# APPLICATION OF SMALL UNMANNED AERIAL SYSTEMS FOR MONITORING CYLINDRICAL BUILDINGS

A Thesis

by

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ABSTRACT

Inspection of cracks on the surface of tall structures including chimneys, towers, containment buildings, and other cylindrical shapes is executed by visual monitoring to some extent, for which skilled field crews often climb up the cylindrical structures and special equipment such as cranes are used, preventing frequent monitoring and being in many cases a time consuming, expensive and dangerous practice.

Small Unmanned Aerial Systems (SUAS) may be a solution for visual inspection and recognition of cracks on the surface of structures in comparison with traditional methods, taking into consideration their use in other non-military fields such as agriculture, engineering and construction.

These devices can be controlled manually or autonomously with computer applications. Manual control has some challenges related to the necessity of flying the SUAS very close to the structure and maintaining their line of sight, and for that reason, autonomous missions may be a convenient option in order to use those devices for the inspection and recognition of cracks in structures.

This work assesses the possibility of using autonomous missions in SUAS for the visual inspection of cylindrical structures. A series of computer applications were developed in order to control the SUAS and their flight around a simple cylindrical building while taking pictures. This study also tests the applications to see if they are working properly with a certain level of tolerance.

This research gives a clear idea as to how accurately one can autonomously control the position of SUAS for cylindrical structures' monitoring, which will be used to develop more sophisticated applications in the future.

# DEDICATION

This work is dedicated to my parents, family and friends for their never ending support and motivation during every step in my life. Thanks for everything!!!

# ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Kang, who introduced me to the visualization technology world in construction, and my committee members, Dr. Lavy and Dr. Clayton, for their guidance and support in the development of this research.

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## NOMENCLATURE AND DEFINITIONS

| | |
|---|---|
| App | Application program |
| Drone | An aircraft that can be operated remotely by a control |
| DX | Horizontal distance between the center of the taken photos and the center of coordinates in the autonomous mission |
| GPS | Global Positioning System |
| Open source code | Code that can be modified because its design is accessible by the public |
| RPA | Remotely Piloted Aircraft |
| RPV | Remotely Piloted Vehicles |
| SUAS | Small Unmanned Aerial Systems |
| Telemetry | Measurement and transmission of data by wire, radio, and other remote sources |
| UAS | Unmanned Aerial Systems |
| UAV | Unmanned Aerial Vehicles |
| Waypoints | Coordinates that define a point in space |

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# 1. INTRODUCTION

## *1.1. Inspection of cylindrical buildings and safety in construction*

Currently, it is common to find structures with a cylindrical shape in chimneys and towers, nuclear containment buildings, and water tanks, which require the use of specialized crews and devices in order to monitor cracks and other pathologies in their surface.

Diameters between 15 m to 36 m and heights with more than 10 m can be found in water tanks (Caldwell 2016), diameters between 6 m to 92 m with heights between 6 m to 18 m are usual in oil storage tanks (Petrowiki 2013), and containment buildings in nuclear plants may have more than 50 m in diameter and 70 m in height (Dubai Media Incorporated 2016).

In order to assure safety in those structures it is necessary to perform periodical assessments which can be defined by the state or country regulations, and an example of it is the inspection required in Korea's nuclear plants according to the Government Ministry of Science and Technology (Park and Hong 2009). However, in traditional methods personnel work at heights using different equipment such as cranes, etc. preventing frequent inspections because they are time consuming, expensive, and accident prone.

### *1.1.1. Safety*

According to a report provided by the Occupational Safety and Health Administration (OSHA) in 2005, in that time 6.5 million people worked on any given day, in nearly 252,000 construction sites across U.S. The fatal injury rate in this industry was higher than the national average for all industries and some potential hazards for employees were associated with falls from heights, scaffolding collapse, ladder, stairway and crane related fatalities (Occupational Safety and Health Administration 2005).

Falls from heights are related to the large number of fatalities in the construction field and some of their causes include unstable working surfaces, human error and failure to use protection equipment.

In the case of scaffolding, falls occur when those systems are not assembled or used inadequately, causing an estimate of 4,500 injuries and 50 fatalities per year.

Falls from stairways and ladders are the cause of approximately 24,882 injuries and 36 fatalities per year.

Cranes can be the cause of different accidents when they are not inspected properly or during their use and some examples are workers caught within the crane's swing radius, crane's contact with a power line or struck worker by an overload.

The largest proportion of fatal falls is associated with young workers especially during the first month of employment and aging workers who tend to lose mental and physical capacities for their work (Lin et al. 2011).

### *1.2. Problem*

Use of SUAS to monitor possible pathologies in cylindrical buildings represent an opportunity to improve safety for workers and reduce time, cost and planning in the inspections. Nevertheless, the use of those devices also represents a challenge because the limitations in the pilot's visibility and battery lifetime may not be convenient for their safe utilization in manually flights (Kang et al 2015).

Autonomous flights using computer applications may be another option to carry out this kind of work with SUAS, however, some of the apps require an internet connection to download the site's map for the mission, manual definition of the task waypoints, user knowledge about most adequate path for the work, and awareness about the camera focus point for the mission. These issues can give a wrong idea about the advantages of using autonomous missions in SUAS for the inspection of cylindrical structures.

Taking in consideration all that, this study was performed to assist and evaluate the use of autonomous flights in SUAS for monitoring cylindrical buildings represented by containment buildings, water tanks, silos and other structures.

### *1.3. Research questions*

- Is it possible to use open source code platforms to develop applications for autonomous flights in SUAS which can have better performance than commercial apps in particular works such as cylindrical buildings scanning?
- Are the developed applications stable and accurate to plan missions in cylindrical buildings? And if they are, what is the accuracy between the planned and actual path in the drone?

### *1.4. Research objectives*

- To develop two mobile applications for SUAS autonomous flights with different characteristics in an open source platform to promote some solutions to current limitations in existing commercial applications.

- To test the created mobile applications and their accuracy in the planned and actual SUAS path in order to avoid any malfunctions before sending the waypoints around cylindrical buildings.

### *1.5. Organization of the thesis*

Chapter 2 provides a literature review about the current state of drones and SUAS in different fields, UAV models, applications for autonomous flights and accuracy related to GPS. Chapter 3 presents the methodology and experiments' design in order to accomplish the goal and objectives of this thesis.

In chapter 4, the results of this study are shown and discussed. The summary, conclusions and recommendations for future work are mentioned in chapter 5.

# 2. LITERATURE REVIEW

## *2.1. Difference among UAS, UAV, and drones*

Unmanned Aerial or aircraft systems include all the technology to control Unmanned Aerial Vehicles (UAVs). Drones refer to UAVs which are programmed remotely for the development of a mission (Lone Star UAS Center of Excellence & Innovation 2016).

## *2.2. UAS evolution*

The development of UAS started in the military field in the early 1900s and some of their examples are the Queen Bee drone of 1933 that was implemented by the Royal Navy for gunnery practice and the US Air Force Firebees used in different missions in the Vietnam War and by Israel in the October War in the 70's. With the advancement of navigation systems, radio-controlled platforms, high resolution imagery, mobile devices and other technologies allowed using UAS in another non-military context. The increment in their utilization and popularity can be observed in the internet trends, wherein 2013 the word drone was searched 10 times more than in 2005, and in conferences like the quadrennial International Society for Photogrammetry and Remote Sensing (ISPRS) congress of 2004 in which sessions did not cover subject of UAS in comparison with the 2012 ISPRS congress where nine sessions and 50 papers were related to them (Colomina and Molina 2014).

Some values related to the evolution of UAS are shown in a report by Blyenburgh & Co. where it is possible to observe the increment in models and patents, producers, and utilization of UAS in civil and commercial purposes between 2005 and 2013. The same publication provides other important information such as the decrement of UAS military initiatives from 2009 to 2013 and it is illustrated in Figure 1 (Blyenburgh & Co. 2013).

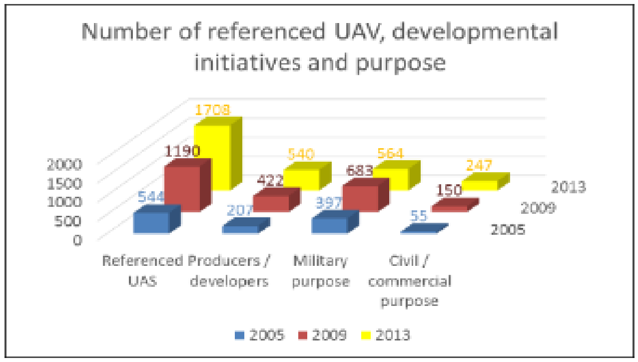



**Figure 1 Number of referenced UAS, developmental initiatives, and purposes (Blyenburgh & Co. 2013)**

According to the Mary Meeker's annual Internet trends report for 2015 (Kleiner Perkins Caufield & Byers 2015), the drone market size this year has an expected value of $1.7 billion and it is distributed in different countries as it is mentioned in Figure 2.

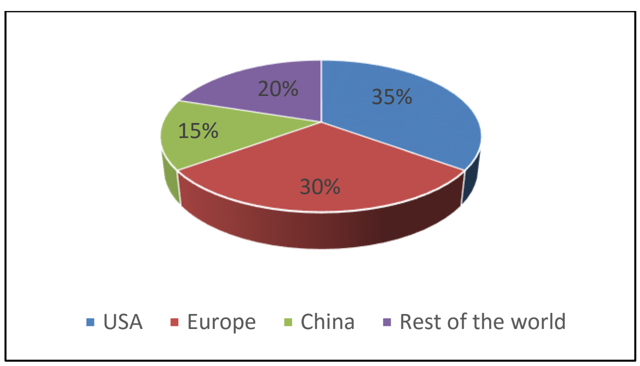



**Figure 2 Global consumer drones – Revenue by region, 2014 (Kleiner Perkins Caufield & Byers 2015)**

Taking into consideration the importance that UAS are getting right now and in the future, the U.S. Federal government has authorized to some universities to fly drones in U.S. airspace, including Georgia Tech (Grayson 2014) which is carrying out research in topics related to construction and monitoring.

### *2.3. Example of non-military applications of UAS*

Unmanned Aerial Systems (UAS), Remotely Piloted Vehicles (RPV), Remotely Piloted Aircraft (RPA), Unmanned Aerial Vehicles (UAV) or drones have been traditionally used in military operations. In recent years, researchers have been utilizing UAS in a non-military context taking advantage of their low cost, fast speed, maneuverability, and safety to complement or replace satellites and manned vehicles to gather information. Some of the main application fields of UAS include the forestry and agricultural fields, emergency and disaster management, traffic surveillance and management, photogrammetry for 3D modeling, remote-sensing based inspection systems, and many other subjects. However, there is a lack of research in the literature about the employment of UAS in civil engineering applications (Siebert and Teizer 2014).

#### *2.3.1. Structures inspection*

In a research done by Metni and Hamel (Metni and Hamel 2007) it can be observed how UAS can be used for periodic visual inspections of bridges and how it can represent advantages against traditional procedures in work accident risk reduction, budget savings related to less logistics and working hours, the elimination of traffic interruption processes, and the possibility of using nondestructive techniques such as infrared inspection for crack detection. They obtained images with good resolution in which cracks of 1/10 mm can be detected.

Morgenthal and Hallermann (Morgenthal and Hallermann 2014) see the drones as elements with the potential to develop visual inspection of chimneys, towers, and other structures, where cracks can be found in considerable heights. Usually, those inspections are demanding and expensive because they may require the use of scaffoldings and specialized crews and equipment, which can produce a lot of disturbances and endanger the workers' lives. This can be done relatively easy, fast and economic with UAS, however, the data acquisition quality depends on different factors such as the camera characteristics, environmental conditions, and object properties being analyzed.

#### *2.3.2. Geology*

In a study developed by Niethammer et al., a drone is equipped with a digital compact camera to track a landslide quickly with a high resolution, which provides some advantages in comparison with other artifacts such as motorized paragliders, blimps and balloons which can be highly affected by wind or can be hardly used in mountainous areas (Niethammer et al. 2012). The results show that fissures of approximately 0.1 meters can be identified with UAS, which cannot be easily obtained with satellites and other manned airborne systems. Also, soil moisture changes and landslide displacement can be measured with regular image acquisition and drone surveys. However, there are some disadvantages in the work carried out related to errors in the imagery provoked by small trees, bushes and restrictions in radio bandwidth for ground communication and unpredictable conditions that require a good UAS pilot to work the mission manually.

### *2.3.3. Roads and infrastructure inspection*

Ruzgiene et al. (Ruzgiene et al. 2015) carried out an investigation to demonstrate the capability and efficiency of a UAV with respect to the quality of the information obtained and its cost. The workflow for image acquisition in that research is the following: definition of the project, flight planning, independent photogrammetric flight mission and data quality reviewing. The research concludes that drones in conjunction with photogrammetry provide low cost, small area, fast data to be used in image processing of high quality. According to this work, the cost of analyzing an area of 50-100 ha can vary from 800 to 3400 €, depending on the height to take the images. That gives some options to their users about what quality is more affordable considering their necessities.

Máthé and Busoniu (Máthé and Busoniu 2015) mentioned different survey vision and control methods that can be applied to UAVs such as quadrotors in order to inspect railways, taking in consideration their low-cost and small size which reduces the probability of damaging a train in case of an inevitable collision. This work was divided into two cases, one for the close inspection of railway infrastructure such as bridges, and other for recording the tracks, sleepers, points, and/or cabling. According to their results, they found a lot of challenges in the current vision techniques for object classification and for obstacle avoidance in quadcopters.

## *2.4. Multirotor as a SUAS*

### *2.4.1. Fixed wings vs. Multirotors*

There are different models of UAS and some of the most important are Fixed Wings and Multirotors. The first ones are mainly used for aerial mapping and large areas covering such as mines sites, stockpiles and topographical surveys; the second ones can be used for detail inspection in hard-to-reach places such as towers, bridges, and other structures because they have a propeller-based system which gives the possibility to fly in any direction, vertical or horizontal (SUAS News 2013).

Other characteristics for Fixed Wings include high speeds, object resolution of cm or inch per pixel, large landing area, high flight time and wind resistance; while Multirotors may have a low speed, object resolution of mm per pixel, small landing area, low flight time and wind resistance (Sensefly 2015).

### *2.4.2. Automatic control of Multirotors*

Some typical components of a fully assembled UAV include flight controllers with different sensors (gyroscope, barometer, and accelerometer), GPS Module, Radio Control (RC) receiver, motors, propellers, speed controllers, and batteries. Sometimes a camera can be attached to a system which includes a gimbal controller with roll and tilt motors (Liu et al 2014).

The system is complemented with a Radio Control (RC) transmitter and a Ground Control Station (GCS) software which gives the possibility to the monitor vehicle telemetry and carries out mission planning activities (ArduPilot Dev Team 2016). It can be seen in Figure 3.


**Figure 3 Multicopter UAS (ArduPilot Dev Team 2016)**

### *2.5. Current commercial apps for autonomous flights in UAS*

Coordinates for the flight can be sent from the GCS to the UAV via wireless telemetry (which uses radio frequencies in different bands such as FM, Wi-fi or microwave) in order to control the UAV autonomous flight and it is achieved with the waypoint GPS Navigation technology in the drone flight controller (Dronzon 2014).

Some drone manufacturers are enabling the use of applications for autonomous flights and some examples are:

#### *2.5.1. ArduPilot and 3DRobotics drones*

Tower (Figure 4), Mission Planner (Figure 5), APM Planner 2 (Figure 6), MAVProxy, DroidPlanner, DroidPlanner 2, AndroPilot, MAVPilot, iDroneCtrl and QGroundControl (Ardupilot 2015).

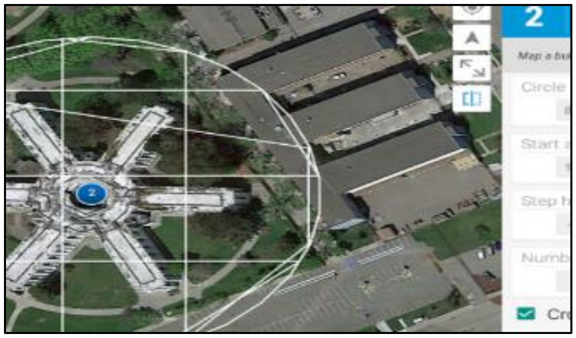



**Figure 4 Tower (Ardupilot 2015)**

**Figure 5 Mission Planner (Ardupilot 2015)**

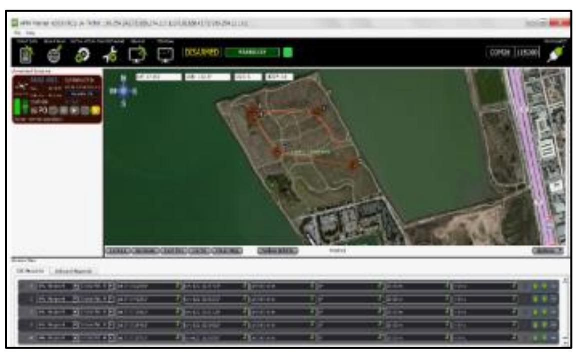


**Figure 6 APM Planner 2 (Ardupilot 2015)**

Some of the flight missions that can be done with these apps are the following:

- Tower: waypoints (Points of interest), Set Yaw (The drone rotates according to the given angle), Land, Takeoff, spline waypoints (smooth curves in the points of interest), Circle waypoints (to orbit an object with the camera pointed at it), Region of Interest points (camera centered on an object regardless of flight path), Survey (flight pattern needed to cover a region of the map is automatically generated), Structure scanner (automated 3D scans of large structures), follow me (camera centered on the user while the drone follows his movement), and Dronie function (the drone flies back and away from subject) (3D Robotics 2015a) .

- Mission planner: waypoints (Points of interest), Set Yaw (The drone rotates according to the given angle), Land, Takeoff, Region of Interest points, Circle, Survey, Area (Displays the area of the current polygon), SimpleGrid (simple auto-made survey grid without camera control) (Ardupilot 2015)

### *2.5.2. Bebop parrot drones*

Fight plan (Parrot 2015). Some of the functions that can be developed with this app are related to waypoints (Points of interest), Set Yaw (The drone rotates according to the given angle), Land, Takeoff, hover, and camera angle.

### *2.5.3. DJI drones*

iPad Ground Station and PC Ground Station have functions related to waypoints, Point of interest and follow me (DroneZon 2015).

## *2.6. Open source code in UAS*

Drone manufacturers such as 3DRobotics are offering in their devices the possibility to work on an open source platform to encourage innovation and to allow developers to create new computer applications or to improve some of the existing ones to have a better product (3D Robotics 2015b). According to the developer skill and knowledge, the app can be created in distinct computer platforms including Android, Python, or iOS soon (3D Robotics 2015c) and they are explained in the following paragraphs:

### *2.6.1. Android*

Android is an operating system for different smartphones and tablets owned by Google which comes in different versions (Bolton 2011).

Some of the languages for developing programs in this operating system are Java, C#, C++, and HTML5; however, Java is the traditional language for Android (Belova 2015).

### *2.6.2. Python*

Python is a programming language well recognized by its interpreted, interactive and object-oriented characteristics. It can be run on Unix variants, on the Mac, and on computers under MS-DOS, Windows, and OS/2 (Python Software Foundation 2016).

### *2.6.3. iOS*

iOS is the Apple's operating system used to run the iPhone, iPad and iPod Touch devices (Nations 2015).

Swift is the programming language that at the moment is used for iOS and it builds taking the best characteristics of C and Objective-C programming languages (Apple Inc. 2016).

