different stone surface as a way to compare the influence of different surfaces on the accuracy of solving the positioning.

4.1.2 Verification 2

- **Test description and objectives**

After verification 1, some problems were found with GNSS-R systems working with UAVs. There were two main objectives in verification 2, one of which was to confirm that reflected signals were not received well because the drone is too close to the ground. Another goal was to test whether the operation of the UAV would have an impact on the received signal by generating interference. The verification was also divided into two parts keeping the ground type the same, firstly placing the drone stationary on a tripod and subsequently keeping the drone hovering in the air at about the same height as the tripod.

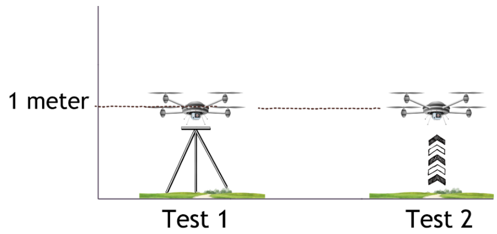


Figure 23. Verification 2 test procedure

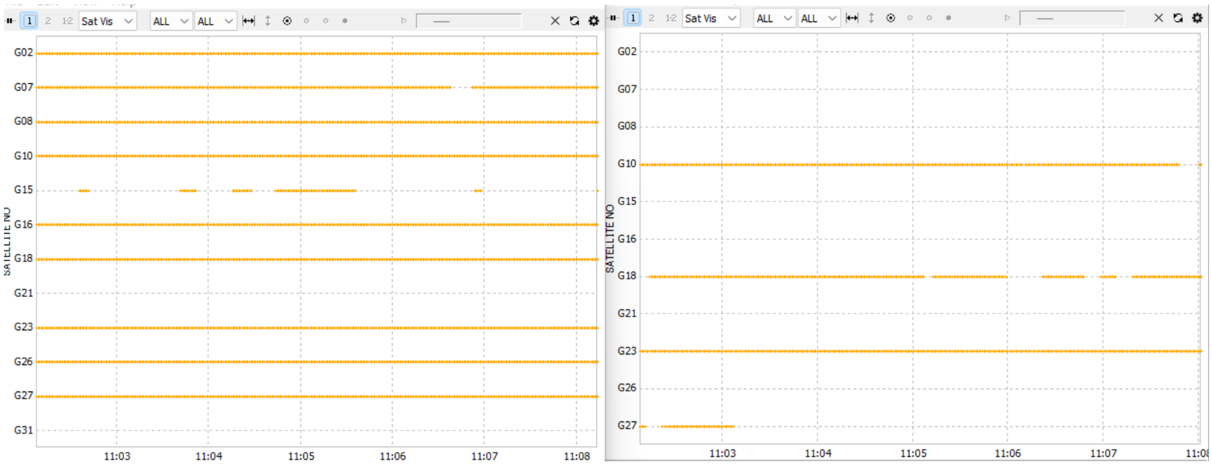
- **The first test**

The drone was not flown and was placed on a tripod for about ten minutes as shown below.

Figure 24. The first test scenario of Verification 2

Once the data collection was finished, the received signals were analyzed using RTKPLOT. In RTKPOST I used Static processing mode as the UAV was kept stationary on the tripod. The processing results are shown in the figures below.

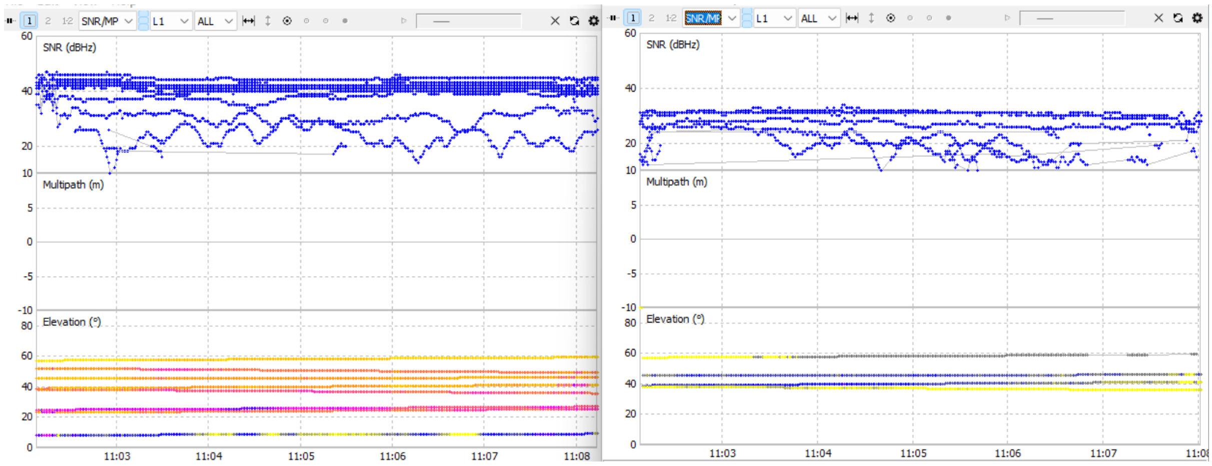
- **Sat-Vis results**



Up antenna Down antenna

Figure 25. Sat-Vis Results of the first test in Verification 2

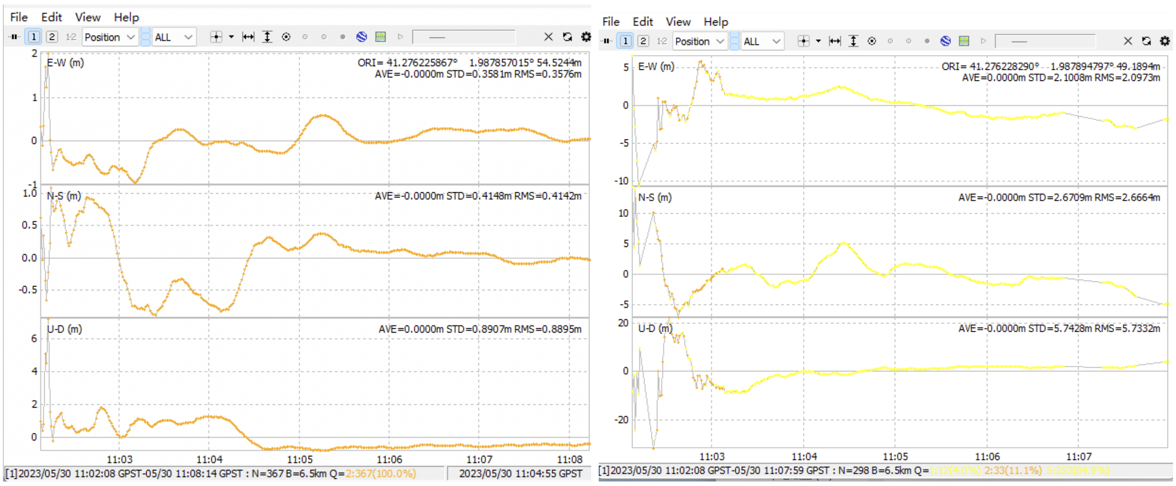
- **SNR/MP/EL results**



Up antenna Down antenna

Figure 26. SNR/MP/EL Results of the first test in Verification 2

- **Processing results in Static mode**



Up antenna Down antenna

Figure 27.Static mode Results of the first test in Verification 2

- **Summary of the processing results**

	Sat-Vis (n)	SNR (dbHZ)	RMS (U-D m)	STD (U-D m)
Up antenna	10	20-45	0.8895	0.8907
Down antenna	4	10-30	5.7332	5.7428

Table 6. Statistics Results of the first test in Verification 2

The analysis of the satellite visibility and SNR/MP/EL graphs show that the upward antenna received signals from ten satellites, of which only two satellites had fewer stable signals. The other satellites had fewer fluctuations in the SNR graphs, indicating good and stable signals and less noise, with the SNR remaining at around 40dbHZ. The downward antenna received signals from four satellites, half of which were more stable and less noisy, with an SNR maintained at 30dbHZ, while the other two satellites were of poorer quality, with their signal-to-noise plots fluctuating widely, with SNR ranging from 10dbHZ to 20dbHZ and more noise. By comparing the satellite elevation, both upwards and downward antennas, almost no satellite elevation angle is below 20 degrees, with most satellites concentrated at 40 to 60 degrees.

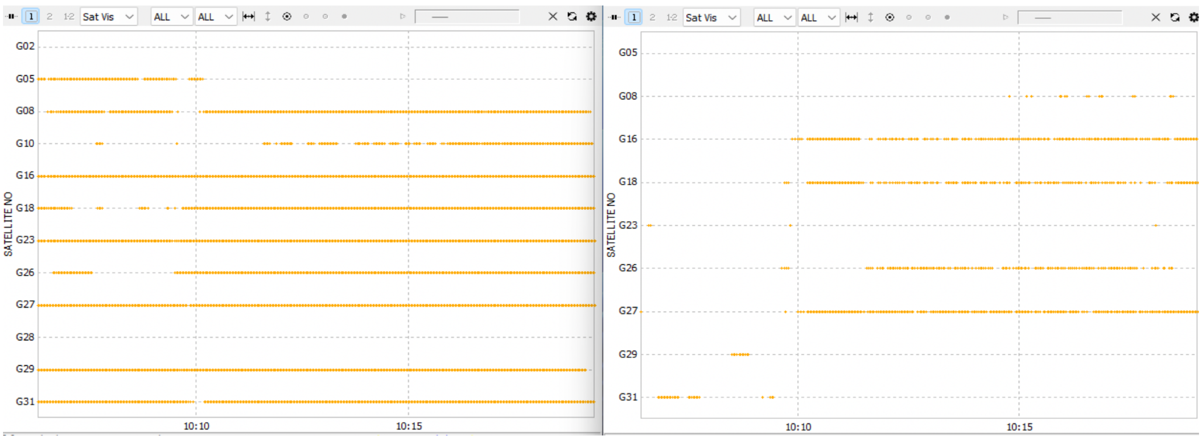
From the RTKPOST results, In the U-D path, the upward antenna error is maintained at about 0.89m, and the downward antenna error is maintained at about 5.7m. It can be seen the STD and RMS values of the up antenna are smaller than those of the down antenna in all three paths, indicating that the accuracy of the up antenna is significantly better than that of the down antenna.

- **The second test**

This test used radar to control the drone and flew it to a height of about one meter in the air to remain stationary, but the wind was quite strong on the day of the test, so the drone could not be completely stationary and was always in a dynamic state, so I chose the Kinematic mode for the RTKPOST analysis. Below are the screenshots of the analysis results.

Figure 28.The second flight scenario of Verification 2

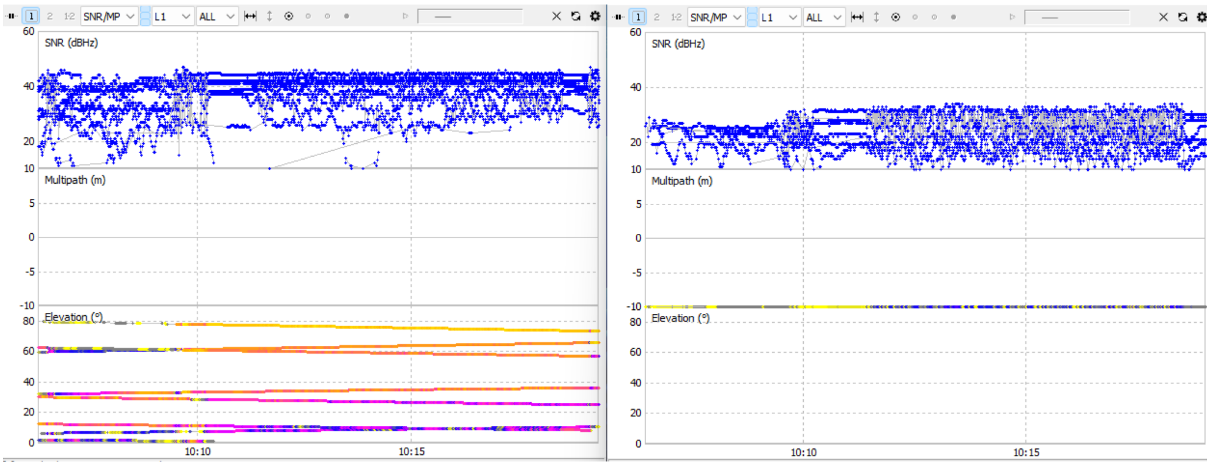
- **Sat-Vis results**



Up antenna Down antenna

Figure 29. Sat-Vis Results of the second test in Verification 2

- **SNR/MP/EL results**



Up antenna Down antenna

Figure 30. SNR/MP/EL Results of the second test in Verification 2

- **Processing results in Kinematic mode**

Up antenna Down antenna

Figure 31. Kinematic mode Results of the second test in Verification 2

- **Summary of the processing results**

	Sat-Vis (n)	SNR (dbHZ)	RMS (U-D m)	STD (U-D m)
Up antenna	10	20-45	59.0802	59.1207
Down antenna	8	10-35	22.3550	22.3374

Table 7. Statistics Results of the second test in Verification 2

The satellite visible picture shows that the upward antenna received signals from ten satellites, four of which were less stable, and the SNR picture shows that the SNR lines of the satellites fluctuate widely, indicating more noise, with the SNR remaining at 20 to 40dbHZ. The downward antenna received signals from seven satellites, mostly after the UAV had taken off, all of which were unstable and maintained a SNR of 10dbHZ to 30dbHZ, indicating poor signal quality and a lot of noise. By observing the elevation angle, although one satellite has an elevation angle of up to 80 degrees, it cannot be ignored that there are at least three satellites with an elevation angle of less than 20 degrees, which is one of the reasons for the poor signal quality.

From the RTKPOST processing results, both antennas converge poorly from the beginning. RMS values for both the up and down antennas are large, upward antenna error of up to 60m, downward antenna error of up to about 22m, which indicates that the processing results are of low accuracy.

- **Conclusion**

The first thing that could be demonstrated was that the downward antenna was indeed unable to collect the reflected signal when the drone was too close to ground. Because the UAV was on the tripod and kept off the ground throughout test 1, the Sat-Vis results and SNR/MP/EL results show that the downward antenna received the signal from the beginning of the test, while test 2 shows that the downward antenna failed to receive the signal a few minutes before the UAV was ready to take off.

Secondly, when the UAV was operated in the second test, more noise was clearly visible from the SNR plot, while Kinematic processing statistics showed that the STD and RMS of both antennas were larger when the UAV was operated, indicating a greater dispersion of both errors and solutions. This indicates that when the UAV is operating, its own components generate some interference, which reduces the performance of the GNSS-R system.

4.2 Stationary Test

In the verification experiments in the previous subsection, it was learned through two verification tests that the reflected signal is difficult to be received by the downward antenna when the UAV is placed directly on the ground, and it was also verified that interference is generated a lot when the UAV is in operation, thus reducing the signal quality and increasing the noise. Therefore, in the following subsections, two sets of stationary tests will be performed, with the UAV all placed on a tripod to receive the signal. Besides trying to verify the effect of different terrain surfaces on positioning accuracy, it also aims to test whether the change of GNSS-R receiver position on the UAV will reduce certain interference problems.

4.2.1 Stationary 1

- **Test description and objectives**

In first stationary test consists of two sets of tests, the drone was all placed on a tripod and put on different surfaces to compare the quality of the signal and processing results. The first test was carried out on a surface covered with stones on the roof, and the other one was conducted on the ground with a grassed area.