## 2.7. GPS specifications

Autonomous flights in UAS depends on the GPS characteristics. Table 1 has some values about the GPS tolerance for autonomous flights in different UAS models.

**Table 1 GPS horizontal accuracy**

| Model | Manufacturer | Position horizontal accuracy |
|---|---|---|
| SOLO (3D Robotics 2015d) | 3D Robotics | < 5 m |
| Phantom 3 professional (Da-Jiang Innovations Science and Technology Co. 2015) | DJI | < 1.5 m |
| STORM Drone 6 V3 (HeliPal 2015) | HeliPal | < 2.5 m |

## 2.8. Horizontal accuracy in decimal degrees for Texas

Table 2 indicates the estimated levels of accuracy in decimal degrees for latitude and longitude that are possible according to the coordinates in Texas (Texas Commission on Environmental Quality 2013).

**Table 2 Horizontal accuracy in decimal degrees for Texas (Texas Commission on Environmental Quality 2013)**

| Latitude | | | Longitude | | |
|---|---|---|---|---|---|
| **Degree of latitude** | **Degrees** | **Meters** | **Degree of longitude** | **Degrees** | **Meters** |
| 1 | 1 | 110,874.40 | 1 | 1 | 95,506 |
| 1/10 | 0.1 | 11,087.44 | 1/10 | 0.1 | 9,550.6 |
| 1/100 | 0.01 | 1,108.74 | 1/100 | 0.01 | 955.06 |
| 1/1000 | 0.001 | 110.87 | 1/1000 | 0.001 | 95.506 |
| 1/10000 | 0.0001 | 11.09 | 1/10000 | 0.0001 | 9.551 |
| 1/100000 | 0.00001 | 1.11 | 1/100000 | 0.00001 | 0.955 |
| 1/1000000 | 0.000001 | 0.11 | 1/1000000 | 0.000001 | 0.096 |

# 3. METHODOLOGY

This experimental study was done to analyze the possibility of using SUAS for cylindrical structures monitoring such as chimneys, towers, containment buildings and others which may require a lot of planning, crews, and equipment to be scanned with traditional methods.

An adequate method to do it is using autonomous missions that are restricted to the characteristics of the commercial app used to define the flight path.

For that reason, it was necessary to take advantage of some open code platforms and to develop another program that can be customized according to the user necessities, evaluating also its accuracy and the difference between the planned and actual path in the work performed.

The following were the steps defined in order to perform the experiments:

- Development of mobile applications with different characteristics and modes of flight.
- Apps' validation in different mobile devices and verification of the missions sent to the UAV.
- Flights conducted according to the established missions and around a point of reference in order to estimate the accuracy between the planned and actual path.

Subchapters 3.1 to 3.3 describe each of the mentioned points for this research in detail.

*3.1.* *Apps development*

In this study, three apps were developed for 3DRobotics SUAS which use Pixhawk as autopilot taking in consideration that these devices work in an open source code platform.

The codes were developed in Android taking in consideration that a big quantity of smartphones and tablets of different brands such as Nexus, Samsung, Huawei, HTC, Sony, LG and many others are based on that platform. The software to write the code was Android Studio 1.2 (Creative Commons Attribution 2.5. 2016) and Figure 7 can be seen how it is started.

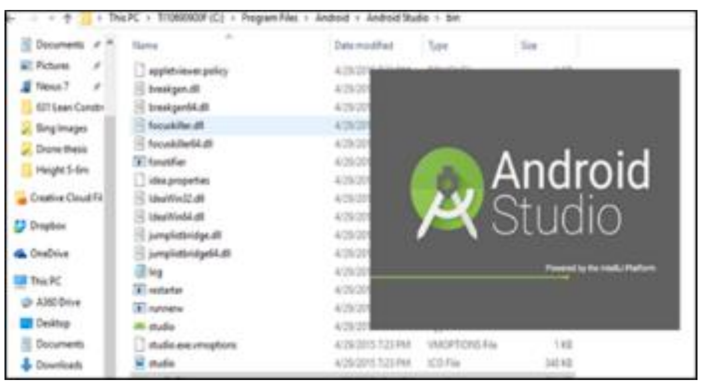



**Figure 7 Android Studio 1.2 starting**

The apps' input data can be defined by the user, however, these ones worked with coordinates, radius, height, height step and a number of turns to configure the path. When these parameters are selected the user pushes a button in the app and the information is sent to the drone with USB and radio adapters (3D Robotics 2015e).

*3.2. Mode of flight*

- Application 1: The drone flies around a point starting with an initial height and after that in equal intervals according to the number of steps defined (As it is indicated in Figure 8).

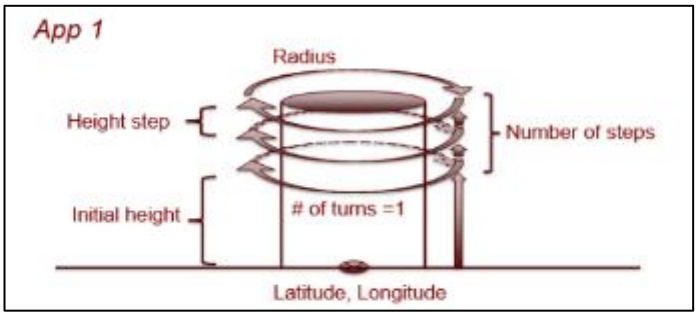



**Figure 8 Path proposed application 1**

- Application 2: The drone flies around a point with constant radius until reaching a determined height, after that the radius changes at a constant rate until the structure's maximum height is reached (As it is indicated in Figure 9).

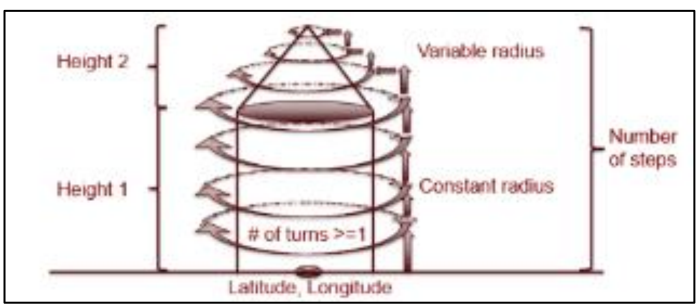



**Figure 9 Path proposed application 2**

The chosen paths can be implemented in cylindrical structures such as towers, silos, chimneys and containment buildings, and if it is necessary to do some modifications in the path equation it can be done in the code directly.

UAS can focus the camera on the path that it is following (Option 1 Figure 10) or at a point that is external to its path (Option 2 Figure 10). For the developed apps, the drone has the instruction to focus an external point to the path which is the coordinates' center in the structure to be scanned that is represented in the Option 2 in Figure 10

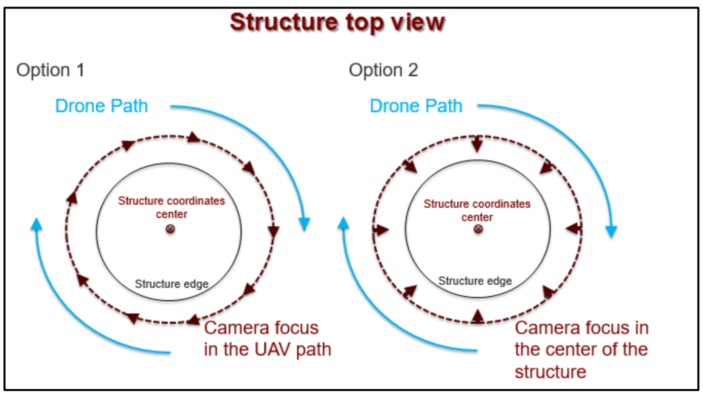



**Figure 10 Camera focus options during the UAS flights**

### *3.3. Flight tests and accuracy*

The apps were tested in an exterior open space in order to count with a non-congested and wide-open airspace aiming to avoid risks of accidents, which may be feasible in a place close to buildings.

The SUAS flew around a pole of approximately 6 meters that has the characteristic of assembling and mobility and the range for the height in the device path varied from 2 m to 12 m.

Figure 11 .A. to .F. demonstrates some images of the pole used for developing the missions.


**Figure 11 (A) Mobile pole's main foundation. (B) Extra weights for the foundation. (C) Mobile pole's elements. (D) Mobile pole's elements joined. (E) Mobile pole's elements wrapped with a color tape of 1 meter each section. (F) Mobile pole's partial erection.**

The pole's coordinates were obtained with the app GPS Coordinates (Woozilli 2013) and before starting the mission a validation was done reading the mission coordinates graphically from the UAV with the app Droidplanner 2 (Benemann 2014). The icons for both applications can be seen in Figure 12 .A. and .B.

A B

**Figure 12 (A) GPS Coordinates app icon. (B) Droidplanner 2 app icon.**

After this, three different evaluations were done:

- Evaluation 1: App stability was checked in order to avoid any software malfunction or crashing when used.
- Evaluation 2: Accuracy between the planned and actual path was assessed collecting information from the SUAS-GPS telemetry about the path coordinates (X: Longitude, Y: Latitude, Z: Altitude) and orientation (Yaw angle and Pitch angle) approximately every second during the SUAS flight and it was drawn according to Figure 13 for different values of Z:

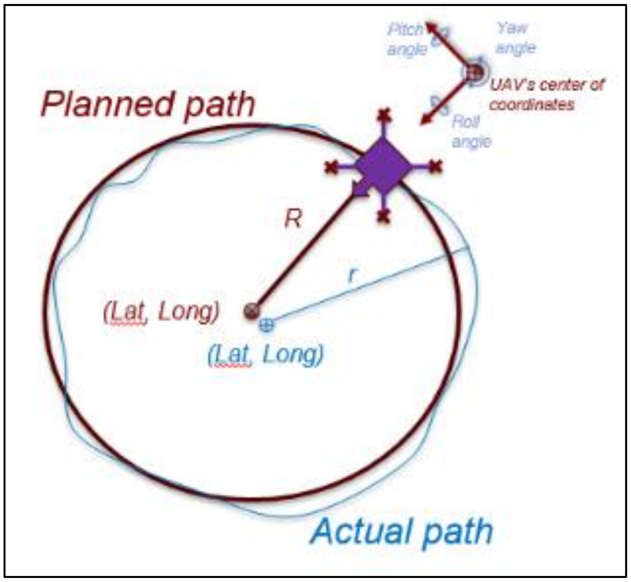



**Figure 13 Planned and actual path difference**

The actual path drawings allowed to obtain information about the actual radius (r), actual UAV's yaw angle, actual pitch angle and actual coordinates during the flight. This information was compared with the planned coordinates, planned radius (R), estimated yaw angle and planned pitch angle in order to estimate the following differences:

- Absolute Latitude difference= | Planned center structure Latitude - Actual center structure Latitude |

- Absolute Longitude difference = | Planned center structure Longitude - Actual center structure Longitude |

- Absolute Altitude difference= | Planned center structure Altitude - Actual center structure Altitude |

- Absolute Radius difference = | Planned radius (R) - Actual radius (r) |

- Absolute Yaw angle difference = | Estimated Yaw angle – Actual Yaw angle |

- Absolute Pitch angle difference = | Planned pitch angle – Actual pitch angle |

Each difference was measured to obtain a representative quantity of data in order to quantify averages, standard deviations, coefficients of variation and maximum and minimum values to give some conclusions about the UAV path in each mission.

- Evaluation 3: A camera was installed in the SUAS and pictures were taken during the flight each 0.5 to 2 seconds, according to the mission and camera characteristics. The number of photos in which the pole was not in the center of the images (Figure 14: Option B) was counted in order to estimate the number of images in which the drone did not focus the point of interest (Eq. percentage of wrong focus).

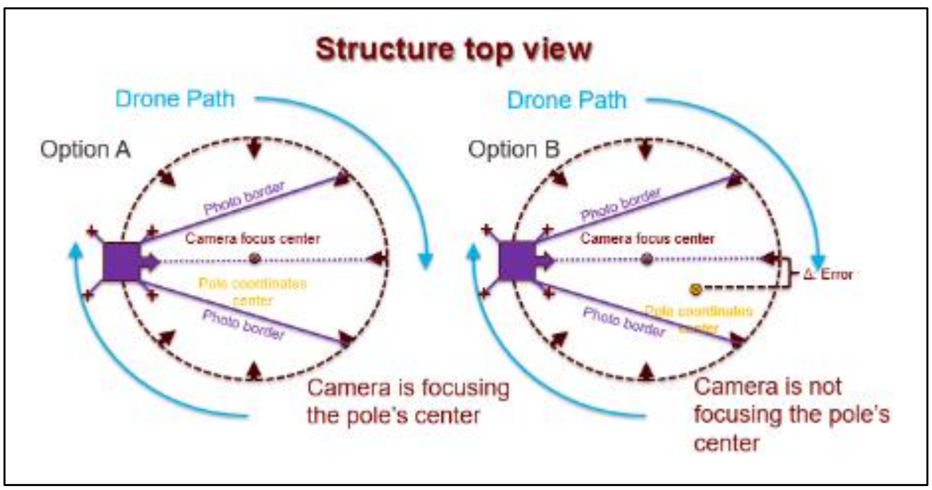



**Figure 14 Planned and actual path difference and errors**

$$Eq.\,\%\,wrong\ focus = \frac{\sum Option\ B\ photos}{\sum Option\ A\ photos + \sum Option\ B\ photos} \times 100\%$$

A significant number of images were also used to analyze the absolute radius difference and the horizontal distance between the center of the picture and the pole (DX) in order to verify and compare the results in the evaluation 2. It was done by applying the effect of the distance on photo scale in a similar manner as it is applied in photogrammetry (Fahsi 1998). Figure 15 illustrates how longer distances produce smaller scales, and how the approximated distance in which a photo was taken  can be found with triangle relationships and some known parameters.

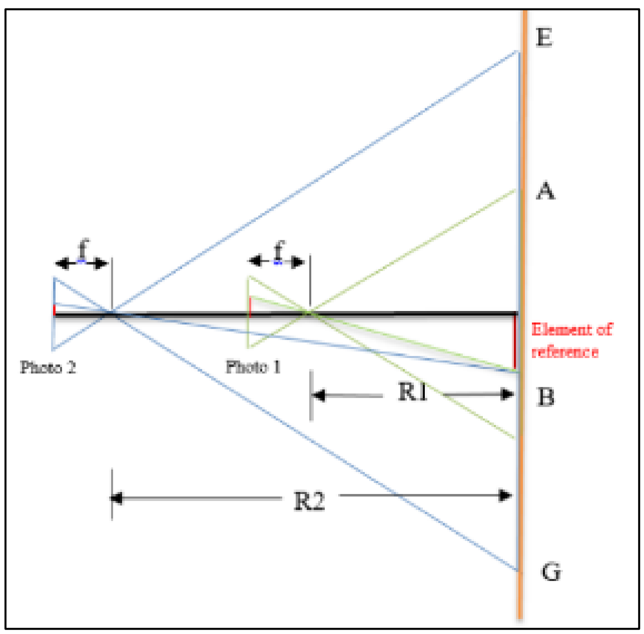



**Figure 15 Effect of distance on the photo scale and the image coverage**

According to Figure 15, if the distance (R1) and the frame height or the image coverage (AB) are known in a photo (calibration photo), the distance in another photo (R2) can be calculated if there is also information about its frame height or the image coverage (EG). It can be done with the following relation:

$$\frac{R1}{AB} = \frac{R2}{EG}$$

And this equation can be reorganized as: $R2 = \frac{R1 * EG}{AB}$

Using this equation, the approximated distance between the camera and the pole for the images was found according to their frame height or image coverage and the information from the calibration photos.

Another method to evaluate the flight path was proposed in which a laser would be installed in the center of the drone and pointing to the ground, in order to record the actual path and compare it with a line in the ground according to the planned path. However, this procedure was initially disregarded taking into account that vibrations in the drone or environmental conditions may deviate the laser and give a wrong idea about the real drone position.

# 4. RESULTS AND DISCUSSION

This chapter presents the created mobile applications and the data collection from the field evaluation. It is complemented with the analysis and discussion of the results.

## *4.1. Apps developed*

Three different mobile applications have been done and they require that the mobile device has the app 3DRServices-v1.2.19, updated 06-08-2015, in order to establish communication between the apps and the drone. The following is the apps' description.

### *4.1.1. Structure_Scan_Coordinates app*

The base to create this app was an existing one called "Hello Drone" and its code is available on the website of Dronekit by 3D Robotics (3D Robotics 2015f). This app was modified in with Android Studio 1.2 (Creative Commons Attribution 2.5. 2016) and it is exposed in Figure 7. In order to obtain a different layout and send the mission to the UAV according to the path mentioned in Figure 8. The following graphics display the design for the layout (Figure 16) and the code for the main activity of the app in Android Studio 1.2 (Figure 17).

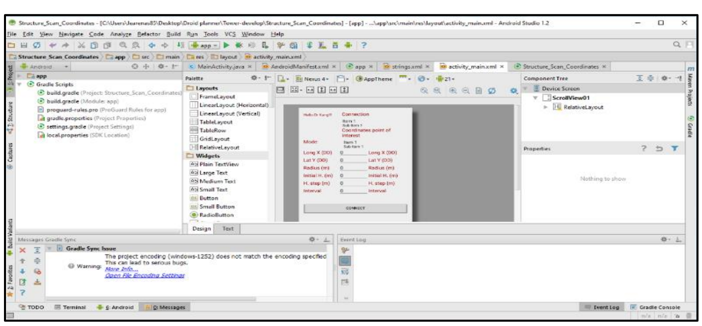


**Figure 16 Layout design of Structure_Scan_Coordinates app**

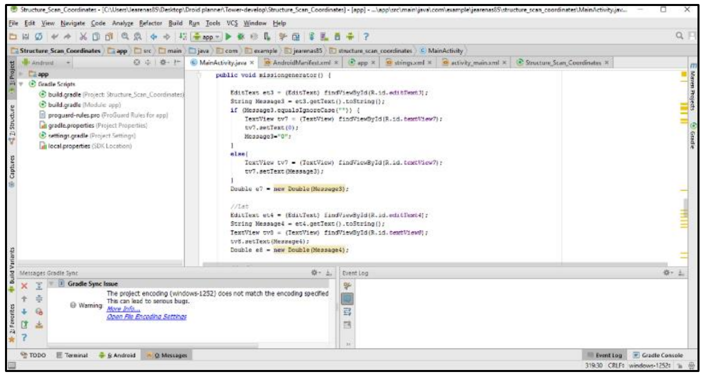


**Figure 17 Java code for the main activity in Structure_Scan_Coordinates app**

Table 3 demonstrates the fields and button that have been added to this app.

**Table 3 Fields for the Structure_Scan_Coordinates app**

| | |
|---|---|
| **Long X (DD)** | Field to input the longitude's coordinate in decimal degrees. |
| **Lat Y (DD)** | Field to input the latitude's coordinate in decimal degrees. |
| **Radius (m)** | Field to input the radius length in meters for each circumference. |
| **Initial H. (m)** | Field to input the initial height in meters in which the UAV will start the mission |
| **Interval** | Field to input the number of total vertical points or steps for the mission. |
| **H. step (m)** | Field to input the distance between two consecutive height steps. |
| **Connect – Disconnect button** | When the app and the UAV are disconnected, this button connects and sends the mission to the drone. When the app and the UAV are connected, this button disconnects and finishes with the communication. |

After the app was written modified, the final product in a mobile device such as a Nexus Tablet can be seen as it is shown in the following screenshots.