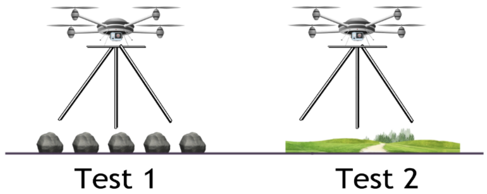


Figure 32. Stationary 1 test procedure

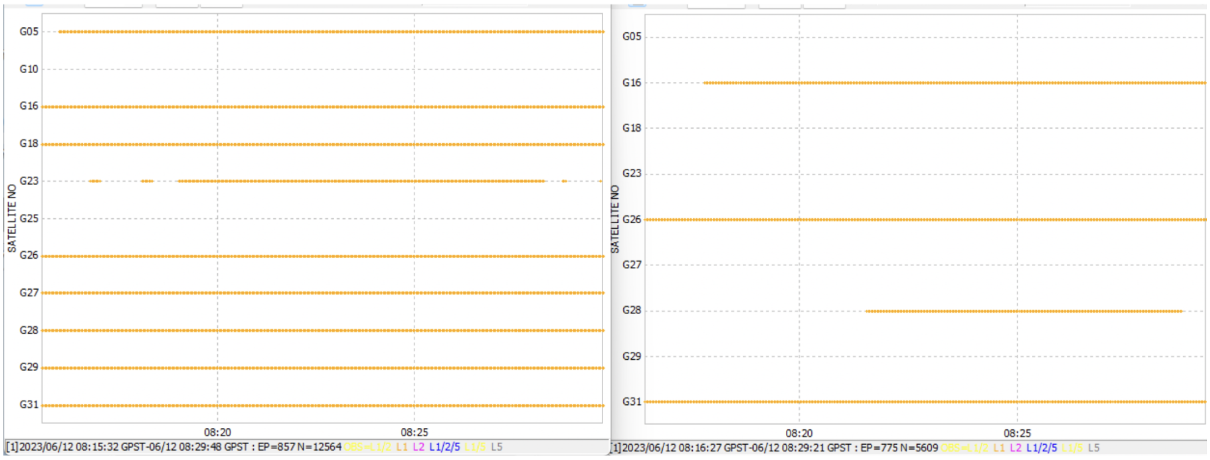
- **The first test**

In this test the drone did not perform a flight mission and was simply placed on a tripod in the picture below, with the type of ground being stone.

Figure 33. The first test stone scenario in Stationary 1

The figures below show the processing results using RTKPLOT of signals received by the receiver. In RTKPOST I used Static processing mode as the UAV was kept stationary on the tripod.

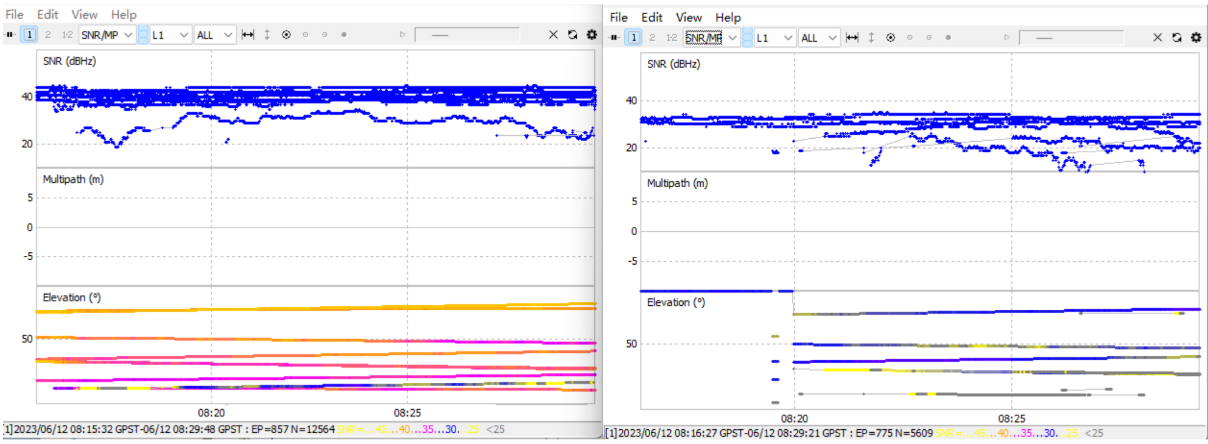
- **Sat-Vis results**



Up antenna Down antenna

Figure 34. Sat-Vis Results of the first test in Stationary 1

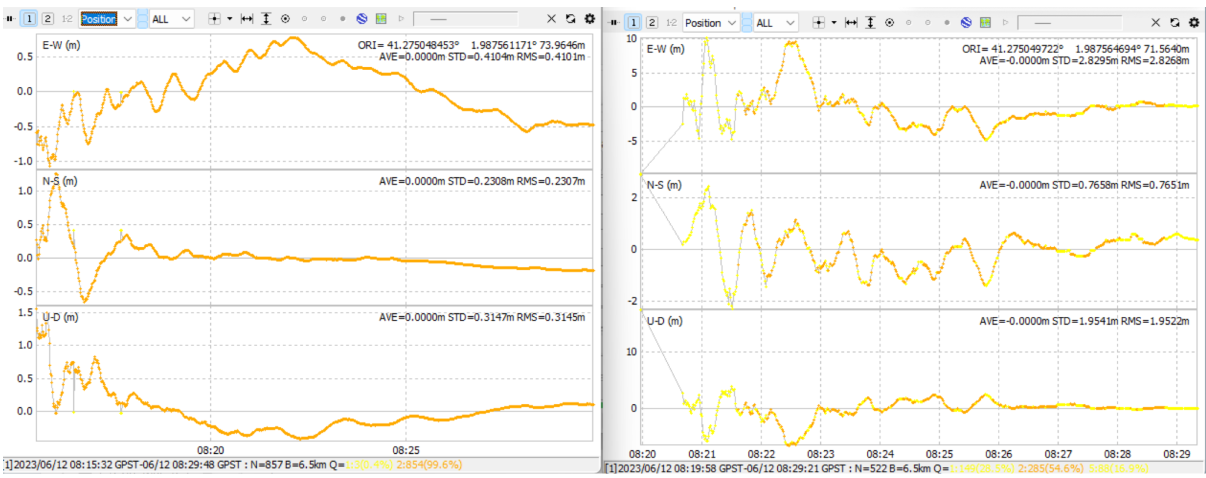
- SNR/MP/EL results



Up antenna Down antenna

Figure 35. SNR/MP/EL Results of the first test in Stationary 1

- Processing results in Static mode



Up antenna Down antenna

Figure 36. Static mode Results of the first test in Stationary 1

- **Summary of the processing results**

	Sat-Vis (n)	SNR (dbHZ)	RMS (U-D m)	STD (U-D m)
Up antenna	9	35-43	0.3145	0.3147
Down antenna	4	10-35	1.9522	1.9541

Table 8. Statistics Results of the first test in Stationary 1

The SNR/MP/EL picture shows that the SNR of the direct signal received by receiver is stable and fluctuates less, remaining at 35-45dbHZ, while the SNR of the reflected signal is slightly lower and fluctuates slightly more, indicating more signal noise.

In the results of the STATIC processing mode, In the U-D path, the processing result error of the upward antenna is about 0.3m, while the error of the downward antenna is about 2m, the processing results of other paths are similar, indicating that the processing result of the upward antenna is more accurate. It can also be seen from the images that the reflected antenna images are processed with more fluctuations and more noise.

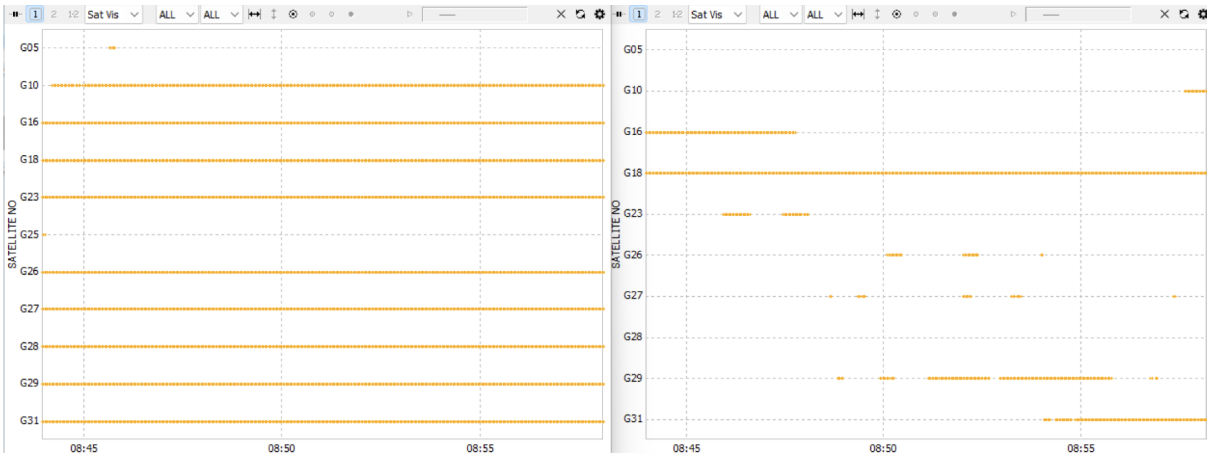
- **The second test**

In the second test, the drone also did not fly and remained stationary on a tripod at the same height. The difference from the first test was that it was carried out on flat ground instead of the roof of a building and the type of ground was no longer stone but grass.