Figure 18 .A. displays the icon for this app, Figure 18 .B. illustrates the first layout for the app before entering the data and pushing the "Connect" button in order to send the mission to the UAV. Figure 19 .A. shows the connection with the UAV after pushing the

“Connect” button, Figure 19 .B. displays the moment when the mission is sent to the UAV which occurs after the connection with this device.

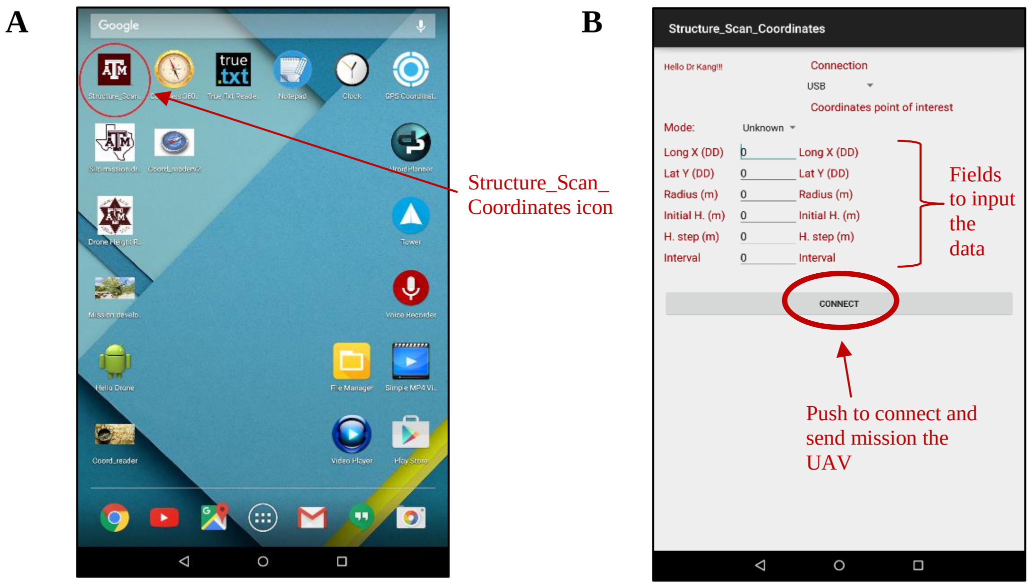



**Figure 18 (A) Structure_Scan_Coordinates app’s icon. (B) Structure_Scan_Coordinates app’s mobile layout.**

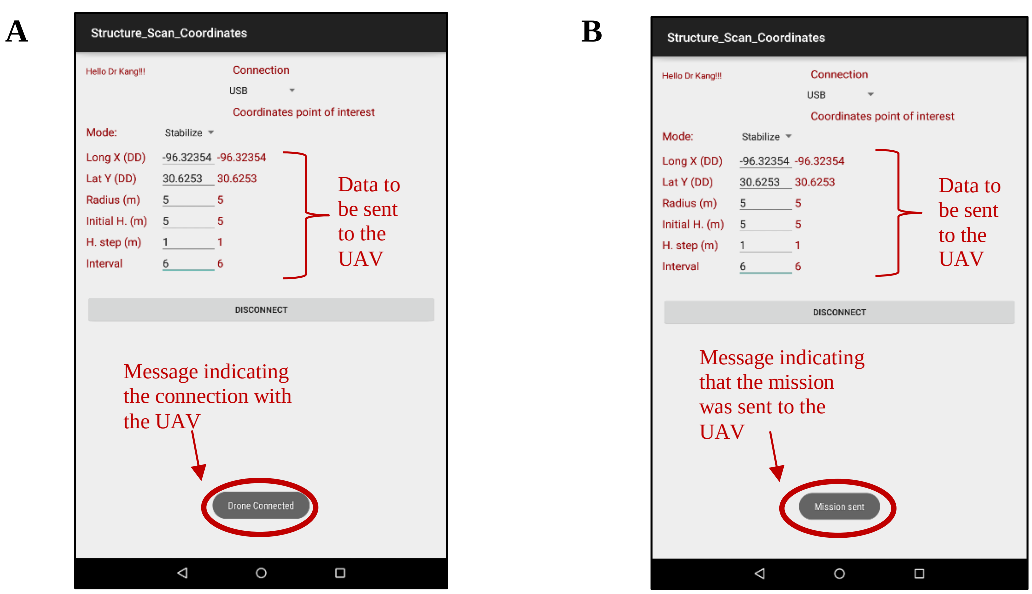



**Figure 19 (A) Structure_Scan_Coordinates app’s connection with the UAV. (B) Structure_Scan_Coordinates app’s mission sent to the UAV.**

### *4.1.2. Drone Height Reduction*

As in the case of the Structure_Scan_Coordinates, the base to create this app was another app called "Hello Drone" and its code is available on the website of Dronekit by 3D Robotics (3D Robotics 2015f). This app was modified with Android Studio 1.2 (Figure 7) in order to obtain a different layout and send the mission to the UAV according to the path mentioned in Figure 9. The following graphics display the design for the layout (Figure 20) and the code for the main activity in the app (Figure 21).

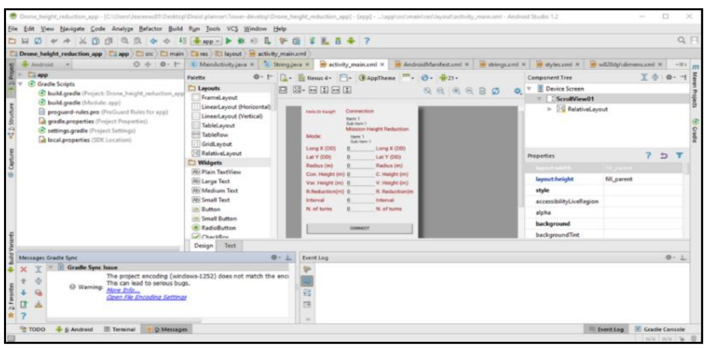


**Figure 20 Layout design of Drone Height Reduction app**

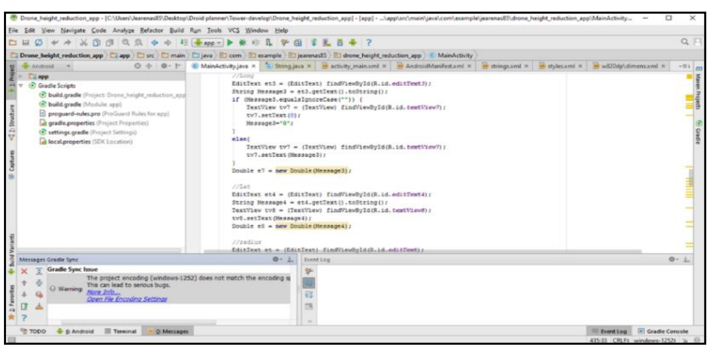


**Figure 21 Java code for the main activity in Drone Height Reduction app**

Table 4 displays the added fields and button for this app.

**Table 4 Fields for the Drone Height Reduction app**

| | |
|---|---|
| **Long X (DD)** | Field to input the longitude's coordinate in decimal degrees. |
| **Lat Y (DD)** | Field to input the latitude's coordinate in decimal degrees. |
| **Radius (m)** | Field to input the radius length in meters for each circumference. |
| **Con. Height (m)** | Field to input the height in meters in which the UAV will fly with a constant radius. |
| **Var. Height (m)** | Field to input the height in meters in which the UAV will fly with a variable radius. |
| **R. Reduction (m)** | Field to input the length in meters in which the radius will be diminished in each step during the flight in the "Var. Height" |
| **Interval** | Field to input the number of total vertical points or steps for the mission. "Con. Height" and "Var. Height" will be summed and its result will be taken as the total height in order to be split by the "Interval". |
| **N. of turns** | Number of turns around the structure for each height step. |
| **Connect – Disconnect button** | When the app and the UAV are disconnected, this button connects and sends the mission to the drone. When the app and the UAV are connected, this button disconnects and finishes with the communication. |

The final product can be seen in a mobile device such as a Nexus Tablet as it is shown in the following screenshots. Figure 22 .A. displays the icon for this app, Figure 22 .B. illustrates the first layout for the app before entering the data and pushing the "Connect" button in order to send the mission to the UAV. Figure 23 .A. presents the connection with the UAV after pushing the "Connect" button, and Figure 23 .B. shows the moment when the mission is sent to the UAV which occurs after the connection with this device.

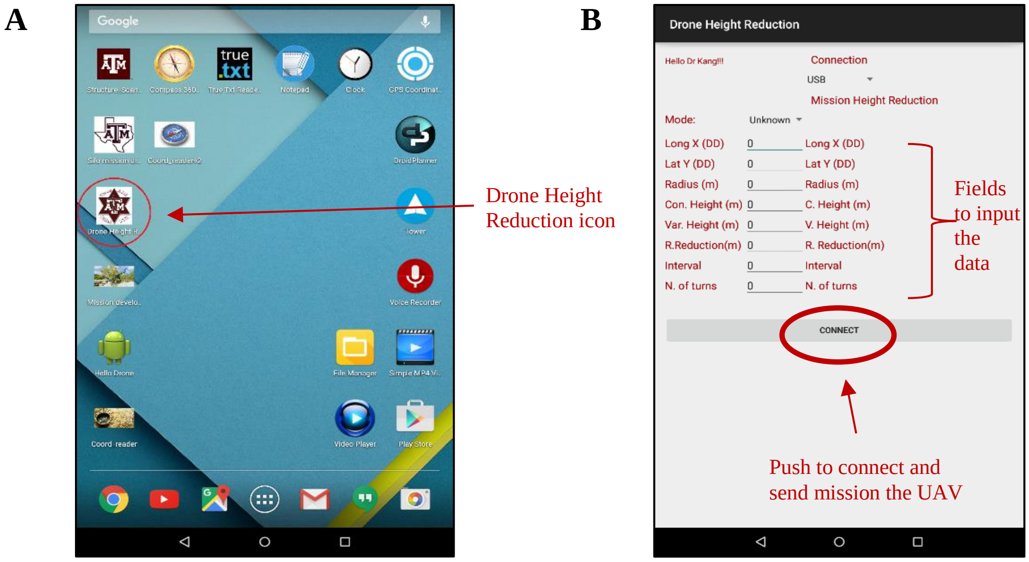



**Figure 22 (A) Drone Height Reduction app's icon. (B) Drone Height Reduction app's mobile layout.**

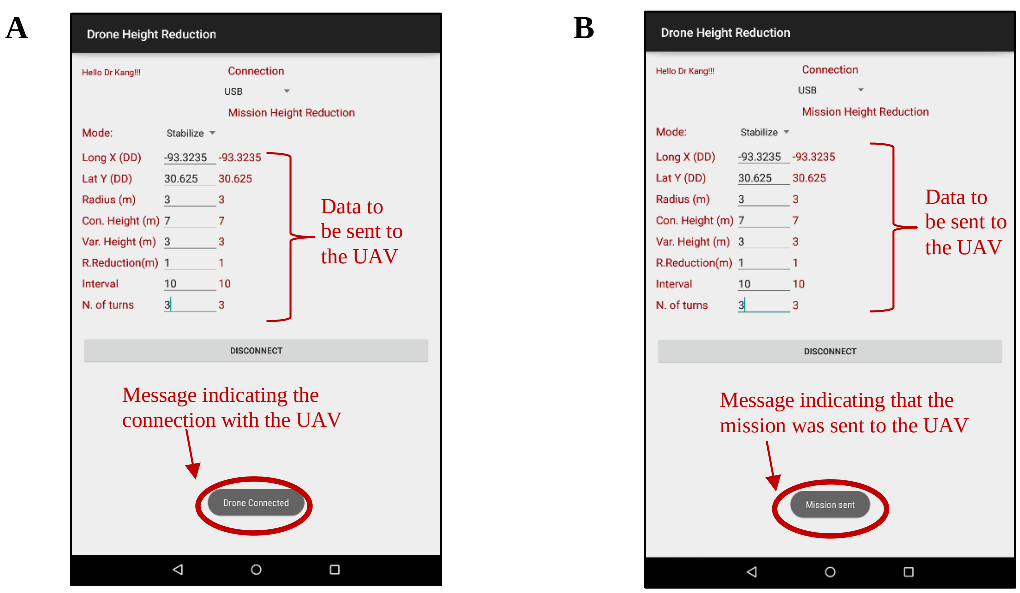



**Figure 23 (A) Drone Height Reduction app's connection with the UAV. (B) Drone Height Reduction app's mission sent to the UAV.**

### *4.1.3. Coord_readerv2*

In order to do the evaluation number 2 mentioned in subchapter 3.3, it was necessary to develop a third app to read the coordinates from the UAV-GPS during its flight and save them in an independent ".txt" file in the mobile device. This app was programmed using as a base the "Hello Drone" app (3D Robotics 2015f) and modifying its code with Android Studio 1.2 in order to obtain the required product. The following graphics display the design for the layout (Figure 24) and the code for the main activity in the app (Figure 25).

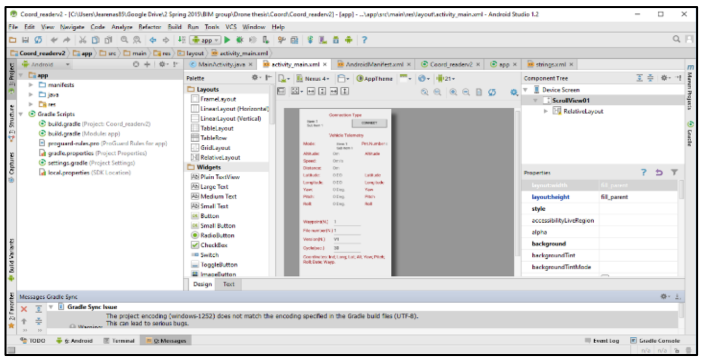


**Figure 24 Layout design of Coord_readerv2 app**

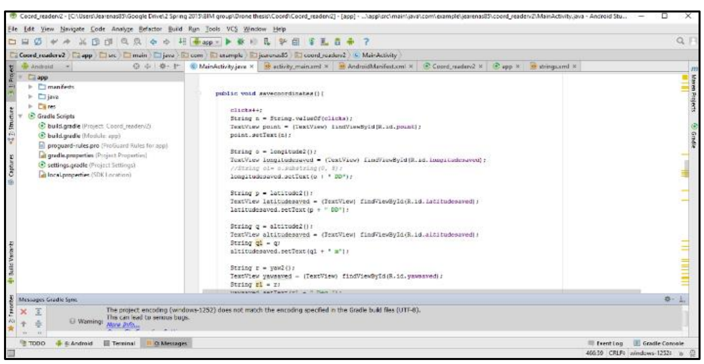


**Figure 25 Java code for the main activity in Coord_readerv2 app**

For this app, Table 5 displays the added fields and button.

**Table 5 Fields for the Coord_readerv2 app**

| | |
|---|---|
| **Connect – Disconnect button** | When the app and the UAV are disconnected, this button connects and establishes communication with the drone in order to read its orientation and coordinates. When the app and the UAV are connected, this button disconnects and finishes with the communication. |
| **Altitude** | Field that shows the altitude in meters for the UAV's flight |
| **Latitude** | Field that shows the latitude in decimal degrees for the UAV's flight |
| **Longitude** | Field that shows the longitude in decimal degrees for the UAV's flight |
| **Yaw** | Field that shows the yaw angle orientation in degrees for the UAV's flight |
| **Pitch** | Field that shows the pitch angle orientation in degrees for the UAV's flight |
| **Roll** | Field that shows the roll angle orientation in degrees for the UAV's flight |
| **Waypoint (N.)** | Field to input manually in the ".txt" file the number of the waypoint in the UAV's flight |
| **File number (N.) and Version (N.)** | Field to input manually in the file number and version for the name of the ".txt" file |
| **Cycle (sec)** | Field to input the period of time in seconds in which the UAV's orientation and coordinates will be saved in the ".txt" file |
| **Save point button** | Button to start to save the UAV's orientation and coordinates information in the ".txt" file. It works according to the period defined in the field Cycle |

The final product can be seen in a mobile device such as a Nexus Tablet as shown in the following screenshots. Figure 26 .A. displays the icon for this app, in Figure 26 .B. can be seen the first layout for the app before pushing the "Connect" button in order to establish communication with the UAV.

Figure 27 .A. illustrates the coordinates and orientation for the UAV after pushing the button "Connect", Figure 27 .B. shows the moment when the ".txt" file is generated after pushing the button "Save Point", the Figure 28 .A. and Figure 28 .B. show the coordinates and the orientation information collected for the ".txt" file in the mobile device.

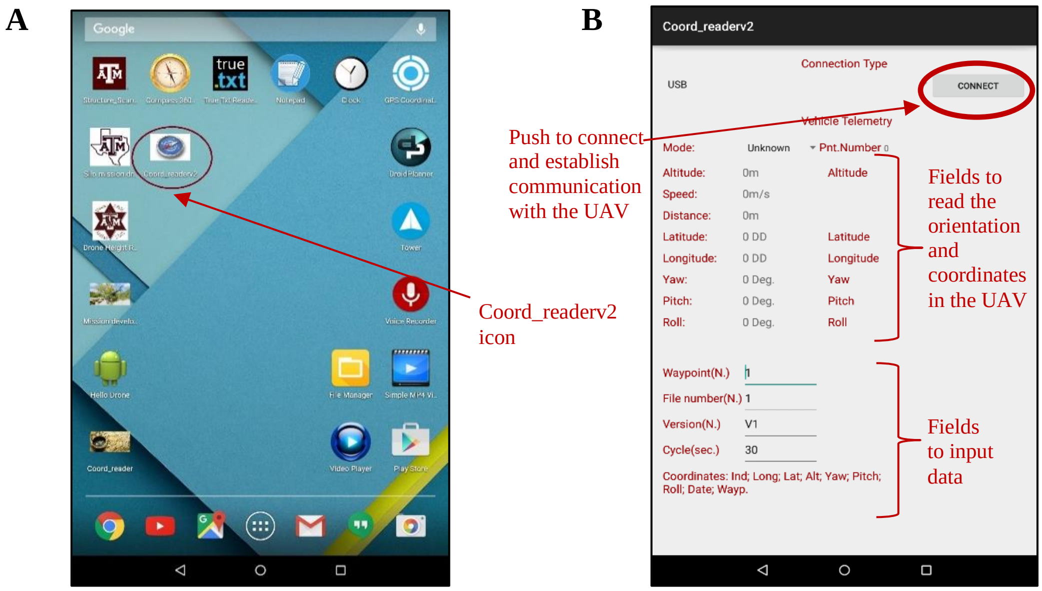



**Figure 26 (A) Coord_readerv2 app's icon. (B) Coord_readerv2 app's mobile layout.**

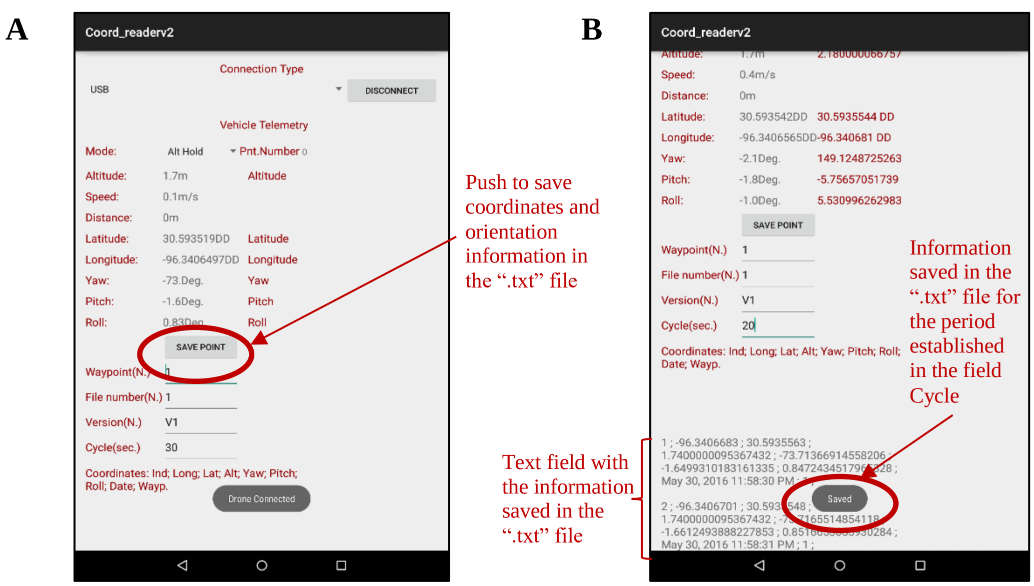
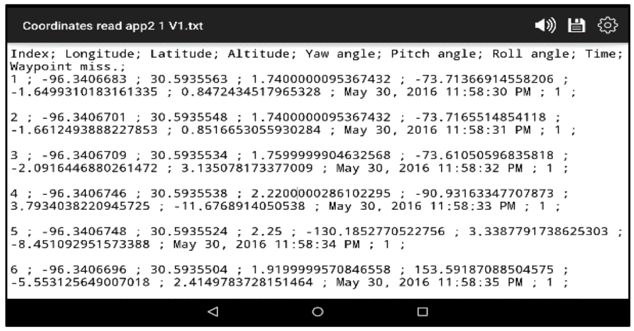



**Figure 27 (A) Coord_readerv2 app's connection with the UAV. (B) Coord_readerv2 app's after saving coordinates in the ".txt" file.**

**A**



Coordinates read app2 1 V1.txt

Index; Longitude; Latitude; Altitude; Yaw angle; Pitch angle; Roll angle; Time; Waypoint miss.;
1 ; -96.3406683 ; 30.5935563 ; 1.7400000095367432 ; -73.71366914558206 ; -1.6499310183161335 ; 0.8472434517965328 ; May 30, 2016 11:58:30 PM ; 1 ;

2 ; -96.3406701 ; 30.5935548 ; 1.7400000095367432 ; -73.7165514854118 ; -1.6612493888227853 ; 0.8516653055930284 ; May 30, 2016 11:58:31 PM ; 1 ;

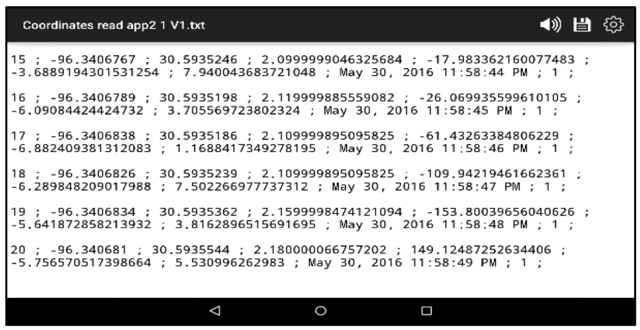
3 ; -96.3406709 ; 30.5935534 ; 1.7599999904632568 ; -73.61050596835818 ; -2.0916446880261472 ; 3.135078173377009 ; May 30, 2016 11:58:32 PM ; 1 ;

4 ; -96.3406746 ; 30.5935538 ; 2.2200000286102295 ; -90.93163347707873 ; 3.7934038220945725 ; -11.6768914050538 ; May 30, 2016 11:58:33 PM ; 1 ;

5 ; -96.3406748 ; 30.5935524 ; 2.25 ; -130.1852770522756 ; 3.3387791738625303 ; -8.451092951573388 ; May 30, 2016 11:58:34 PM ; 1 ;

6 ; -96.3406696 ; 30.5935504 ; 1.9199999570846558 ; 153.59187088504575 ; -5.553125649007018 ; 2.4149783728151464 ; May 30, 2016 11:58:35 PM ; 1 ;

**B**



Coordinates read app2 1 V1.txt

15 ; -96.3406767 ; 30.5935246 ; 2.0999999046325684 ; -17.983362160077483 ; -3.6889194301531254 ; 7.940043683721048 ; May 30, 2016 11:58:44 PM ; 1 ;

16 ; -96.3406789 ; 30.5935198 ; 2.119999885559082 ; -26.069935599610105 ; -6.09084424424732 ; 3.705569723802324 ; May 30, 2016 11:58:45 PM ; 1 ;

17 ; -96.3406838 ; 30.5935186 ; 2.109999895095825 ; -61.43263384806229 ; -6.882409381312083 ; 1.1688417349278195 ; May 30, 2016 11:58:46 PM ; 1 ;

18 ; -96.3406826 ; 30.5935239 ; 2.109999895095825 ; -109.94219461662361 ; -6.289848209017988 ; 7.502266977737312 ; May 30, 2016 11:58:47 PM ; 1 ;

19 ; -96.3406834 ; 30.5935362 ; 2.1599998474121094 ; -153.80039656040626 ; -5.641872858213932 ; 3.8162896515691695 ; May 30, 2016 11:58:48 PM ; 1 ;

20 ; -96.340681 ; 30.5935544 ; 2.180000066757202 ; 149.12487252634406 ; -5.756570517398664 ; 5.530996262983 ; May 30, 2016 11:58:49 PM ; 1 ;

**Figure 28 (A) Text file generated with the information collected in Coord_readerv2 app during the first six seconds. (B) Text file generated with the information collected in Coord_readerv2 app during the last six seconds.**

## *4.2. Data collected and analysis*

Different missions were performed in order to gather data about how the developed mobile applications were working and to try to compare the planned and actual path in the flight. In the next sections the missions' characteristics are described. The information obtained for the different evaluations is presented in subchapter 4.3.

### *4.2.1. Test 1 - app 1, date 02 -20-2016*

#### *4.2.1.1. Mission definition*

In Table 6 are illustrated the parameters for this mission according to the latitude and longitude information taken from the mobile application "GPS Coordinates". It should be mentioned that the last four or five digits in those app's coordinates are not fixed which can induce an error in the mission lower than 11.09 m in the latitude and 9.551 m in the longitude, according to the values from in subchapter 2.8.

**Table 6 Mobile application and parameters used in test 1 - app 1**

| | |
|---|---|
| **Mobile app used** | Structure_Scan_Coordinates |
| **Long X (DD)** | -96.29941135 |
| **Lat Y (DD)** | 30.56940231 |
| **Radius (m)** | 7.6 |
| **Initial H. (m)** | 2 |
| **H. step (m)** | 1 |
| **Interval** | 10 |

In the Figure 29 .A. to Figure 29 .F. it can be observed how the mission is sent and verified in the UAV.

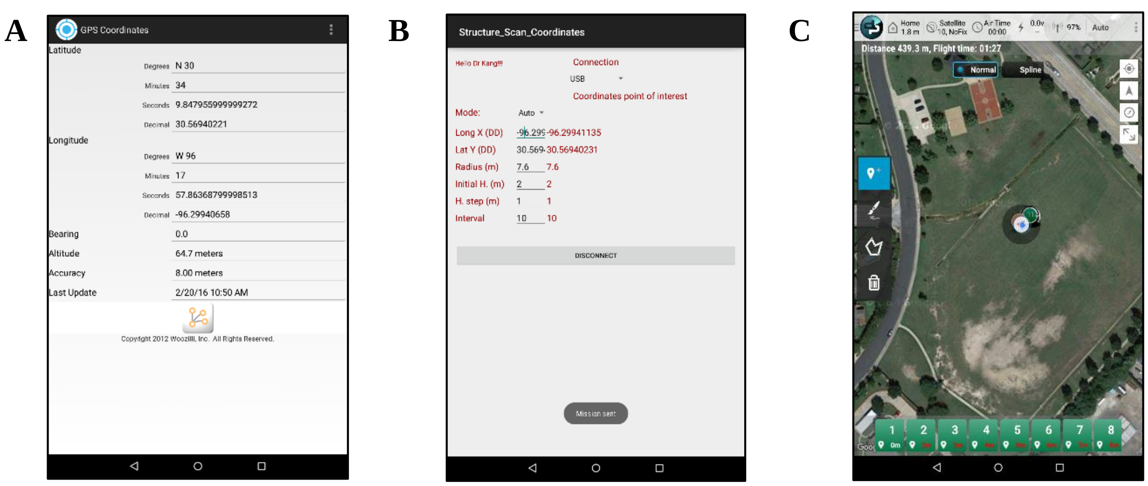



**Figure 29 (A) GPS Coordinates in the point of interest. (B) Mission 1 sent with the Structure_Scan_Coordinates. (C) Mission read from the UAV in Droidplanner 2. (D) First waypoint for the mission in Droidplanner 2. (E) Second waypoint for the mission in Droidplanner 2. (F) Last waypoint for the mission in Droidplanner 2.**

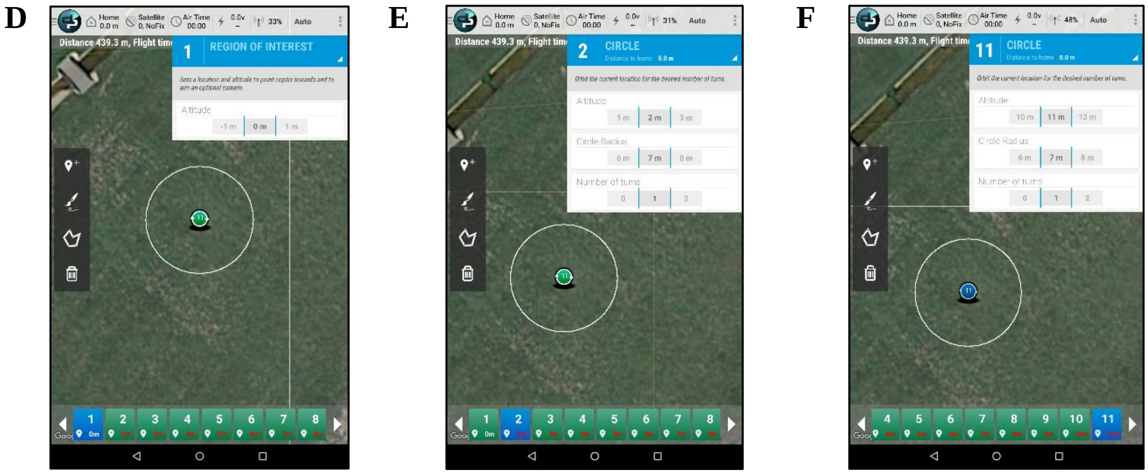



**Figure 29 Continued**

### *4.2.1.2. Evaluation 1*

According to evaluation 1 proposed in subchapter 3.3., the app worked without any inconvenience for this mission.

### *4.2.1.3. Evaluation 2*

The evaluation 2 proposed in subchapter 3.3 could not be carried out because the UAV used in this mission (an IRIS of 3DRobotics) did not have an antenna, affecting the long distance communication and the coordinate collection during the drone's flight. It should be mentioned that usually this model of UAV has an antenna (Figure 30 .A.), however, the one that was used in this work did not have one because it was broken in the past (Figure 30 .B.).

A B

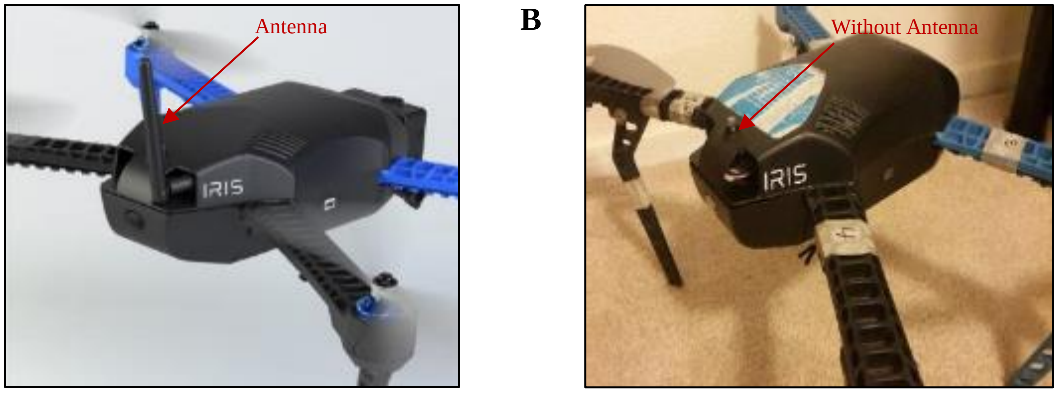



**Figure 30 (A) Iris rear view showing radio telemetry antenna (Gunn 2014). (B) Rear view of the IRIS used for the actual mission.**

### *4.2.1.4. Evaluation 3*

Photos between a height of 2 m and 6 m 1 m increments were taken each 0.5 seconds in order to do the evaluation 3 proposed in subchapter 3.3.

Taking into consideration the issues to do the evaluation 2, the photos taken during this process were used to do an actual flight path reconstruction in order to test the accuracy between the real and the planned path according to the objective 2 of this research mentioned in subchapter 1.4.

A calibration photo (photo 1GOPR4121) was taken at a distance of 7.6 m in order to have a reference of the frame height when the third section of the pole has a height of 1 m (Figure 31 and Figure 32).

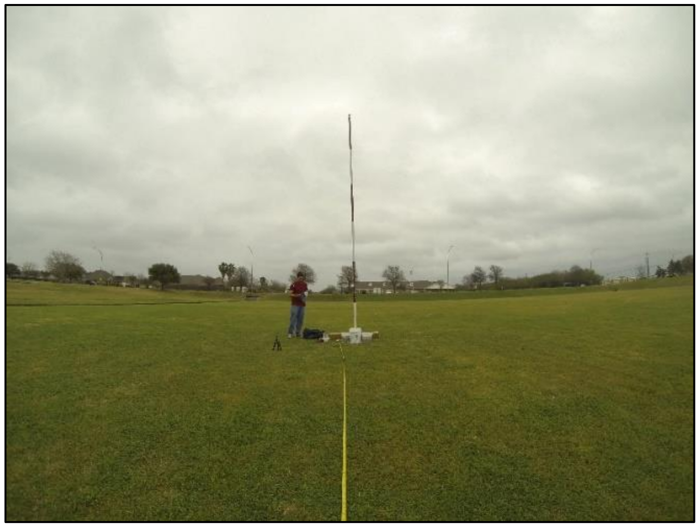


**Figure 31 Calibration photo 1GOPR4121**

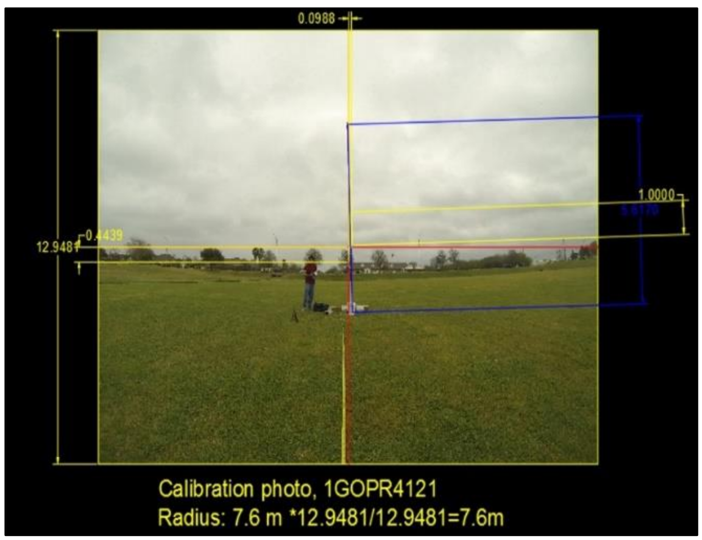



**Figure 32 Calibration photo 1GOPR4121 with measurements**

Approximately 256 photos were taken between a height of 2 m and 6 m, however, taking into consideration that for this app the drone took the photos with some inclination, the first analysis developed was a comparison between the actual photos and some of them modified in Adobe Photoshop CC 2015 in order to correct the inclination and trying to obtain equal heights for each section of the pole, which each one of them must have a value of 1 meter. For this analysis, 4 photos at a height of 3 m were initially used, Figure 33 and Figure 34 illustrate the work done for one of the photos (G0024895) and Table 7 displays the final value of the other photos considered in this work without any modification; Figure 35 and Figure 36 and Table 8 show the values with the modification in Photoshop.

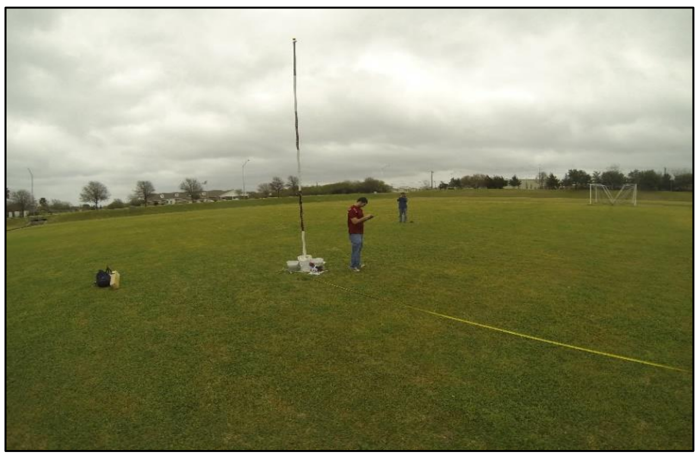


**Figure 33 Photo G0024895 at a height of 3 m**

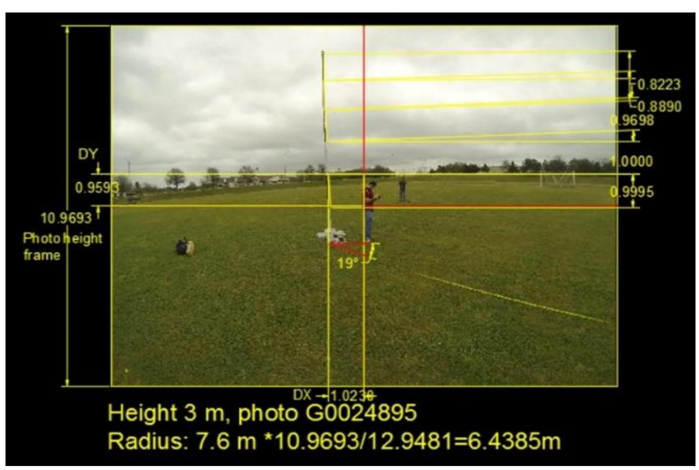



**Figure 34 Photo G0024895 at a height of 3 m with measurements**

**Table 7 Measurements for the original photos which were taken from a height of 3 m in Test 1 - app 1**

| Number | Photo not modified G002 - | DX(m) | DY(m) | Photo frame height (m) | Actual Radius(m) | X-Y axe | Planned radius (m) |
|---|---|---|---|---|---|---|---|
| 1 | 4883 | -1.722 | 0.515 | 9.197 | 5.398 | 0.000 | 7.600 |
| 2 | 4895 | -1.020 | 0.959 | 10.969 | 6.439 | 0.000 | 7.600 |
| 3 | 4907 | -1.659 | 0.201 | 12.551 | 7.367 | 0.000 | 7.600 |
| 4 | 4919 | -3.157 | 1.789 | 14.207 | 8.339 | 0.000 | 7.600 |