Figure 37. The second test grass scenario in Stationary 1

Since the UAV is at stationary, the mode of processing data is still selected as Static, and the processing results are shown in the following figures.

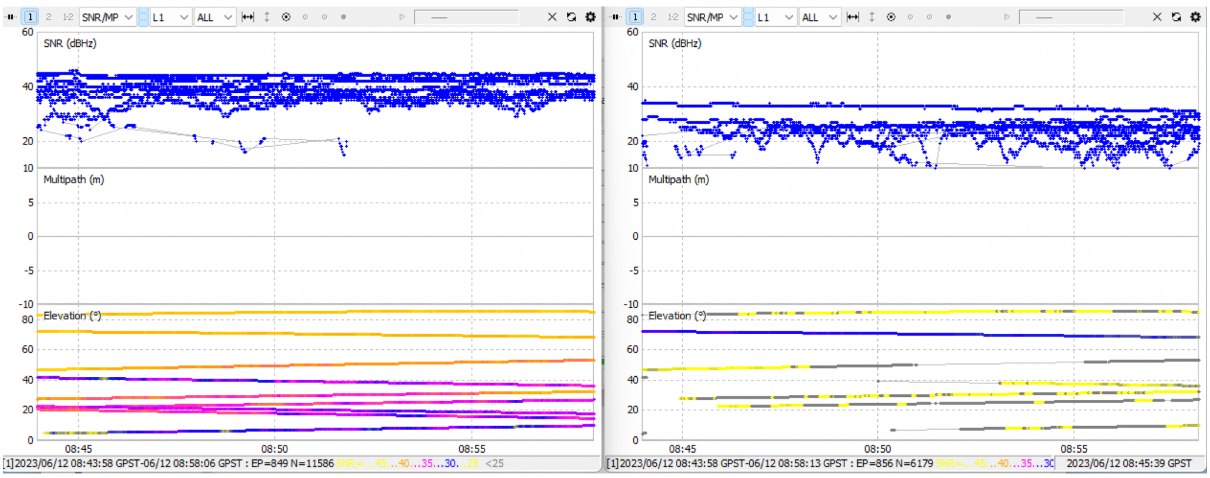
- **Sat-Vis results**



Up antenna Down antenna

Figure 38. Sat-Vis Results of the second test in Stationary 1

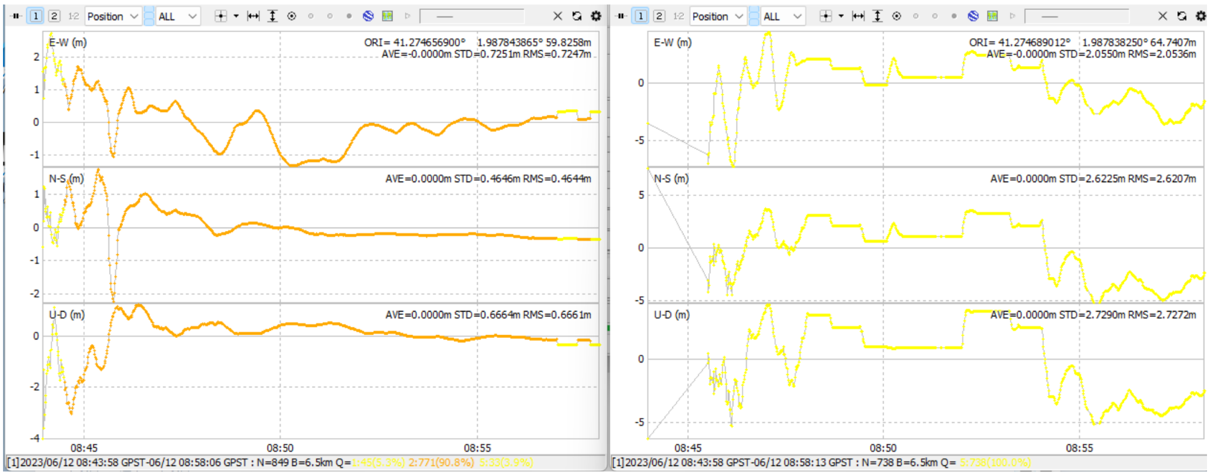
- **SNR/MP/EL results**



Up antenna Down antenna

Figure 39. SNR/MP/EL Results of the second test in Stationary 1

- **Processing results in Static mode**



Up antenna Down antenna

Figure 40. Static mode Results of the second test in Stationary 1

- **Summary of the processing results**

	Sat-Vis (n)	SNR (dbHZ)	RMS (U-D m)	STD (U-D m)
Up antenna	9	30-45	0.6661	0.6664
Down antenna	8	10-35	2.7272	2.7290

Table 9. Statistics Results of the second test in Stationary 1

The satellite visibility image shows that the upward antenna received signals from a total of 9 satellites, and the downward antenna received signals from 8 satellites, but despite this, it can be seen from the discontinuous lines that only one of these eight satellites provided a stable signal, the same problem can be seen from the signal-to-noise ratio image, where only one satellite maintained a SNR of about 35 dbHZ, and the other SNRs ranged from 10 dbHZ to 30 dbHZ, indicating more signal noise.

In the results of the STATIC processing mode, In the UD direction, the error of the upward antenna is maintained at about 0.6m and the error of the downward antenna is maintained at about 2.7m. The image of the downward antenna obviously fluctuates too much, and the convergence time is longer.

- **Conclusion**

From the perspective of the SNR, the GNSS antenna always has a high SNR on both rocky and grassy surfaces, which means that the direct signal can be detected and decoded more easily, thus improving better communication quality, while the opposite means that the reflected signal is interfered with too much noise and the reflected signal quality is weaker.

By looking at the elevation, in the stone roof scene, the satellites are mostly concentrated at 50 degrees, while in the grass, the satellites are more scattered from 5 to 80 degrees, with only two satellites above 60 degrees, which does not guarantee the quality of the final position.

In terms of surface type, the statistic shows stone surfaces give better results than grass surfaces. The roof has a height of about ten meters, which is more open and reduces interference with the signal from other buildings. At the same time, the stone surface is smooth and has the same reflective effect as a mirror, which can reflect the signal more clearly. Whereas the grass test was carried out on flat land with more buildings and woods to block the signal or multiple reflections.

In general, it can be concluded from the stationary 1 experiment that more accurate solution positioning can be obtained when GNSS-R works on the stone surface than grass.

4.2.2 Stationary 2

- **Test description and objectives**

In previous tests, it has been verified that the operation of UAVs causes some interference to the GNSS-R system, thus reducing the reception quality of the signal, especially the quality of the reflected signal. So in this test, the position of the reflective receiver was changed, it was kept away from the body of the UAV. The positioning accuracy of the stone surface was shown better in static test 1, so this test was also conducted on the stone surface.

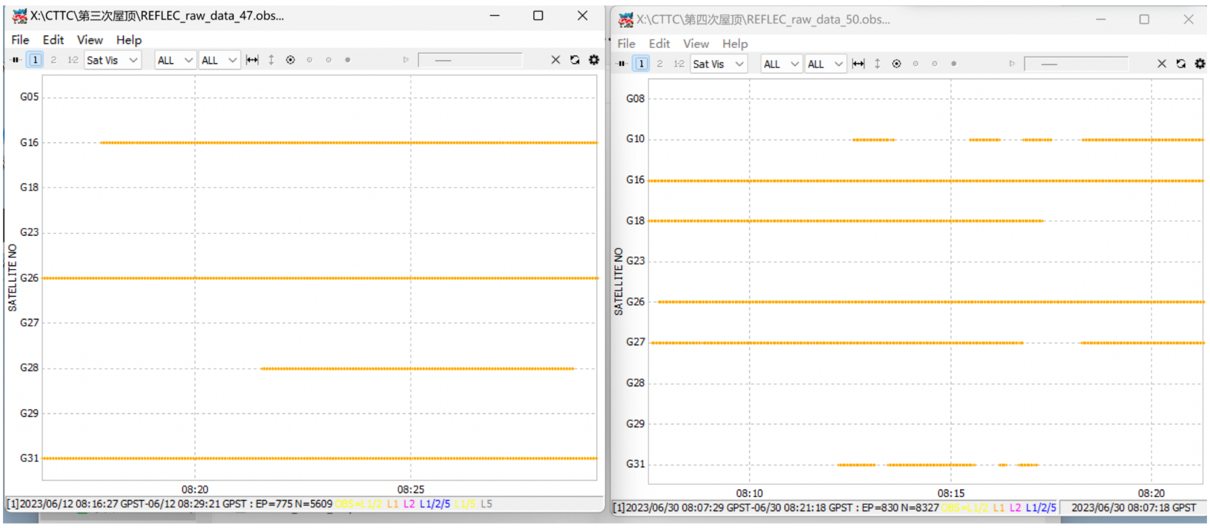
Only one test is included in stationary 2, the UAV and GNSS-R system is stationary on the tripod to receive signals, the results are directly compared with the test 1 results in stationary1. The objective is to verify whether the change of the reflective receiver position can reduce the interference problem and achieve better positioning accuracy.