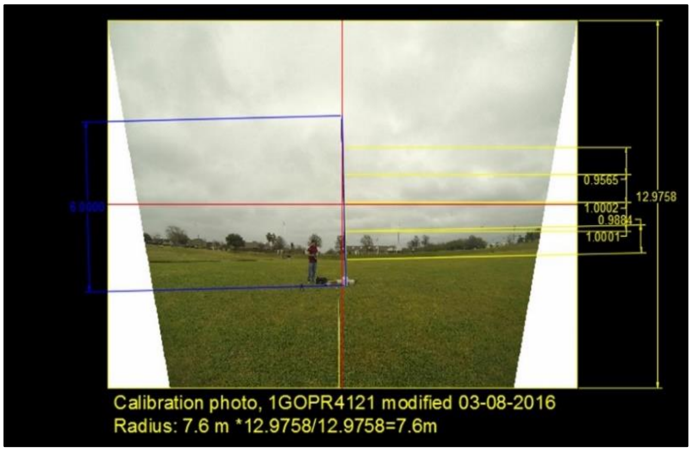



**Figure 35 Calibration photo 1GOPR4121 modified with Adobe Photoshop CC 2015**

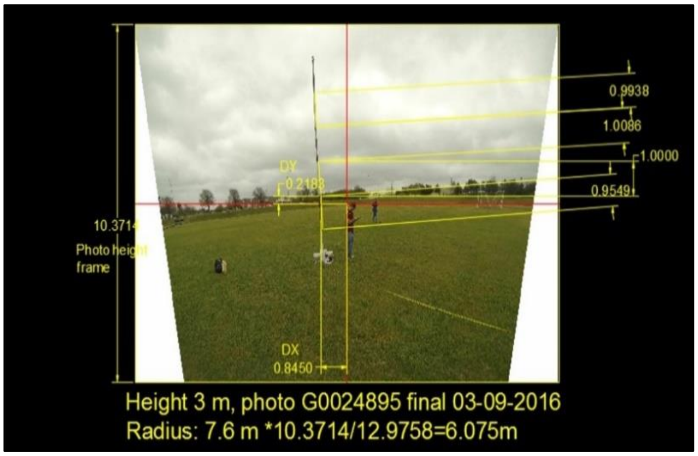



**Figure 36 Photo G0024895 modified with Adobe Photoshop CC 2015. Total height of 3 m with measurements**

**Table 8 Measurements for the modified photos which were taken from a height of 3 m in Test 1 - app 1**

| Number | Photo modified G002 - | DX(m) | DY(m) | Photo frame height (m) | Actual Radius(m) | X-Y axe | Planned radius (m) |
|---|---|---|---|---|---|---|---|
| 1 | 4883 | -1.386 | -0.354 | 8.869 | 5.195 | 0.000 | 7.600 |
| 2 | 4895 | -0.845 | 0.218 | 10.371 | 6.075 | 0.000 | 7.600 |
| 3 | 4907 | -1.420 | -0.636 | 12.397 | 7.261 | 0.000 | 7.600 |
| 4 | 4919 | -2.657 | 0.805 | 13.351 | 7.819 | 0.000 | 7.600 |

The images Figure 37, Figure 38 and Figure 39 show the comparison between unmodified and modified photos and Table 9 shows the difference in meters and the percentage of error between both methods.

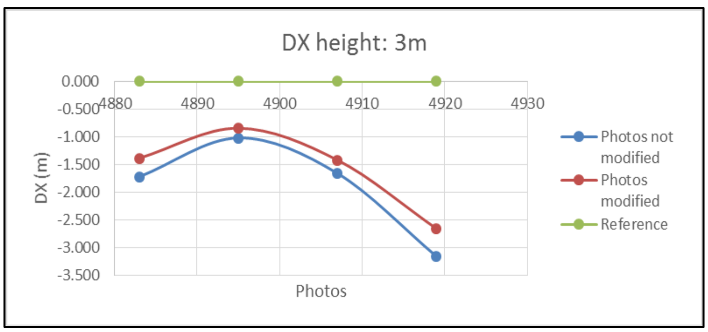



**Figure 37 Horizontal distance (DX) between the center of the photo and the pole at a height of 3 m in Test 1 - app 1**

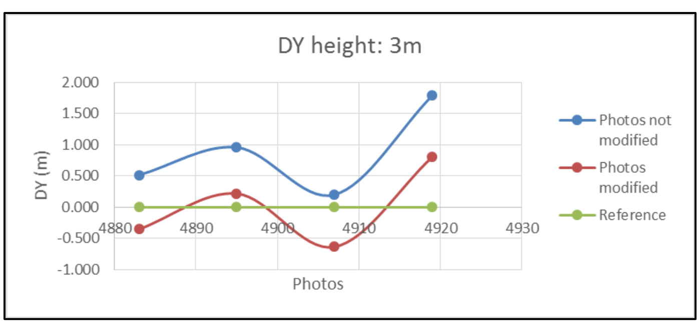



**Figure 38 Vertical distance (DY) between the center of the photo and initial height of the mission (2m) at a height of 3 m in test 1 - app 1**

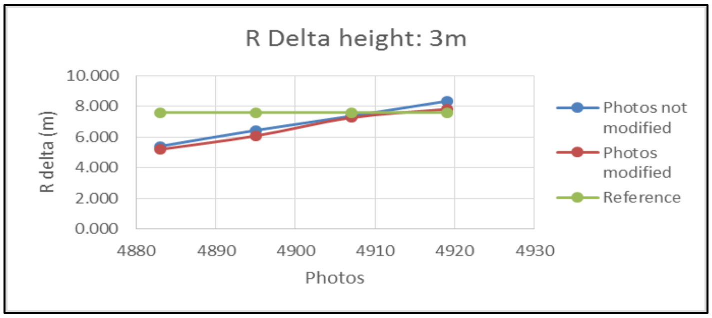



**Figure 39 Planned and actual radius estimation in different points at a height of 3 m in Test 1 - app 1**

**Table 9 Percentage of difference for the calculation of radius between original and modified photos**

| **Photo G002 -** | **Actual Radius difference (m)** | **% Actual R. Diff** |
|---|---|---|
| 4883 | 0.204 | 3.92% |
| 4895 | 0.364 | 5.99% |
| 4907 | 0.106 | 1.46% |
| 4919 | 0.520 | 6.65% |
| Average | 0.298 | 4.50% |

The average error between both methods when calculating the radius is approximately 4.5% and the higher values were identified in photo G0024919 with a difference of almost 6.7%. The same analysis was performed for 4 photos at a height of 6 m during the flight of the UAV (Appendix A.3.), and the obtained average error for both methods was of 1.3%, with a higher value of 3.9% in the photo G0025072. For that reason, the analysis in the following photos is done with unmodified photos.

After defining that the UAV inclination for the photos was going to be disregarded in this study, 8 photos for each height were examined as it is shown in the Figure 40 in order to obtain the distance between the center of the photo and the pole (DX) and the height of the frame in order to estimate the radius (Figure 41). With that information it was possible to develop Table 10 which gives information about the average, maximum and minimum values of DX and the planned and actual radius. This data was used to draw an approximate path of the UAV when it was performing the mission at a height of 3 m (Figure 44); the position of the UAV with respect to the tape that was oriented near to the magnetic south was measured from the drawing and was utilized to build the column "Angle UAS-East (Degrees)" in Table 10.

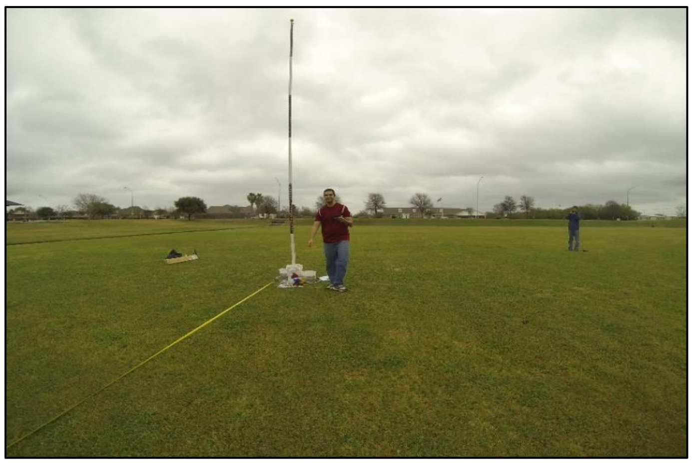


**Figure 40 Photo G0024889 at a height of 3 m**

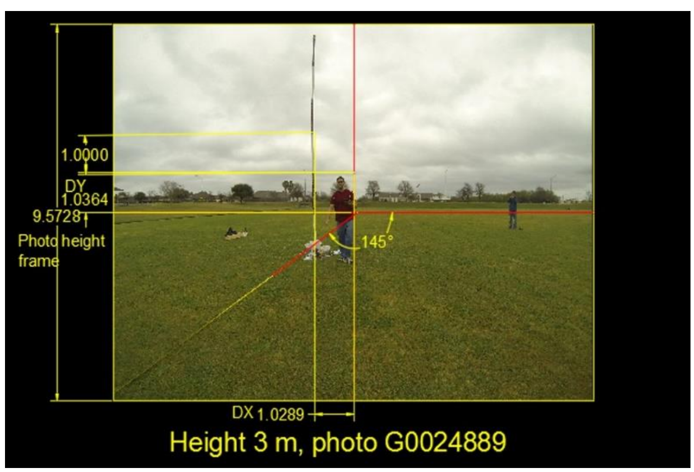



**Figure 41 Photo G0024889 at a height of 3 m with measurements**

**Table 10 Measurements for 8 photos taken at a height of 3 m in Test 1 - app 1**

| N. | Photo G002 | DX(m) | Abs DX(m) | DY(m) | Photo frame height (m) | Actual Radius (m) | Planned radius (m) | Radius diff. (m) | Abs radius diff. (m) | Angle UAS-East (Degrees) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4883 | -1.722 | 1.722 | 0.515 | 9.197 | 5.398 | 7.600 | -2.202 | 2.202 | 15.000 |
| 2 | 4889 | -1.029 | 1.029 | 1.036 | 9.573 | 5.619 | 7.600 | -1.981 | 1.981 | -24.000 |
| 3 | 4895 | -1.020 | 1.020 | 0.959 | 10.969 | 6.439 | 7.600 | -1.161 | 1.161 | -152.000 |
| 4 | 4901 | -1.343 | 1.343 | 0.128 | 11.874 | 6.970 | 7.600 | -0.630 | 0.630 | -168.000 |
| 5 | 4907 | -1.659 | 1.659 | 0.201 | 12.551 | 7.367 | 7.600 | -0.233 | 0.233 | -186.000 |
| 6 | 4913 | -2.024 | 2.024 | 0.400 | 13.217 | 7.758 | 7.600 | 0.158 | 0.158 | -232.000 |
| 7 | 4919 | -3.157 | 3.157 | 1.789 | 14.207 | 8.339 | 7.600 | 0.739 | 0.739 | -315.000 |
| 8 | 4925 | -0.540 | 0.540 | 1.582 | 13.751 | 8.071 | 7.600 | 0.471 | 0.471 | -351.000 |
| **Aver.** | | | 1.562 | | | 6.995 | | | 0.947 | |
| **Std. dev.** | | | 0.798 | | | 1.098 | | | 0.774 | |
| **Coef. Var.** | | | 51.13% | | | 15.70% | | | 81.72% | |
| **Max.** | | | 3.157 | | | 8.339 | | | 2.202 | |
| **Min.** | | | 0.540 | | | 5.398 | | | 0.158 | |

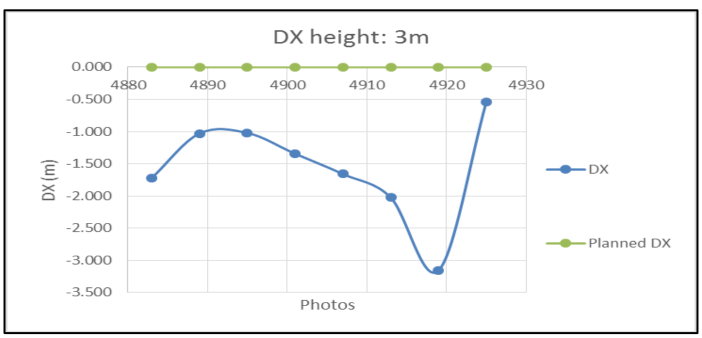



**Figure 42 Horizontal distance (DX) between the center of the photo and the pole at a height of 3 m in 8 different points, Test 1 - app 1**

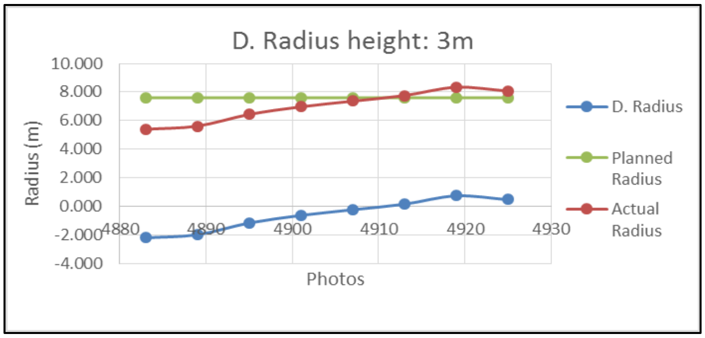



**Figure 43 Planned and actual radius estimation in different points at a height of 3 m in 8 different points, Test 1 - app 1**

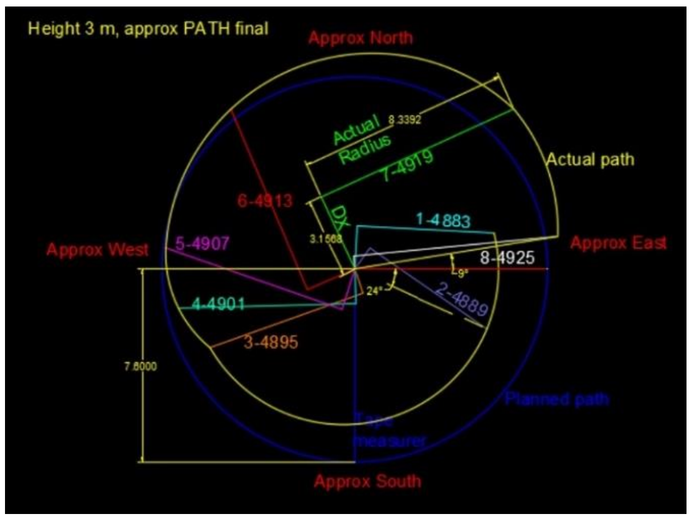



**Figure 44 Planned and actual path at a height of 3 m in Test 1 - app 1, evaluation 3**

From Table 10 and Figure 42 and Figure 43, it is possible to conclude that for the height of 3 m in this mission the error between the center of the picture and the pole's center has an average of 1.562 m, with a maximum error of 3.157 m in the photo and a minimum of 0.54 m. For the absolute radius difference, the average was 0.947 m, with a maximum difference of 2.202 m in the photo and a minimum of 0.158 m, which means that the average actual radius had a value of 6.995 m, the maximum radius was 8.339 m and the minimum was 5.398 m.

Table 10 was produced at a height of 3, Table 11 was created for the other heights between 2 m and 6 m and according to its content, Figure 45 and Figure 46 were created, which summarize and illustrate the DX error and radius difference in all the examined photos. The information given in Table 11 was classified for each height to create Table 12.

**Table 11 DX and radius difference for all the photos analyzed in Test 1 - app 1**

| Ref. | Id. | N. | Photo G002 | DX(m) | Abs. DX (m) | DY (m) | Photo frame height (m) | Act. Rad. (m) | Plan. Rad. (m) | Rad. diff. (m) | Abs. Rad. diff. (m) | Angle UAS - East (Deg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2m height | 1 | 1 | 4830 | -0.972 | 0.972 | 1.940 | 12.233 | 7.180 | 7.600 | -0.420 | 0.420 | -2.000 |
| | 2 | 2 | 4835 | -1.345 | 1.345 | 1.473 | 12.084 | 7.093 | 7.600 | -0.507 | 0.507 | -106.000 |
| | 3 | 3 | 4840 | -1.029 | 1.029 | 0.865 | 12.358 | 7.254 | 7.600 | -0.346 | 0.346 | -161.000 |
| | 4 | 4 | 4845 | -1.114 | 1.114 | 0.995 | 13.109 | 7.695 | 7.600 | 0.095 | 0.095 | -174.000 |
| | 5 | 5 | 4850 | -2.595 | 2.595 | 1.019 | 12.440 | 7.302 | 7.600 | -0.298 | 0.298 | -172.000 |
| | 6 | 6 | 4855 | -2.581 | 2.581 | 1.622 | 12.848 | 7.541 | 7.600 | -0.059 | 0.059 | -191.000 |
| | 7 | 7 | 4860 | -2.619 | 2.619 | 1.663 | 12.723 | 7.468 | 7.600 | -0.132 | 0.132 | -305.000 |
| | 8 | 8 | 4865 | -2.585 | 2.585 | 1.786 | 12.380 | 7.267 | 7.600 | -0.333 | 0.333 | -332.000 |
| 3m height | 9 | 1 | 4883 | -1.722 | 1.722 | 0.515 | 9.197 | 5.398 | 7.600 | -2.202 | 2.202 | 15.000 |
| | 10 | 2 | 4889 | -1.029 | 1.029 | 1.036 | 9.573 | 5.619 | 7.600 | -1.981 | 1.981 | -24.000 |
| | 11 | 3 | 4895 | -1.020 | 1.020 | 0.959 | 10.969 | 6.439 | 7.600 | -1.161 | 1.161 | -152.000 |
| | 12 | 4 | 4901 | -1.343 | 1.343 | 0.128 | 11.874 | 6.970 | 7.600 | -0.630 | 0.630 | -168.000 |
| | 13 | 5 | 4907 | -1.659 | 1.659 | 0.201 | 12.551 | 7.367 | 7.600 | -0.233 | 0.233 | -186.000 |
| | 14 | 6 | 4913 | -2.024 | 2.024 | 0.400 | 13.217 | 7.758 | 7.600 | 0.158 | 0.158 | -232.000 |
| | 15 | 7 | 4919 | -3.157 | 3.157 | 1.789 | 14.207 | 8.339 | 7.600 | 0.739 | 0.739 | -315.000 |
| | 16 | 8 | 4925 | -0.540 | 0.540 | 1.582 | 13.751 | 8.071 | 7.600 | 0.471 | 0.471 | -351.000 |
| 4m height | 17 | 1 | 4930 | -0.598 | 0.598 | 0.452 | 13.628 | 7.999 | 7.600 | 0.399 | 0.399 | 29.000 |
| | 18 | 2 | 4936 | -1.293 | 1.293 | -0.015 | 11.623 | 6.822 | 7.600 | -0.778 | 0.778 | 19.000 |
| | 19 | 3 | 4942 | -2.717 | 2.717 | -0.054 | 10.593 | 6.218 | 7.600 | -1.382 | 1.382 | 13.000 |
| | 20 | 4 | 4948 | -2.129 | 2.129 | -0.231 | 9.306 | 5.462 | 7.600 | -2.138 | 2.138 | -34.000 |
| | 21 | 5 | 4954 | -2.020 | 2.020 | -0.359 | 10.437 | 6.126 | 7.600 | -1.474 | 1.474 | -140.000 |
| | 22 | 6 | 4960 | -2.019 | 2.019 | -0.248 | 12.692 | 7.449 | 7.600 | -0.151 | 0.151 | -169.000 |
| | 23 | 7 | 4966 | -2.053 | 2.053 | -0.347 | 12.205 | 7.164 | 7.600 | -0.436 | 0.436 | -194.000 |
| | 24 | 8 | 4972 | -2.644 | 2.644 | 0.263 | 12.839 | 7.536 | 7.600 | -0.064 | 0.064 | -252.000 |
| | 25 | 9 | 4979 | -1.474 | 1.474 | 0.480 | 12.665 | 7.434 | 7.600 | -0.166 | 0.166 | -335.000 |
| 5m height | 26 | 1 | 4985 | -0.666 | 0.666 | 0.223 | 12.596 | 7.393 | 7.600 | -0.207 | 0.207 | 32.000 |
| | 27 | 2 | 4991 | -1.415 | 1.415 | 0.086 | 10.806 | 6.343 | 7.600 | -1.257 | 1.257 | 25.000 |
| | 28 | 3 | 4997 | -2.495 | 2.495 | 0.397 | 10.469 | 6.145 | 7.600 | -1.455 | 1.455 | 15.000 |

**Table 11 Continued**

| Ref. | Id. | N. | Photo G002 | DX(m) | Abs. DX (m) | DY (m) | Photo frame height (m) | Act. Rad. (m) | Plan. Rad. (m) | Rad. diff. (m) | Abs. Rad. diff. (m) | Angle UAS - East (Deg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5m height | 29 | 4 | 5003 | -2.018 | 2.018 | 0.225 | 9.723 | 5.707 | 7.600 | -1.893 | 1.893 | -16.000 |
| | 30 | 5 | 5009 | -2.054 | 2.054 | -0.241 | 10.136 | 5.949 | 7.600 | -1.651 | 1.651 | -127.000 |
| | 31 | 6 | 5015 | -1.391 | 1.391 | -0.905 | 12.189 | 7.154 | 7.600 | -0.446 | 0.446 | -171.000 |
| | 32 | 7 | 5021 | -1.977 | 1.977 | -0.421 | 12.795 | 7.510 | 7.600 | -0.090 | 0.090 | -186.000 |
| | 33 | 8 | 5027 | -3.088 | 3.088 | 0.396 | 12.242 | 7.186 | 7.600 | -0.414 | 0.414 | -219.000 |
| | 34 | 9 | 5033 | -4.382 | 4.382 | 0.733 | 12.210 | 7.167 | 7.600 | -0.433 | 0.433 | -311.000 |
| 6m height | 35 | 1 | 5042 | -1.809 | 1.809 | -0.745 | 12.861 | 7.549 | 7.600 | -0.051 | 0.051 | 46.000 |
| | 36 | 2 | 5048 | -1.628 | 1.628 | -1.075 | 11.366 | 6.671 | 7.600 | -0.929 | 0.929 | 23.000 |
| | 37 | 3 | 5054 | -3.027 | 3.027 | -0.476 | 10.695 | 6.277 | 7.600 | -1.323 | 1.323 | 12.000 |
| | 38 | 4 | 5060 | -2.536 | 2.536 | -0.735 | 10.439 | 6.127 | 7.600 | -1.473 | 1.473 | -40.000 |
| | 39 | 5 | 5066 | -2.368 | 2.368 | -0.713 | 10.865 | 6.377 | 7.600 | -1.223 | 1.223 | -135.000 |
| | 40 | 6 | 5072 | -1.644 | 1.644 | -1.391 | 12.633 | 7.415 | 7.600 | -0.185 | 0.185 | -173.000 |
| | 41 | 7 | 5078 | -2.082 | 2.082 | -1.038 | 13.417 | 7.875 | 7.600 | 0.275 | 0.275 | -198.000 |
| | 42 | 8 | 5084 | -2.952 | 2.952 | -0.683 | 13.731 | 8.059 | 7.600 | 0.459 | 0.459 | -250.000 |
| | 43 | 9 | 5086 | -3.116 | 3.116 | -0.736 | 13.218 | 7.759 | 7.600 | 0.159 | 0.159 | -280.000 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aver.** | | | | | 1.975 | | | 7.015 | | | 0.713 | |
| **Std. dev.** | | | | | 0.814 | | | 0.761 | | | 0.639 | |
| **Coef. Var.** | | | | | 41.21% | | | 10.85% | | | 89.62% | |
| **Max.** | | | | | 4.382 | | | 8.339 | | | 2.202 | |
| **Min.** | | | | | 0.540 | | | 5.398 | | | 0.051 | |

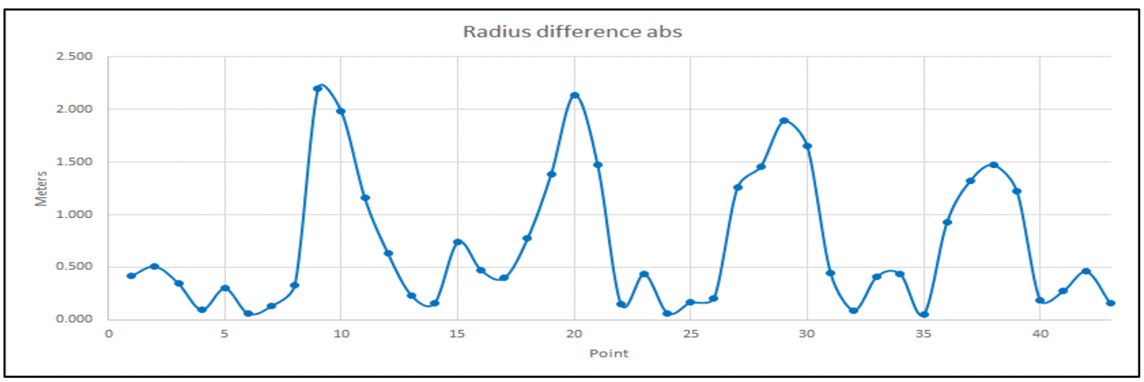



**Figure 45 Absolute radius difference for all the photos analyzed in Test 1 - app 1**

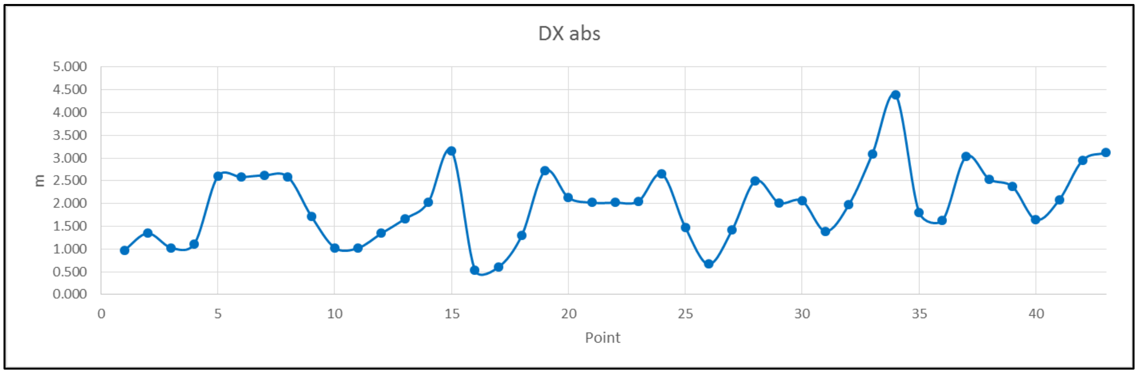



**Figure 46 Horizontal distance between the center of the picture and the pole position (DX abs) for all the photos analyzed in Test 1 - app 1**

**Table 12 Summary of planned and actual data and differences for each height from photos in Test 1 - app 1**

| | Point | 1 | 2 | 3 | 4 | 5 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Planned Test 1 – app 1** | Height (m) | 2.000 | 3.000 | 4.000 | 5.000 | 6.000 | | | | | |
| | Abs DX (m) | 0 | 0 | 0 | 0 | 0 | | | | | |
| | Radius (m) | 7.600 | 7.600 | 7.600 | 7.600 | 7.600 | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
| **Actual Test 1 – app 1** | Abs DX (m) | 2.144 | 1.562 | 1.883 | 2.165 | 2.351 | 2.021 | 0.306 | 15.15% | 2.351 | 1.562 |
| | Radius (m) | 7.299 | 6.995 | 6.912 | 6.728 | 7.123 | 7.012 | 0.215 | 3.07% | 7.299 | 6.728 |
| **Abs. diff. Test 1 – app 1** | Abs DX (m) | 2.144 | 1.562 | 1.883 | 2.165 | 2.351 | 2.021 | 0.306 | 15.15% | 2.351 | 1.562 |
| | Radius (m) | 0.301 | 0.605 | 0.688 | 0.872 | 0.477 | 0.588 | 0.215 | 36.62% | 0.872 | 0.301 |
| **Abs. diff. Test 1 – app 1 (%)** | Abs DX (m) | 100% | 100% | 100% | 100% | 100% | 100% | 0% | 0% | 100% | 100% |
| | Radius (m) | 4.12% | 8.65% | 9.95% | 12.96% | 6.69% | 0.085 | 0.033 | 39.34% | 12.96% | 4.12% |

From Table 11, it can be understood that the horizontal average error between the center of the photos and the pole for all the mission at a height among 2 m and 6 m was 1.975 m, with a maximum number of 4.382 m and minimum of 0.540 m. The average absolute radius difference from the photos was 0.713 m or 9% with respect to the planned radius (7.6 m), with a maximum value of 2.202 m and a minimum of 0.051 m. The radius had a range between 8.339 m and 5.398 m according to this table.

From Table 12, it is shown that in the height of 6 m the Abs DX had an average value of 2.351 m which was bigger than in the other heights and, in the height of 5 m the radius had an average of 6.728 m which was lower than in the other points.

According to the evaluation number 3 proposed in subchapter 3.3, the following is the percentage for the wrong focus:

$$Eq.\%\, wrong\ focus = \frac{\sum Option\ B\ photos}{\sum Option\ A\ photos + \sum Option\ B\ photos} \times 100\%$$

$$Eq.\%\, wrong\ focus = \frac{43}{0 + 43} \times 100\% = 100\%$$

This means that the center of the photos did not fit with the center of coordinates, and it is supported with the information provided in Table 11 in which the horizontal distance between the pole and the center of the images had an average of 1.975 m with a standard deviation of 0.814 m.

*4.2.1.5. 3D Model for Test 1 – app 1*

Figure 47 until Figure 51 show the 3D model for the flight of the UAV and its orientation at different heights with respect to the pole and according to it was done in Figure 44. In those graphics the height was considered constant in each step, the blue circumference is the planned path, the yellow figure is the actual path and the magenta lines show the UAV orientation from the photos (subchapter 4.2.1.4), the blue line indicates the tape measure that was used to reference the south.

Figure 52 and Figure 53 show a 3D model for the UAV flight according to the planned and actual paths drawn in the images Figure 47 until Figure 51.

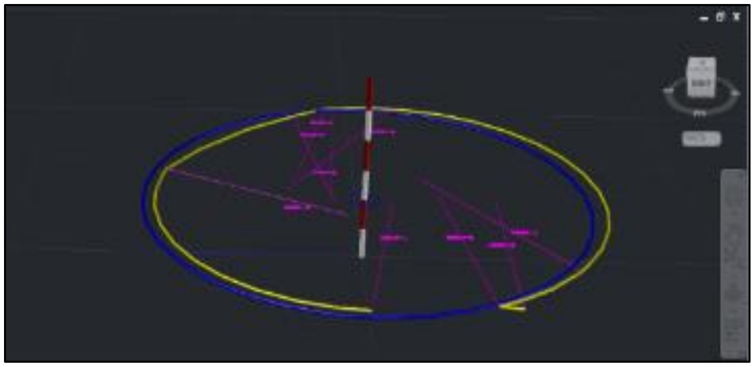


**Figure 47 3D model for the planned and actual path at a height of 2 m, Test 1 - app1**

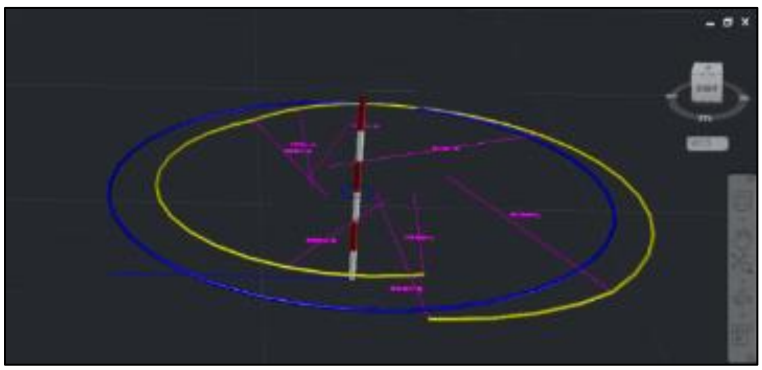


**Figure 48 3D model for the planned and actual path at a height of 3 m, Test 1 - app1**

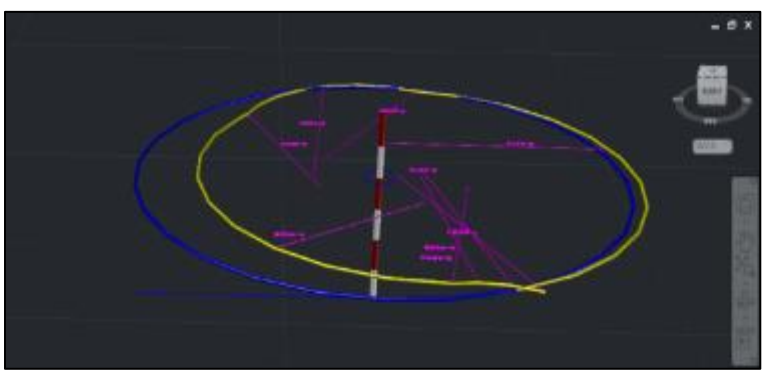


**Figure 49 3D model for the planned and actual path at a height of 4 m, Test 1 - app1**

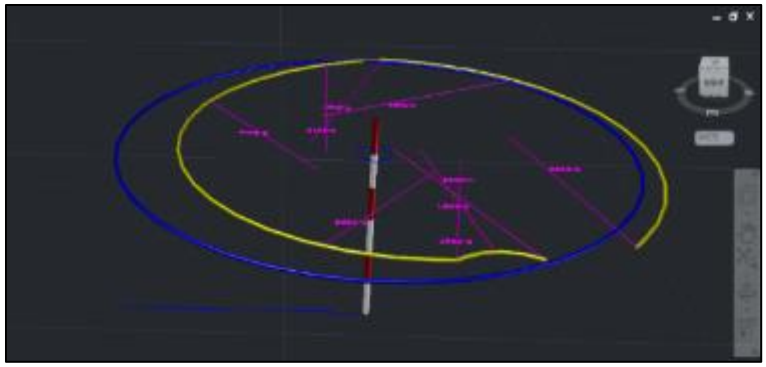


**Figure 50 3D model for the planned and actual path at a height of 5 m, Test 1 - app1**

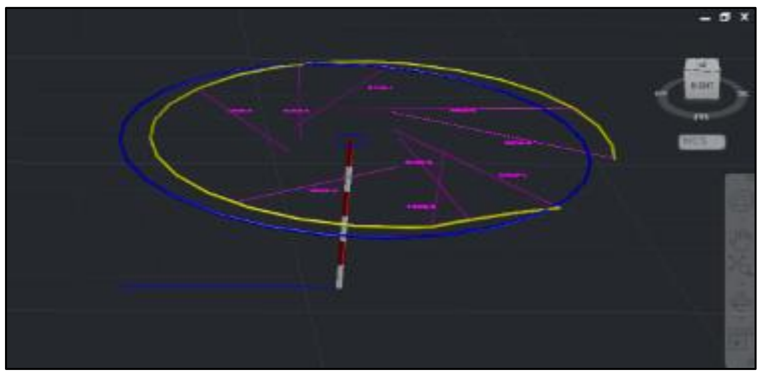


**Figure 51 3D model for the planned and actual path at a height of 6 m, Test 1 - app1**

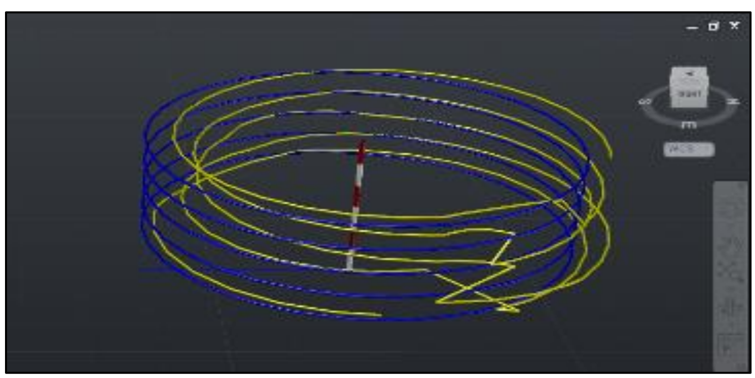


**Figure 52 3D model – view 1 for the planned and actual path, Test 1 - app1**

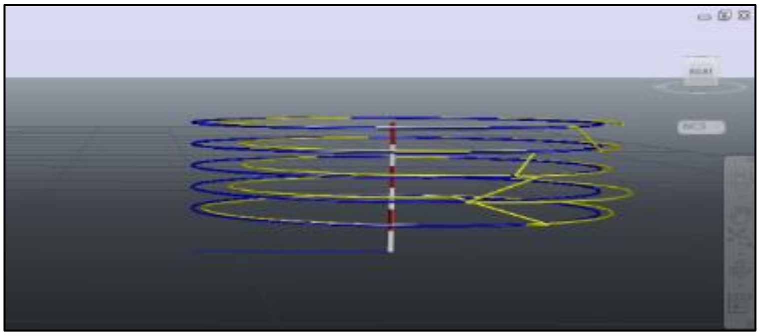


**Figure 53 3D model – view 2 for the planned and actual path, Test 1 - app1**

### *4.2.1.6. Analysis of the mission*

After checking the information collected in subchapters 4.2.1.2, 4.2.1.3 and 4.2.1.4, the following can be stated:

- The actual path for the UAV was not circular as it was pretended in the mission planning, and for each height the path can change according to different variables which can be related to internal factors such as the GPS accuracy in the UAV, or to external factors such as the precision in the coordinates sent to the drone and the wind.
- From previous evaluations, it can be mentioned that the measurements done with photos in the evaluation 3 can have an error of 4.35%, which in a distance of 7.6 m represents an error of approximately 0.33 m (Appendix A.1.). The error in this analysis depends on factors such as the inclination of the camera with respect to the objective at the moment of taking the picture, the camera resolution, and the measurements done by the user.
- The center for the pictures in the UAV can have a difference with the center of coordinates for the mission of approximately 1.975 m with a maximum

difference of 4.382 m and minimum of 0.54 m. It is interesting to mention that according to the orientation of the UAV at the moment of taking the picture it was not focusing to a specific point, however, it seems that the orientation is more related to a region near the point of interest.

- The actual radius in the flight was 0.713 m or 9% lower that the planned one, however, it was a point in which the difference between the actual and planned radius was 2.202 m or approximately 29%. This gives an idea about the risk of collision of the UAV flying autonomously with the structure to be inspected if it is not given a prudent distance to do the work.

### *4.2.2. Test 2 - app 1, date 04-16-2016*

#### *4.2.2.1. Mission definition*

The following are the established parameters for this mission according to the latitude and longitude information taken from the mobile application “GPS Coordinates” (Table 13). It should be mentioned that the last four or five digits in those app’s coordinates are not fixed which can induce an error in the mission lower than 11.09 m in the latitude and 9.551 m in the longitude, according to the values from subchapter 2.8.