Figure 41. Test stone scenario in Stationary 2

From the previous tests the reflection antenna is more affected by the interference, and only the position of the reflection signal receiver was changed in this test, so in the following signal processing, the focus is on the results of the reflection antenna. Compare the positioning results and statistics before and after changing the position of the reflective receiver respectively.

The images on the left are the results of the processing before the change of receiver position, which is test 1 of Stationary 1, marked as pos1. The images on the right are the results of the processing after the change of receiver position, marked as pos2.

- **Sat-Vis results**

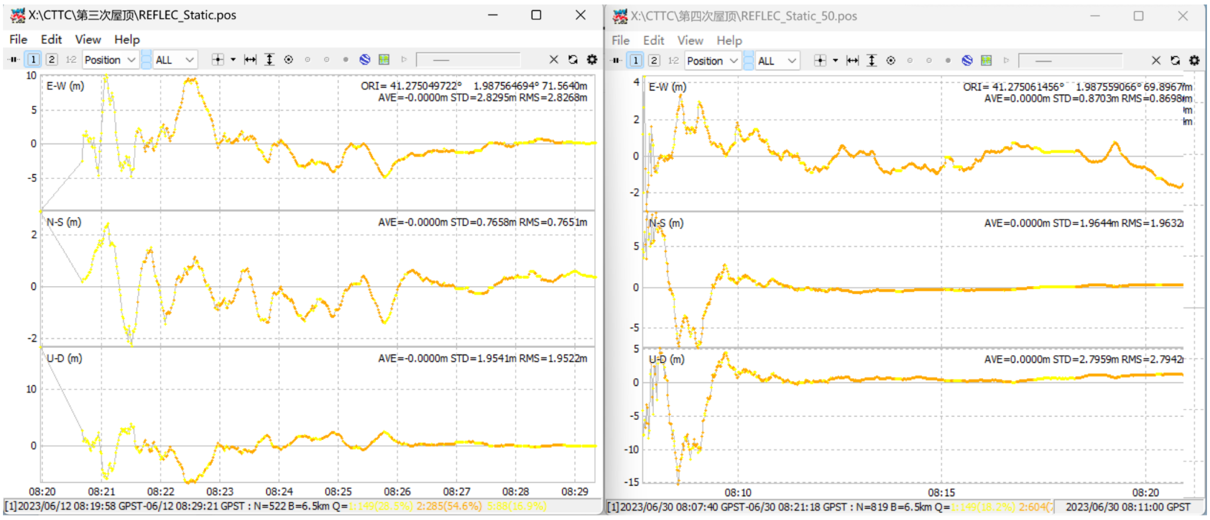


Pos1 of down antenna Pos2 of down antenna

(Pos1 indicates the old position, pos2 indicates the new position)

Figure 42. Sat-Vis Results of the Stationary 2

- **Processing results in Static mode**



Pos1 of down antenna Pos2 of down antenna

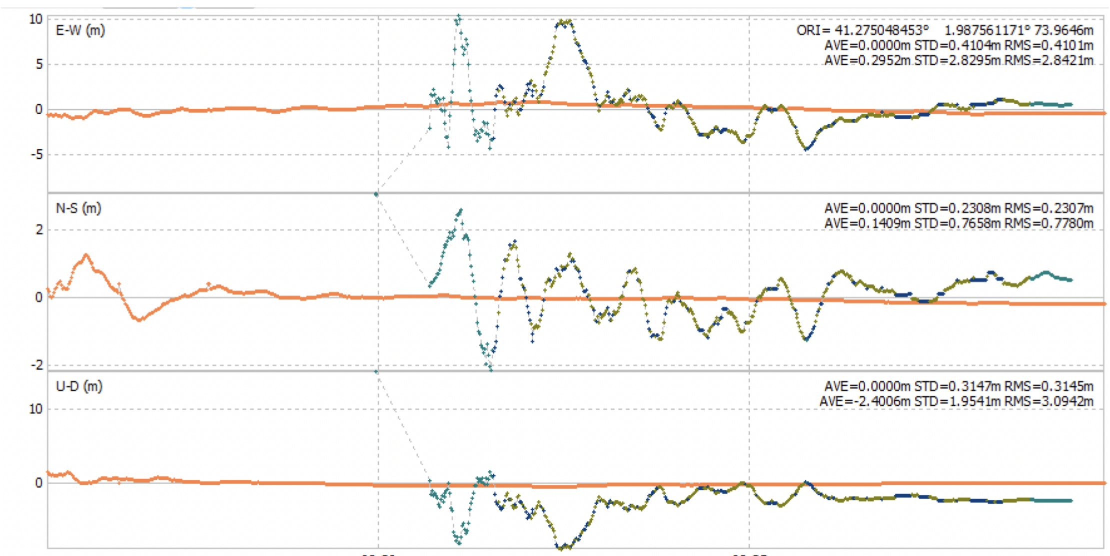
Figure 43. Static mode Results of the Stationary 2

- **Summary of the processing results**

	Sat-Vis (n)	SNR (dbHZ)	RMS (U-D m)	STD (U-D m)
Pos1	4	30-45	1.9522	1.9541
Pos2	6	10-35	2.7942	2.7959

Table 10. Statistics Results of the Stationary 2

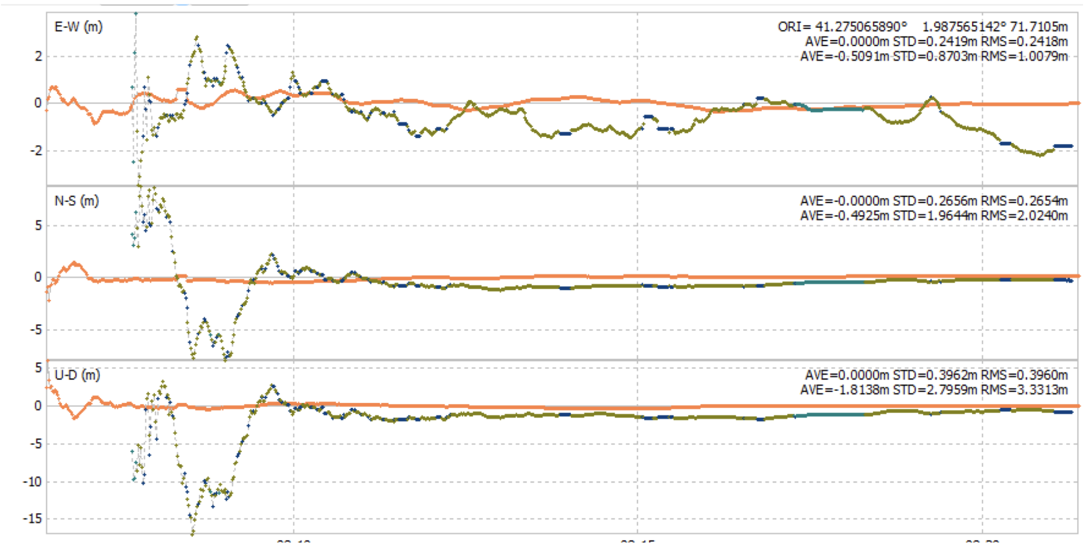
- Comparison results of upward and downward antennas in Static processing mode Before the receiver changed its position.



(Upward antenna solved in red and the downward antenna solved in green)

Figure 44. Pos 1 Comparison Results of the Stationary 2

- Comparison results of upward and downward antennas in Static processing mode <u>After</u> the receiver changed its position.



(Upward antenna solved in red and the downward antenna solved in green)

Figure 45. Pos 2 Comparison Results of the Stationary 2

As can be seen in the satellite visibility graph, two more satellites can be received after changing the receiver position and the static processing results show a smoother curve in the pos2 that represents less noise. It is also noticeable in the comparison graphs of the upper and lower antennas that the signal from the reflector antenna is more stable, converges faster, and picks up the reflected signal faster with the changed location.