**Table 13 Mobile application and parameters used in Test 2 – app 1**

| | |
|---|---|
| **Mobile app used** | Structure_Scan_Coordinates |
| **Long X (DD)** | -96.43860183239443 |
| **Lat Y (DD)** | 30.632975982366506 |
| **Radius (m)** | 16 |
| **Initial H. (m)** | 2 |
| **H. step (m)** | 1 |
| **Interval** | 11 |

In Figure 54 .A. to .D. it can be observed how the mission is sent and verified in the UAV.

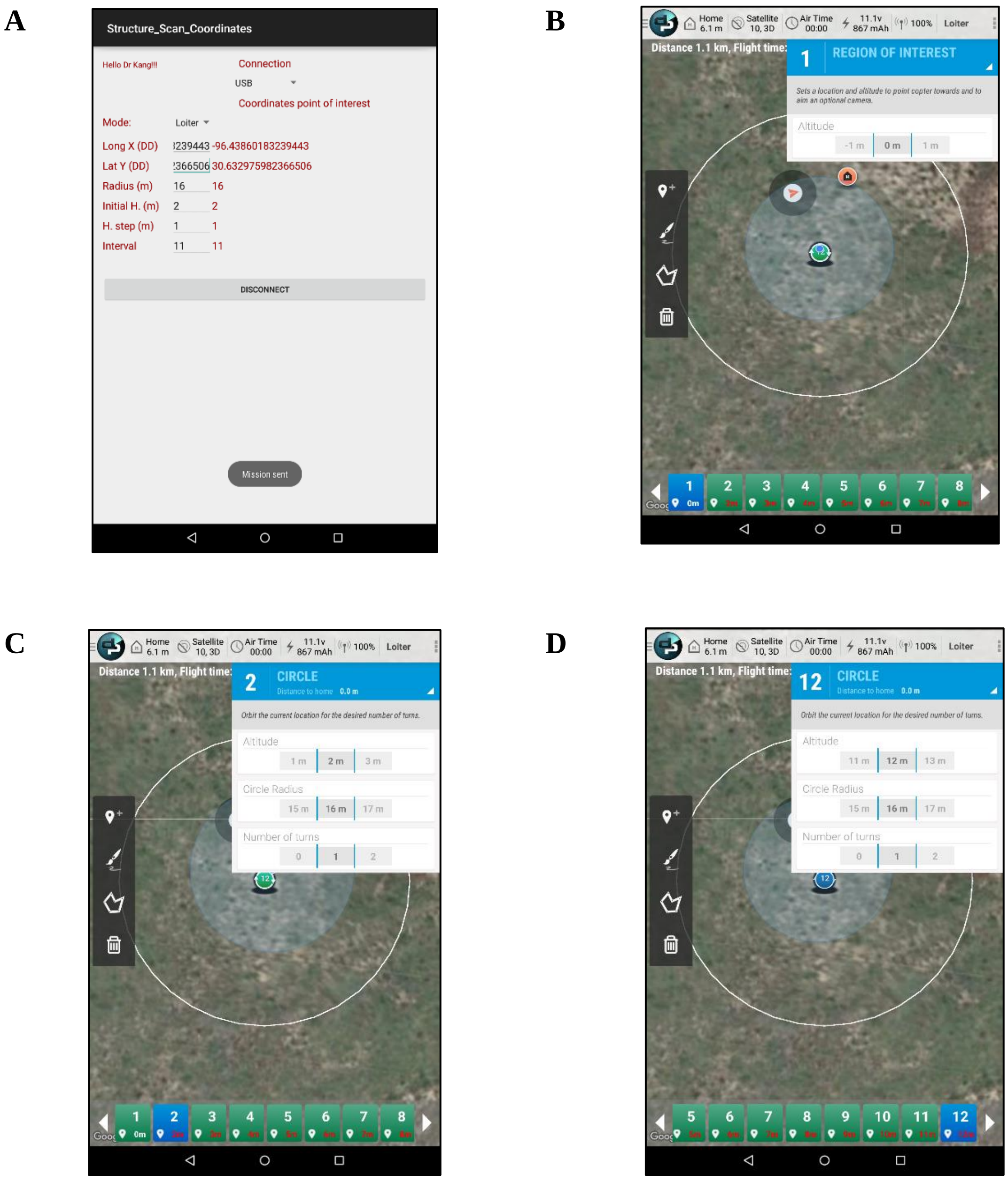



**Figure 54 (A) Mission 2 sent with the Structure_Scan_Coordinates app. (B) First waypoint for the mission in Droidplanner 2. (C) Second waypoint for the mission in Droidplanner 2. (D) Last waypoint for the mission in Droidplanner 2.**

*4.2.2.2. Evaluation 1*

According to the evaluation number 1 proposed in subchapter 3.3, the app worked without any inconveniences for this mission.

*4.2.2.3. Evaluation 2*

For this mission, an IRIS+ drone of 3DRobotics was used in order to develop the evaluation 2 proposed in subchapter 3.3 which was not possible to be done in the "Test 1 – app 1" with the other drone according to the explanation given in subchapter 4.2.1.3.

The information gathered was organized synchronizing the camera and the mobile device clocks (They had a difference of 36 seconds approximately) and separating the data when a change in the height of the images was identified. In subchapter B.1. (Appendix B) it can be found the information split for height steps between 4 and 10 m, and one example is provided in Table 14 at a height of 2 m.

**Table 14 Photos and coordinates were taken from a height of 2m in Test 2 - app 1**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 259 | 15:00:58 | 15:00:22 | 29 | -96.438556 | 30.633104 | 1.880 | -154.6 | -2.8 | -6.9 | Apr 16, 2016 3:00:22 PM |
| 2 | | | | 30 | -96.438513 | 30.633092 | 1.790 | -137.1 | -5.5 | -7.2 | Apr 16, 2016 3:00:23 PM |
| 3 | 260 | 15:01:00 | 15:00:24 | 31 | -96.438475 | 30.633071 | 1.750 | -120.0 | -5.0 | -7.3 | Apr 16, 2016 3:00:24 PM |
| 4 | | | | 32 | -96.438450 | 30.633041 | 1.730 | -101.8 | -3.3 | -7.8 | Apr 16, 2016 3:00:25 PM |

**Table 14 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 261 | 15:01:02 | 15:00:26 | 33 | -96.438443 | 30.633026 | 1.710 | -93.1 | -2.8 | -8.2 | Apr 16, 2016 3:00:26 PM |
| 6 | | | | 34 | -96.438436 | 30.632989 | 1.770 | -74.5 | -1.6 | -8.4 | Apr 16, 2016 3:00:27 PM |
| 7 | 262 | 15:01:04 | 15:00:28 | 35 | -96.438443 | 30.632949 | 1.850 | -57.2 | -0.5 | -7.2 | Apr 16, 2016 3:00:28 PM |
| 8 | | | | 36 | -96.438463 | 30.632912 | 2.090 | -38.4 | 0.5 | -6.5 | Apr 16, 2016 3:00:29 PM |
| 9 | | | | 37 | -96.438479 | 30.632895 | 2.090 | -20.4 | 1.2 | -4.4 | Apr 16, 2016 3:00:30 PM |
| 10 | 263 | 15:01:07 | 15:00:31 | 38 | -96.438535 | 30.632860 | 2.110 | -3.2 | -1.7 | -5.8 | Apr 16, 2016 3:00:31 PM |
| 11 | | | | 39 | -96.438556 | 30.632853 | 2.080 | 14.4 | -0.7 | -4.2 | Apr 16, 2016 3:00:32 PM |
| 12 | 264 | 15:01:09 | 15:00:33 | 40 | -96.438602 | 30.632848 | 1.830 | 30.3 | 0.0 | -4.0 | Apr 16, 2016 3:00:33 PM |
| 13 | | | | 41 | -96.438649 | 30.632855 | 1.530 | 38.2 | -1.4 | -3.7 | Apr 16, 2016 3:00:34 PM |
| 14 | 265 | 15:01:11 | 15:00:35 | 42 | -96.438692 | 30.632872 | 1.510 | 55.6 | -3.6 | -4.1 | Apr 16, 2016 3:00:35 PM |
| 15 | | | | 43 | -96.438723 | 30.632897 | 1.670 | 73.8 | -3.1 | -5.2 | Apr 16, 2016 3:00:36 PM |
| 16 | 266 | 15:01:13 | 15:00:37 | 44 | -96.438745 | 30.632933 | 1.820 | 89.6 | -3.9 | -5.2 | Apr 16, 2016 3:00:37 PM |

**Table 14 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | | | | 45 | -96.438754 | 30.632974 | 1.890 | 108.6 | -4.9 | -5.2 | Apr 16, 2016 3:00:38 PM |
| 18 | | | | 46 | -96.438754 | 30.632992 | 2.000 | 124.8 | -5.2 | -5.6 | Apr 16, 2016 3:00:39 PM |
| 19 | 267 | 15:01:16 | 15:00:40 | 47 | -96.438742 | 30.633032 | 2.120 | 133.9 | -5.7 | -6.1 | Apr 16, 2016 3:00:40 PM |
| 20 | 268 | 15:01:18 | 15:00:42 | 48 | -96.438717 | 30.633065 | 2.220 | 151.2 | -4.4 | -8.7 | Apr 16, 2016 3:00:42 PM |

With this information Figure 55 was developed for the actual path and the planned center at a height of 2m.

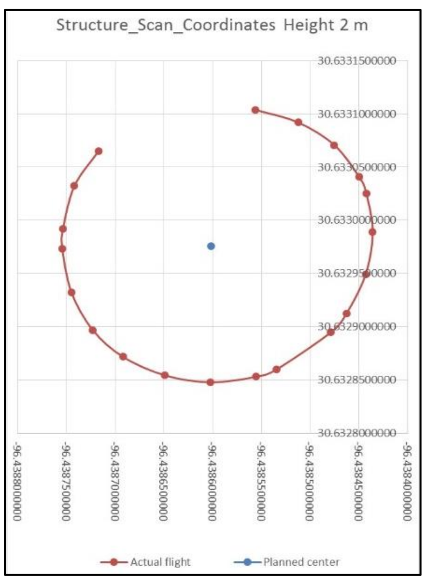



**Figure 55 Actual path and planned center at a height of 2 m in Test 2 – app 1**

Figure 55 was modified in AutoCAD in order to obtain the center of coordinates for the actual path graphically (taken from a green ellipse that was almost symmetrical to the actual path), the planned path (blue circumference), an average of the radius (pink lines) according to four representative points in Figure 56 (index 29, 34, 42 and 48), the estimated yaw angle with respect to the north and according to the UAV orientation and the planned center (pink angles), and the actual yaw angle according to the value read from the UAV (Green adjacent lines to the representative points).

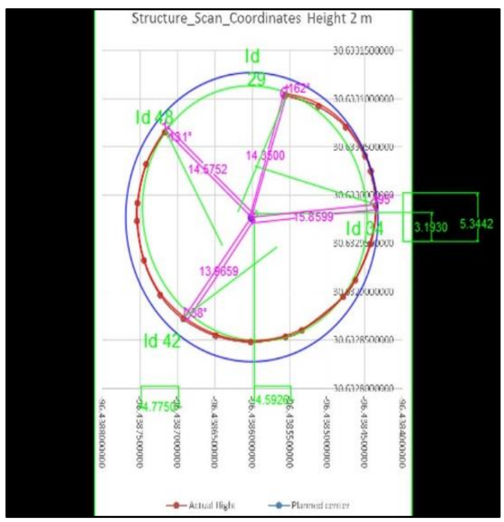



**Figure 56 Planned and actual path at a height of 2 m in Test 2 - app 1, evaluation 2**

The estimated yaw angle and actual radius read from Figure 56 for each representative point can be observed in Table 15. The actual yaw angle was taken according to the data in Table 14 and the planned radius was given as a parameter for the mission. This information was used to create Figure 57 and Figure 58.

Table 15 Planned and actual yaw angle and radius according to the UAV-GPS data at a height of 2 m in Test 2 - app 1

| N. | Index | Est. Yaw (Deg) | Act. Yaw (Deg) | Yaw diff. (Deg) | Abs Yaw diff. (Deg) | Planned radius (m) | Actual Radius (m) | Radius diff. (m) | Abs radius diff. (m) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 29 | -162.000 | -154.590 | 7.410 | 7.410 | 16.000 | 14.350 | -1.650 | 1.650 |
| 2 | 34 | -95.000 | -74.515 | 20.485 | 20.485 | 16.000 | 15.860 | -0.140 | 0.140 |
| 3 | 42 | 38.000 | 55.586 | 17.586 | 17.586 | 16.000 | 13.966 | -2.034 | 2.034 |
| 4 | 48 | 131.000 | 151.167 | 20.167 | 20.167 | 16.000 | 14.575 | -1.425 | 1.425 |
| **Aver.** | | | | | 16.412 | | 14.688 | | 1.312 |
| **Std. dev.** | | | | | 6.140 | | 0.821 | | 0.821 |
| **Coef. Var.** | | | | | 37.41% | | 5.59% | | 62.56% |
| **Max.** | | | | | 20.485 | | 15.860 | | 2.034 |
| **Min.** | | | | | 7.410 | | 13.966 | | 0.140 |

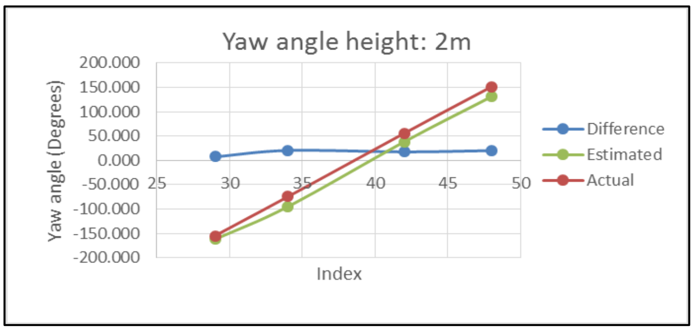



**Figure 57 Yaw angle according to the UAV-GPS at a height of 2 m in Test 2 - app 1**

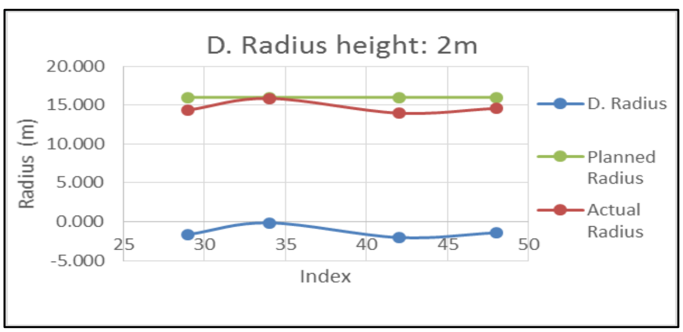



**Figure 58 Radius according to the UAV-GPS at a height of 2 m in Test 2 - app1**

From Table 15 and Figure 57 it can be seen that the UAV is not looking to the center of the pole and the actual orientation of the UAV can have a difference of 16.412

degrees in average with respect to it. For the actual radius, Table 15 and Figure 58 show a difference of 1.312 m in average between the actual and planned path which was not constant in all the height.

The same analysis was done for heights of 4 m, 6 m, 8 m and 10 m. Although the mission was planned until 12 m of height, an issue with the battery in the UAV did not give the opportunity to collect data for this height. Table 16 shows the actual and planned radius and yaw angle for all the representative points in the mission and Figure 59 and Figure 60 show the absolute variation of the radius and the yaw angle.

**Table 16 Planned and actual yaw angle and radius according to the UAV-GPS data for all the representative points in Test 2 - app 1**

| Ref. | Id | N. | Index | Est. Yaw (Deg) | Act. Yaw (Deg) | Yaw diff. (Deg) | Abs Yaw diff. (Deg) | Planned radius (m) | Actual Radius (m) | Radius diff. (m) | Abs radius diff. (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2m height | 1 | 1 | 29 | -162.000 | -154.590 | 7.410 | 7.410 | 16.000 | 14.350 | -1.650 | 1.650 |
| | 2 | 2 | 34 | -95.000 | -74.515 | 20.485 | 20.485 | 16.000 | 15.860 | -0.140 | 0.140 |
| | 3 | 3 | 42 | 38.000 | 55.586 | 17.586 | 17.586 | 16.000 | 13.966 | -2.034 | 2.034 |
| | 4 | 4 | 48 | 131.000 | 151.167 | 20.167 | 20.167 | 16.000 | 14.575 | -1.425 | 1.425 |
| 4m height | 5 | 1 | 81 | 123.000 | 125.461 | 2.461 | 2.461 | 16.000 | 16.412 | 0.412 | 0.412 |
| | 6 | 2 | 87 | -158.000 | -143.198 | 14.802 | 14.802 | 16.000 | 13.850 | -2.150 | 2.150 |
| | 7 | 3 | 94 | -51.000 | -32.345 | 18.655 | 18.655 | 16.000 | 15.357 | -0.643 | 0.643 |
| | 8 | 4 | 102 | 84.000 | 104.651 | 20.651 | 20.651 | 16.000 | 15.230 | -0.770 | 0.770 |
| 6m height | 9 | 1 | 134 | 90.000 | 98.043 | 8.043 | 8.043 | 16.000 | 15.475 | -0.525 | 0.525 |
| | 10 | 2 | 141 | 152.000 | 174.321 | 22.321 | 22.321 | 16.000 | 14.945 | -1.055 | 1.055 |
| | 11 | 3 | 149 | -75.000 | -58.287 | 16.713 | 16.713 | 16.000 | 15.329 | -0.671 | 0.671 |
| | 12 | 4 | 158 | 73.000 | 87.138 | 14.138 | 14.138 | 16.000 | 15.261 | -0.739 | 0.739 |
| 8m height | 13 | 1 | 191 | 66.000 | 64.107 | -1.893 | 1.893 | 16.000 | 15.548 | -0.452 | 0.452 |
| | 14 | 2 | 197 | 149.000 | 170.880 | 21.880 | 21.880 | 16.000 | 15.211 | -0.789 | 0.789 |
| | 15 | 3 | 205 | -81.000 | -62.216 | 18.784 | 18.784 | 16.000 | 15.210 | -0.790 | 0.790 |
| | 16 | 4 | 212 | 32.000 | 49.375 | 17.375 | 17.375 | 16.000 | 15.469 | -0.531 | 0.531 |
| 10m height | 17 | 1 | 245 | 32.000 | 39.931 | 7.931 | 7.931 | 16.000 | 15.577 | -0.423 | 0.423 |
| | 18 | 2 | 251 | 123.000 | 145.034 | 22.034 | 22.034 | 16.000 | 15.133 | -0.867 | 0.867 |
| | 19 | 3 | 258 | -115.000 | -108.421 | 6.579 | 6.579 | 16.000 | 15.003 | -0.997 | 0.997 |
| | 20 | 4 | 266 | 4.000 | 21.279 | 17.279 | 17.279 | 16.000 | 14.625 | -1.375 | 1.375 |

**Table 16 Continued**

| Ref. | Id | N. | Index | Est. Yaw (Deg) | Act. Yaw (Deg) | Yaw diff. (Deg) | Abs Yaw diff. (Deg) | Planned radius (m) | Actual Radius (m) | Radius diff. (m) | Abs radius diff. (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Aver. | | | | | | | 14.859 | | 15.119 | | 0.922 |
| Std. dev. | | | | | | | 6.663 | | 0.613 | | 0.545 |
| Coef. Var. | | | | | | | 44.84% | | 4.05% | | 59.13% |
| Max. | | | | | | | 22.321 | | 16.412 | | 2.150 |
| Min. | | | | | | | 1.893 | | 13.850 | | 0.140 |