Despite this, the STD and RMS statistics did not change much in the two tests, with error values of 2 m to 3 m. The first time was due to too much noise interference during all periods. In the second test, although the interference problem was reduced a little bit, the process of converging the signals in the early stage was still too noisy, which led to a decrease in the overall accuracy of the positioning.

- **Conclusion**

From the above analysis, changing the receiver position can mitigate some interference problems, but it still does not significantly improve the processing accuracy of the reflective receiver. When the drone takes off, the communication system that comes with the drone creates more interference. In this Stationary test the drone was always kept static on the tripod, so the flight test was needed to further confirm whether changing the receiver position would reduce the interference problem during the flight of the drone.

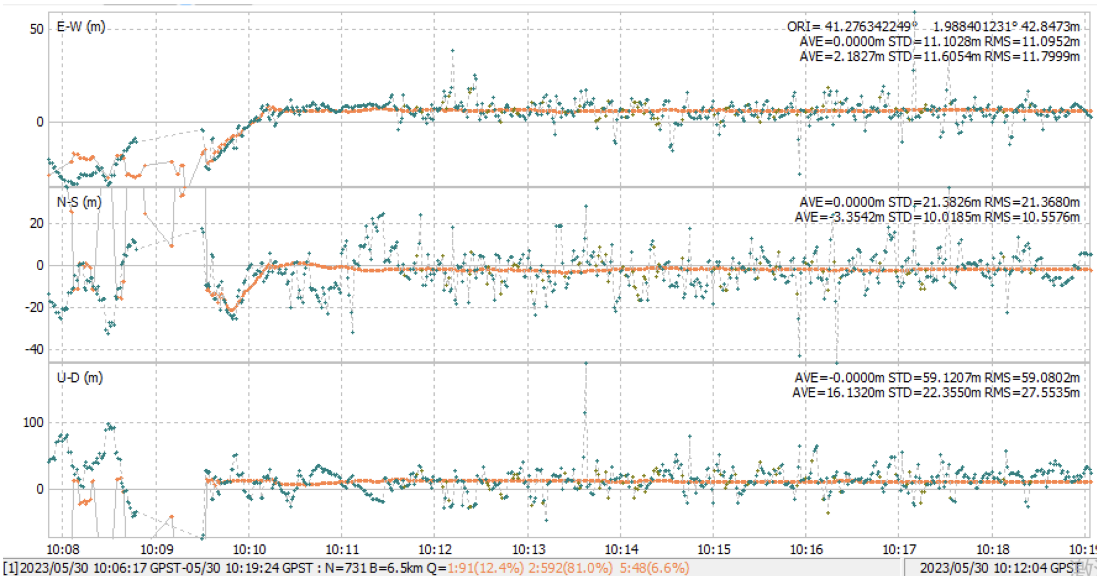
4.3 Flight Test

- **Test description and objectives**

In this section, the main objective is to verify whether the installation of the reflective receiver at a distance from the body of the UAV can reduce the interference generated during the flight of the UAV. Comparison is made mainly through two tests, the first flight test can be directly used with the processing results of test2 in Verification 2, i.e., the UAV is flown to a one-meter hover in the air when the receiver does not change its position. In the second test, the UAV was also flown to hover one meter in the air when the receiver changed its position. The flight site was kept the same for both tests, and the altitude was kept the same.

4.3.1 Flight 1

- Since the data processing results for this flight have already been analyzed in Verification 2, only the comparison results for the upper and lower antennas are presented here, and the processing mode used is Kinematic:



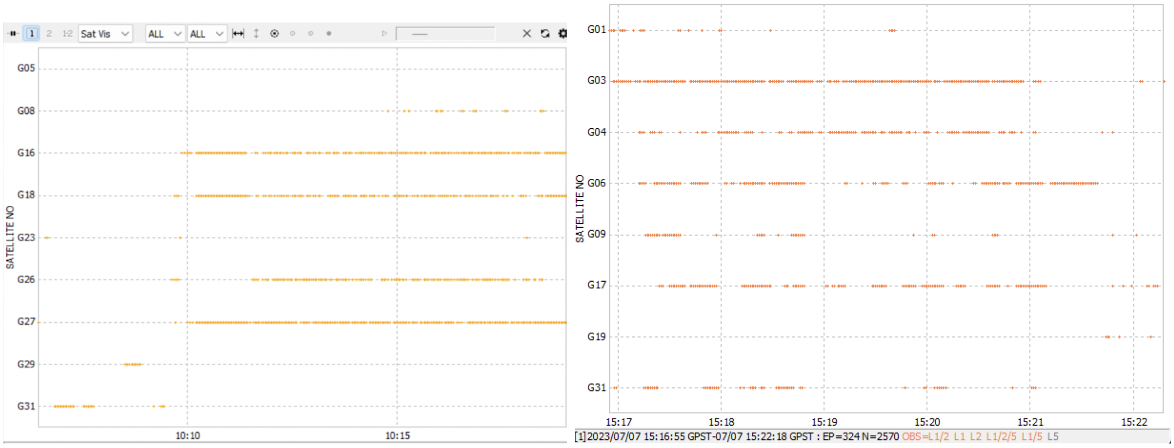
(Red line presents up antenna, green line presents down antenna)

Figure 46. Pos 1 Comparison Results of the Flight 1

4.3.2 Flight 2

This flight test ultimately lasted only 6 minutes because the overall Payload of the drone increased due to the modification of the drone with the addition of the extended plastic plate to hold the reflective receiver in place, resulting in a decrease in the drone's flight time. The weather conditions were good during this test and the drone hovered relatively stable in the air, so I chose the Static processing mode. Again, here I will focus mainly on the quality of the reflected signal, with pos1 being the position of the receiver before the change and pos2 indicating the position of the receiver after the change.

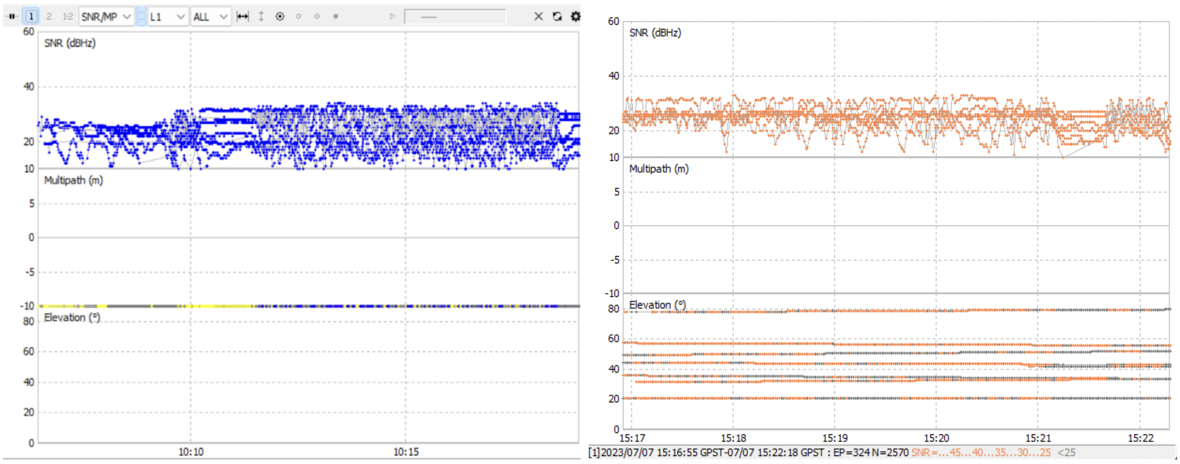
- **Sat-Vis results**



Pos1 of down antenna Pos2 of down antenna

Figure 47. Sat-Vis Results of flight 2

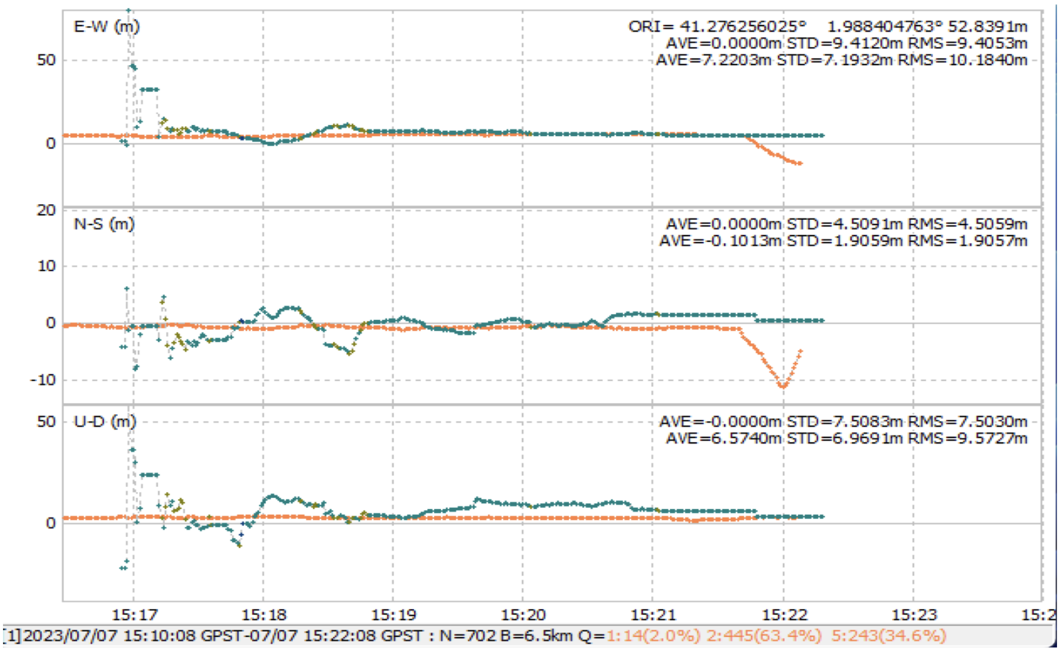
- **SNR/MP/EL results**



Pos1 of down antenna Pos2 of down antenna

Figure 48. SNR/MP/EL Results of flight 2

- **Comparison of up antenna and down antenna in Static mode**



(Red line presents up antenna, green line presents down antenna)

Figure 49. Comparison results of flight 2

- **Summary of the processing results of reflected signal in different position**

	Sat-Vis (n)	SNR (dbHZ)	RMS (U-D m)	STD (U-D m)
Pos 1	4	10-30	27.5535	22.355
Pos 2	6	15-30	9.5727	6.9691

Table 11. Statistics Results of flight 2

From the satellite visible image it can be seen that in pos1 the reflective receiver received only 4 satellites with relatively strong signals, but 6 satellite signals were in pos2. From the signal-to-noise ratio image, it is apparent that as the receiver moves away from the UAV, the noise in the received signals is significantly reduced. In pos1, the average error in the positioning of the reflected signals is about 22m, while in pos2 the average error is reduced to 6.9m, and the average error of the direct signals is also greatly reduced.

- **Conclusion**

By comparing the positioning results of these two flights, it is shown that the changing of the position of the reflective receiver does reduce the interference problem, but the accuracy of the final processing remains at the meter level, which still needs to be optimized.

Chapter 5. Optimization of subsequent tests

In the previous chapter, all the experimental procedures were described and recorded, the signal data obtained from the tests were processed and analyzed, two main conclusions were drawn that the first is the accuracy of the GNSS-R system on the gravel ground is better than that on the grass, and the other one is a certain degree of interference can be reduced when the GNSS-R receiver is far away from the main body of the UAV.

Obviously, these conclusions need to be further verified and optimized by more experiments, because the final processing results of the reflector antenna in GNSS-R did not obtain a high degree of accuracy, and there was still more noise in the received satellite signals. However, time constraints do not allow for more tests and analyses, so this chapter will contain the design and recommendations for follow-up experiments, starting with UAV component installation and RTKPOST configuration respectively. Hoping that through these optimizations, the interference of the UAV on the GNSS-R can be minimized, the error of the collected satellite signals can be reduced, and the effect of different ground surfaces on the positioning accuracy of the GNSS-R can be further verified, making the final conclusions more reliable and valid.

5.1 UAV Installation

In all the test results in Chapter 4 it can be seen that the reflector antennas did not perform well enough, and after the test comparisons it was found that the biggest reason for this comes from the interference to the GNSS-R system when the UAV is operating, so the main purpose of this subsection is to put forward some suggestions for the integration of the GNSS-R and the UAV, as a way of improving the performance of the UAS, at the same time to minimize the problem of interference, to improve the quality of the signals in the communication, and to optimize the final positioning accuracy, only when the interference problem is minimized, the conclusions drawn from the study of other issues will be more reliable.

5.1.1 Interference Issue

Firstly, the main causes of interference caused by UAV to GNSS-R system are briefly analyzed below:

a. **Signal interference by the drone**

As the figure below shows, the electronic equipment and communication systems already on board the UAV generate different sources of radiation. The radio modem used for telemetry, camera, and other components exposes the GNSS-R system to electromagnetic compatibility issues, thus reducing the overall performance of the receiver[11].

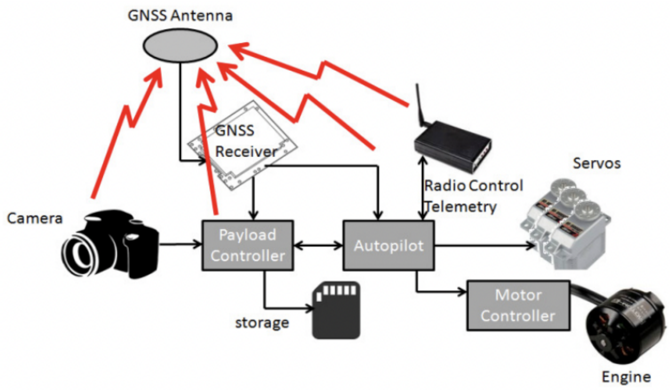


Figure 50. Interference from UAS

b. Obstruction interference from drone

The space of the UAV used in the test is limited, so both the receiver and the antenna in GNSS-R are too close to the electronic system on the UAV, especially when the UAV takes off, the rapidly rotating propellers physically block the whole GNSS-R, which all contribute to the degradation of signal strength.

5.1.2 Component Modification Recommendations

Combining the above analysis of the interference problem and the shortcomings of the UAV used in the project, I give these recommendations for the follow-up test:

- **Replacement of drones**

If conditions allow, it would be a good idea to replace the drone with a new one, the current one is overpay loaded with components installed in other projects such as the IMU and the camera, resulting in a limited flight time (only 5 minutes), which greatly reduces the amount of time to receive signals.

In the next step of the project, the main purpose is to test the effect of different surface types on the accuracy of the position, so the UAV only needs to be equipped with basic parts, such as engine, radio controller, etc., which reduces the UAV's own payload, and gives more payload to the GNSS-R system, as well as the space for the installation.

The selected drone should preferably have a light payload of its own, be able to guarantee a flight time of 15-20 minutes, and have a relatively large payload area for the installation of the GNSS-R system.

- **Installation of filters**

Filters can be installed on the UAV. Filters can suppress or pass signals in a specific frequency range, by selecting a specific filter, filter out the drone's own interference signals, thereby reducing the impact on the GNSS-R receiver. However, the characteristics of the UAV accessories in the experiment need to be considered, otherwise the GNSS-R receiver may not be able to receive the signal.

- **Adding masks to drones**

Shielding materials can be used around the UAV's remote controller, communication module, etc., such as using tinfoil to create a shield to reduce the electromagnetic radiation it produces.

- **Assembly**

When assembling GNSS-R and UAVs, it is necessary to arrange the antenna position and attitude to reduce the blocking and interference of GNSS signals by the UAV propeller.

- **Selection of test site**

Try to choose an open and flat location with fewer obstructions, so as to minimize the physical obstructions to the GNSS signal. This is because, as was also found in Chapter 4, when the test surfaces were all grass, the accuracy of the solved positioning differed more because of the different locations of the tests, due to the different surrounding built environments.

5.2 RTKPOST Configuration

RTKPOST as a post-processing software can be used to minimize the errors of satellite signals through different file configurations and option settings. In the previous experiment, only used the base station as a reference station, in the following tests the signal processing can be optimized in the following ways, to remove more errors and to achieve a more accurate and less dispersive positioning solution.

5.2.1 File Configurations

In addition to being loaded with a navigation file, a precision ephemeris file, RTKPOST allows to add another file more.

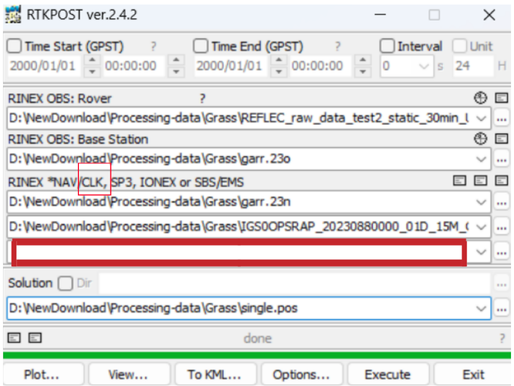


Figure 51. File configuration interface in rtkpost

- **Clock products**

In the next data processing, a new clock correction file can be added to the file configuration. The atomic clock in GNSS satellites is a high-precision clock device, but the oscillation frequency of the atomic clock may change slightly in the process of long-time use, and a small error in the satellite clock will lead to a significant error in the position calculated by the receiver, so in order to compensate for the clock error, accurate satellite clock information can be downloaded, and the clock correction file contains the clock bias parameter of each satellite, which corrects the time delay in the propagation of the satellite signal.

5.2.2 Option Settings

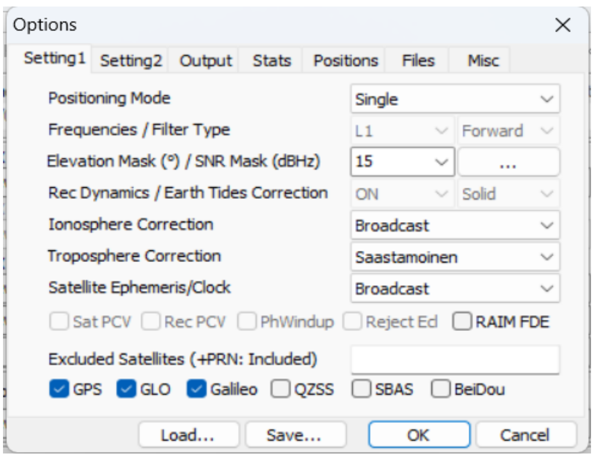


Figure 52. Configuration interface in rtkpost

- **Adjusting the Elevation Mask**

When there are more obstructions such as buildings in the test environment, the elevation angle can be appropriately adjusted to filter out satellites with lower elevation angles.

- **Adjusting the SNR Mask**

Adjust the appropriate SNRmask, when the SNRmask is too low, many weaker satellite signals will be involved in the calculation, which will reduce the overall positioning accuracy, after the SNRmask is increased, only the satellites with higher signal strength will be involved in the calculation, which will increase the stability and accuracy of the final calculation results.

- **Trying out different tropospheric models/ionospheric models**

The ionosphere, the layer of the atmosphere between 50 and 1,000 kilometers above the Earth, contains charged particles that can alter the transmission time of satellite signals and can lead to substantial errors in satellite positions.

The troposphere is the layer of the atmosphere closest to the Earth's surface, changes in humidity, temperature, and atmospheric pressure can cause tropospheric delays.

The tropospheric model/ionospheric model can play a role in correcting these errors. In the next experiments, it is possible to try to use different tropospheric models/ionospheric models to observe the difference in convergence effect, stability, and accuracy, to select the most suitable model and minimize the errors.

Chapter 6. Conclusions

6.1 Main results of work

During the completion of this master thesis, in the early stage, I read some literature related to the integration of GNSS-R technology with UAVs and distilled vital information from them, such as the types of UAVs, what payloads on UAVs, and the specific applications of GNSS-R. After having some understanding of the technical background, I started to learn how to process the data files with RTKPOST, including how to download the navigation files from the website and understand the features of the different processing modes, then I started to learn how to analyze the processing results of the signals, and to know how to analyze the different parameters and concepts in RTKPOST, such as the ionosphere-troposphere, the pseudorange processing modes, and so on.

Before the start of the test, with the help of professors, the UAV and GNSS-R were assembled, and then a series of different tests were carried out, which were the verification test in the first stage, the static test in the middle stage, and the flight test in the last stage. Through the analysis of the results of each test, the test plan is continuously adjusted to optimize the positioning accuracy of the GNSS-R. Important conclusions were obtained in each of these three different periods of experimentation:

- Verification experiment: UAV operation, especially after take-off, can cause severe interference with GNSS-R systems.
- Stationary experiment: when the UAV is stationary on the tripod, it can be found that the GNSS-R system obtains superior positioning accuracy on stone surfaces than on grass surfaces.
- Flight test: When the receiver is placed in a part far away from the airframe, it can reduce some of the interference and improve the positioning accuracy.

6.2 Lacks and Difficulties in the Work

Although the interference of the UAV was greatly reduced in the final flight test, with the error reduced from more than 50 meters in the first flight test to 6 meters, the error of 6 meters still cannot meet the positioning requirements in many applications, which indicates that the components of the whole UAV system, as well as the processing settings in the RTKPOST, still need to be improved in order to achieve the ideal processing accuracy.

Although the static tests concluded that the processing accuracy on the gravel ground is superior to that on the grass, I think this conclusion lacks some reliability and persuasiveness. Because firstly the whole UAS has an interference problem, which leads to the error of the positioning results both on the grass and on the gravel ground on the level of meters, and the other reason is that I think that the location of the tests also affects the results, because the surrounding building environments are different, which can also have an impact on the signal quality. This means that more tests are needed to give a more accurate and reliable conclusion.

Another difficulty during the project was the limitation of the experimental site. Due to the regulatory safety issues of UAVs, flight experiments on campus can only be conducted in dronelab, which apparently has only one type of land surface, which also limits the design of flight tests.

6.3 Personal summaries

In this project I learned a lot about GNSS, understood some of its basic principles, deepened my understanding of UAV applications especially when GNSS-R and UAVs work together, and of course increased my own experience with experimental design and implementation.

On the other hand, I also realized some of my own shortcomings, not having enough professional knowledge leading to poor consideration of the experimental design, which could have been designed with a more complete experimental plan by considering the interference problem of UAVs on GNSS-R at the beginning and the effect of the UAV placement method on the quality of the received signals.

6.4 Future work and improvements

6.4.1 Recommendations for proposals

- Try to replace the drone with a new one, reassemble the GNSS-R system, and compare the results with the old drone's processing to see if the interference problem has been mitigated.
- Try different parameter settings and file configurations in RTKPOST. For instance, add a clock differential file to RTKPOST and analyse the same test to see if the error decreases. It is also possible to compare whether different ionosphere/ troposphere models affect the accuracy.

- After ensuring that the GNSS-R can achieve decimetre or centimetre level positioning accuracy when the UAV is stationary, the UAV can be flown over different land surfaces to compare whether there is a difference in positioning accuracy, such as water, sand, and gravel, and pay attention to controlling a single variable when designing the tests, so that other factors do not interfere with the final conclusion when analysing the results.

6.4.2 Possible problems encountered

- After replacing the drone with a new one and the interference problem still does not reduce, you can take some other installation options, such as adding filters, adding interference prevention screen shield to the key electronic components of the drone, and debugging the signal frequency.
- If drone lab is unable to fulfil the needs of the test site, it is necessary to make a reservation in advance for other compliant sites to provide more possibilities for the work.

6.5 Sustainable Development

When the problem of UAV interference with GNSS-R is greatly mitigated, the receiver will receive signals with less noise and fewer errors, and will end up with more accurate solutions. And this would provide a good basis for GNSS-R equipped drones to carry out different experiments.

When GNSS-R receives reflected signals from different land surfaces, the signals are affected by refraction, humidity, temperature, etc., and this property can be applied in various fields:

- First of all, it is possible to measure a certain characteristic of a single matter. For instance, the humidity of the soil, the thickness of the snow, the metamorphosis of the coastline, etc.
- On the other hand, it can be used in practical applications to provide better positioning accuracy on specific surfaces, such as in the construction field.
- Moreover, it can also help people in uninhabited areas to conduct geomorphological surveys and rescue activities. In addition to the normal function of acquiring photos, it can be used to hypothesize the characteristics of that surface type based on the different accuracies of the acquired signals.

ACRONYMS

UAV --- Unmanned Aerial Vehicle

GNSS --- Global Navigation Satellite System

GNSS-R --- Global Navigation Satellite System Reflectometry

RTK --- Real-Time Kinematic

PPP --- Precise Point Positioning

DGPS --- Differential Global Positioning System

SNR --- Signal to Noise Ratio

STD --- Standard Deviation

RMS --- Root Mean Square

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