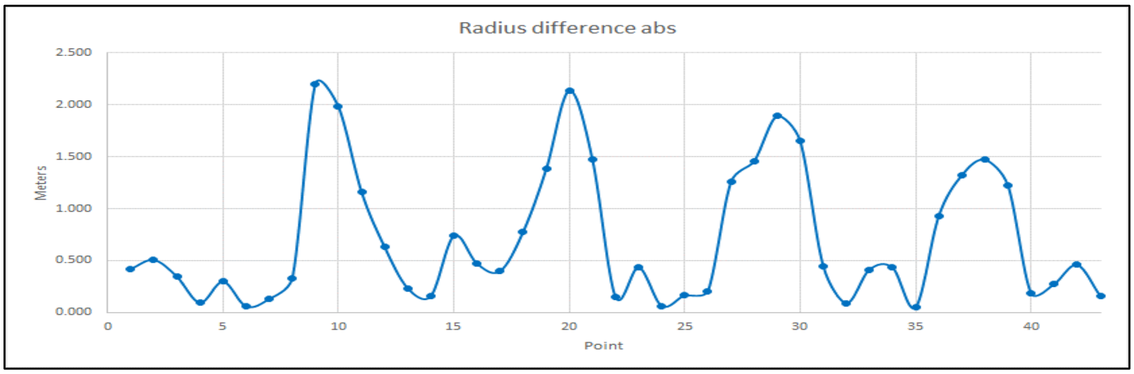



**Figure 59 Absolute radius difference according to the UAV-GPS data for all the representative points in Test 2 - app 1**

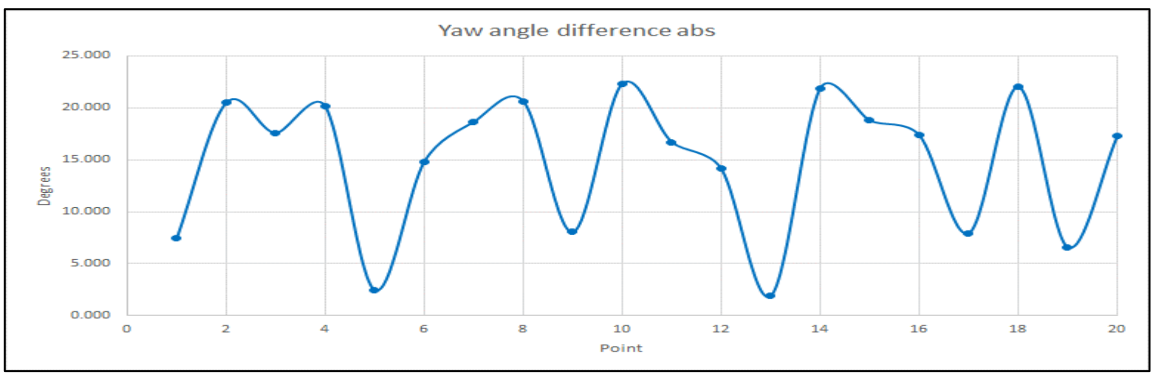



**Figure 60 Absolute yaw angle according to the UAV-GPS data for all the representative points in Test 2 - app 1**

According to Table 16 and Figure 59, it can be seen that the actual radius is in average lower than the planned one and their difference is approximately 0.922 m.

However, there were points in which the actual radius had a minimum value of 13.850 m and maximum of 16.412 m, while the value closer to the planned radius was 15.860 m (point with the index 34). Table 16 and Figure 60 indicate that in general there was a difference between the actual orientation of the UAV with respect to the pole location which was in average 14.859 degrees, with a maximum difference of 22.321 and a minimum difference of 1.893 degrees (points with index 141 and 191).

Table 17 summarizes the data collected for each height according to the evaluation 2 and Figure 61 to Figure 65 show the actual average and planned height, latitude, longitude, pitch angle and radius in 5 different levels in height.

**Table 17 Summary of planned and actual data and differences for each height according to the UAV-GPS in Test 2 - app1**

| | Point | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Planned Test 2 – app 1** | Height (m) | 2.000 | 4.000 | 6.000 | 8.000 | 10.000 |
| | Lat (DD) | 30.632976 | 30.632976 | 30.632976 | 30.632976 | 30.632976 |
| | Long (DD) | -96.438602 | -96.438602 | -96.438602 | -96.438602 | -96.438602 |
| | Pitch angle (degrees) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Radius (m) | 16.000 | 16.000 | 16.000 | 16.000 | 16.000 |
| **Actual Test 2 – app 1** | Height (m) | 1.872 | 3.962 | 5.921 | 7.945 | 9.971 |
| | Lat (DD) | 30.632980 | 30.632972 | 30.632976 | 30.632973 | 30.632975 |
| | Long (DD) | -96.438595 | -96.438602 | -96.438603 | -96.438604 | -96.438603 |
| | Pitch angle (degrees) | -2.725 | -3.100 | -3.440 | -4.315 | -4.202 |
| | Radius (m) | 14.688 | 15.212 | 15.253 | 15.360 | 15.084 |

| | | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
|---|---|---|---|---|---|---|
| **Actual Test 2 – app 1** | Height (m) | | | | | |
| | Lat (DD) | 30.632975 | 0.000003 | 0.00% | 30.632980 | 30.632972 |
| | Long (DD) | -96.438601 | 0.000004 | 0.00% | -96.438595 | -96.438604 |
| | Pitch angle (degrees) | -3.557 | 0.690 | -19.40% | -2.725 | -4.315 |
| | Radius (m) | 15.119 | 0.261 | 1.72% | 15.360 | 14.688 |

**Table 17 Continued**

| | Point | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Abs. diff. Test 2 – app 1** | Height (m) | 0.128 | 0.038 | 0.079 | 0.055 | 0.029 |
| | Lat (DD) | 0.000004 | 0.000004 | 0.000000 | 0.000003 | 0.000001 |
| | Lat (m) | 0.431917 | 0.401244 | 0.042485 | 0.334945 | 0.132475 |
| | Long (DD) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Long (m) | 0.654 | 0.057 | 0.130 | 0.182 | 0.124 |
| | Pitch angle (degrees) | 2.725168396 | 3.100495484 | 3.440057914 | 4.315136451 | 4.201982254 |
| | Radius (m) | 1.312 | 0.788 | 0.747 | 0.640 | 0.916 |
| | | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
| **Abs. diff. Test 2 – app 1** | Height (m) | 0.066 | 0.040 | 60.47% | 0.128 | 0.029 |
| | Lat (DD) | 0.000002 | 0.000002 | 64.03% | 0.000004 | 0.000000 |
| | Lat (m) | 0.269 | 0.172 | 64.03% | 0.432 | 0.042 |
| | Long (DD) | 0.000002 | 0.000003 | 105.42% | 0.000007 | 0.000001 |
| | Long (m) | 0.229 | 0.242 | 105.42% | 0.654 | 0.057 |
| | Pitch angle (degrees) | 3.557 | 0.690 | 19.40% | 4.315 | 2.725 |
| | Radius (m) | 0.881 | 0.261 | 29.59% | 1.312 | 0.640 |

| | Point | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **Abs. diff. Test 2 – app 1 (%)** | Height (m) | 6.40% | 0.94% | 1.31% | 0.68% | 0.29% |
| | Lat (DD) | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Long (DD) | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Pitch angle (degrees) | - | - | - | - | - |
| | Radius (m) | 8.20% | 4.92% | 4.67% | 4.00% | 5.72% |
| | | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
| **Abs. diff. Test 2 – app 1 (%)** | Height (m) | 1.93% | 2.53% | 131.31% | 6.40% | 0.29% |
| | Lat (DD) | 0.00% | 0.00% | 64.03% | 0.00% | 0.00% |
| | Long (DD) | 0.00% | 0.00% | 105.42% | 0.00% | 0.00% |
| | Pitch angle (degrees) | - | - | - | - | - |
| | Radius (m) | 5.50% | 1.63% | 29.59% | 8.20% | 4.00% |

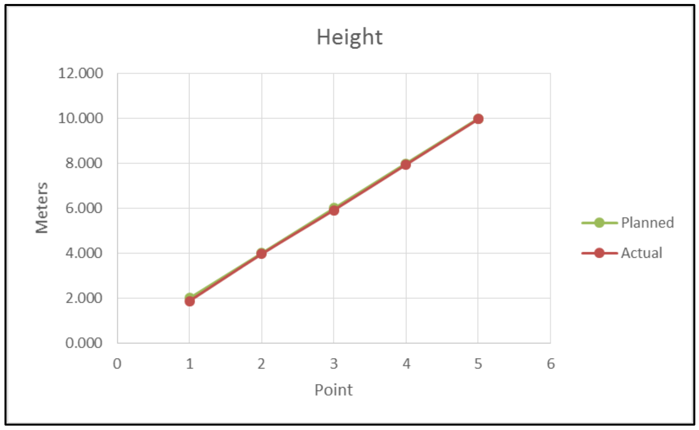



**Figure 61 Actual average and planned height for each point according to the UAV-GPS in Test 2 - app1**

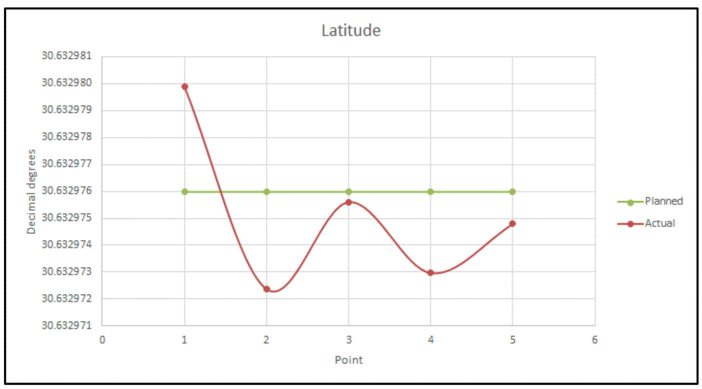



**Figure 62 Actual average and planned latitude for each point according to the UAV-GPS in Test 2 - app1**

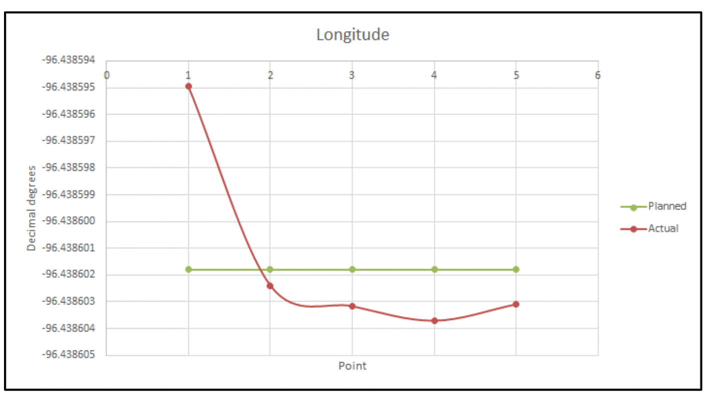



**Figure 63 Actual average and planned longitude for each point according to the UAV-GPS in Test 2 - app1**

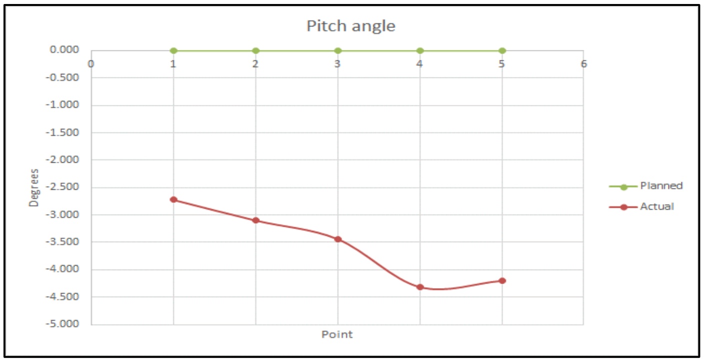



**Figure 64 Actual average and planned pitch angle for each point according to the UAV-GPS in Test 2 - app1**

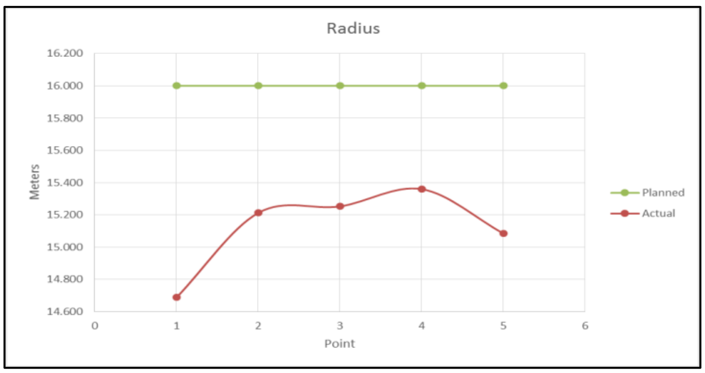



**Figure 65 Actual average and planned radius for each point according to the UAV-GPS in Test 2 - app1**

From Table 17, it can be observed that the error between the planned and actual path in each mission step is in average 0.066 m or 1.93% in height, 0.269 m for the latitude, 0.229 m for the longitude, 3.557 degrees for the pitch angle, and approximately 6% for the radius.

*4.2.2.4. Evaluation 3*

Photos between a height of 2 m and 6 m with of 2 m increments were taken each 2 seconds in order to do the evaluation 3 proposed in subchapter 3.3.

Such as it is mentioned in subchapter 4.2.1.4 for Test 1 – app 1, the photos of this process were used to do an actual flight path reconstruction in order to test the accuracy between the real and the planned path according to the objective 2 of the current research mentioned in subchapter 1.4., in order to complement and compare the information obtained in the evaluation 2 in subchapter 4.2.2.3.

A calibration photo (photo FHD0031) was taken at a distance of 7.6 m in order to have a reference of the frame height when the second section of the pole has a height of 1 m (Figure 66 and Figure 67).

**Figure 66 Calibration photo FHD0031**

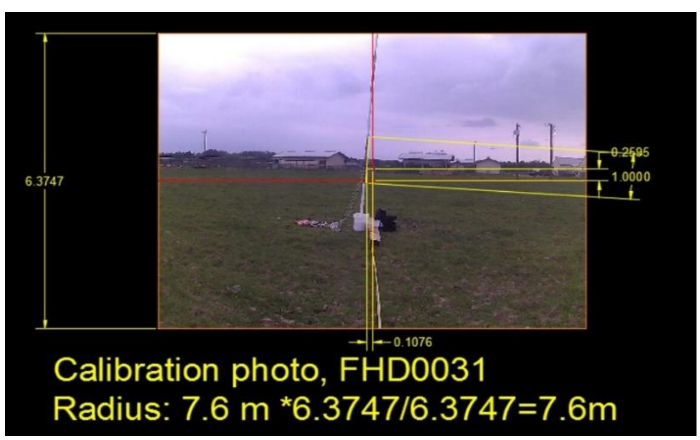



**Figure 67 Calibration photo FHD0031 with measurements**

Approximately 58 photos were taken between a height of 2 m and 6 m and according to the results in subchapter 4.2.1.4, the inclination when the UAV took the pictures was omitted in the calculations.

For this evaluation at least 4 pictures in different quadrants (considering the actual path circumference for each height as the plane) were examined as it is shown in the Figure 68 in order to obtain the distance between the center of the photo and the pole (DX) and the height of the frame in order to estimate the radius (Figure 69). With that information it was possible to develop Table 18 which gives information about the average, standard deviation, coefficient of variation, maximum and minimum values of absolute DX, actual radius, difference between planned and actual radius and the angle difference between consecutive photos. This data was used to draw an approximate path of the UAV when it was doing the mission in a 2 m height (Figure 72); the position of the UAV with respect to the tape that was oriented looking to the magnetic north was measured from the draw and was utilized to build the column "Angle UAS - East (Degrees)" in Table 18.

**Figure 68 Photo FHD0259 at a height of 2 m**

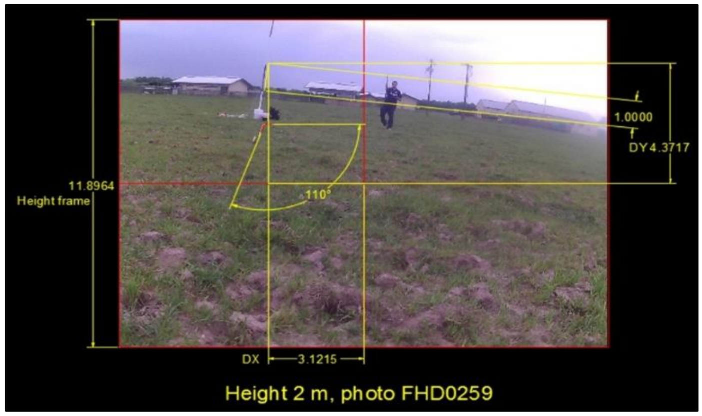



**Figure 69 FHD0259 at a height of 2 m with measurements**

**Table 18 Measurements for 5 photos which were taken at a height of 2 m in Test 2 - app1**

| N. | Photo FHD0 | DX(m) | Abs DX(m) | DY(m) | Photo frame height (m) | Actual Radius (m) | Planned radius (m) | Radius diff. (m) | Abs radius diff. (m) | Angle UAS-East (Degrees) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 259 | -3.122 | 3.122 | 4.372 | 11.896 | 14.183 | 16.000 | -1.817 | 1.817 | 122.000 |
| 2 | 262 | -7.639 | 7.639 | 4.505 | 12.655 | 15.088 | 16.000 | -0.912 | 0.912 | 26.000 |
| 3 | 264 | -7.060 | 7.060 | 4.626 | 11.871 | 14.152 | 16.000 | -1.848 | 1.848 | -25.000 |
| 4 | 265 | -6.655 | 6.655 | 5.027 | 12.300 | 14.664 | 16.000 | -1.336 | 1.336 | -149.000 |
| 5 | 268 | -4.476 | 4.476 | 2.450 | 11.992 | 14.297 | 16.000 | -1.703 | 1.703 | -178.000 |
| **Aver.** | | | 5.790 | | | 14.477 | | | 1.523 | |
| **Std. dev.** | | | 1.912 | | | 0.398 | | | 0.398 | |
| **Coef. Var.** | | | 33.02% | | | 2.75% | | | 26.10% | |
| **Max.** | | | 7.639 | | | 15.088 | | | 1.848 | |
| **Min.** | | | 3.122 | | | 14.152 | | | 0.912 | |

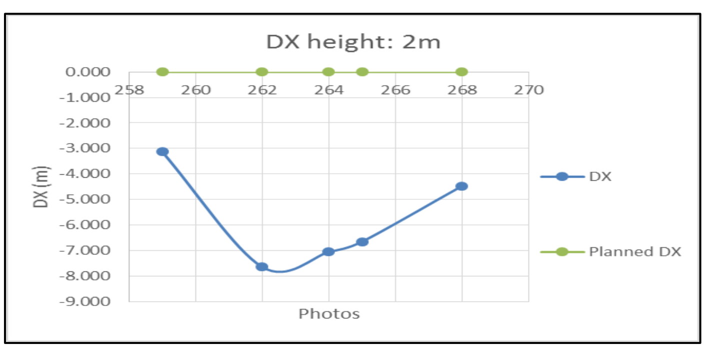



**Figure 70 Horizontal distance (DX) between the center of the photo and the pole at a height of 2 m in 5 different points, Test 2 - app1**

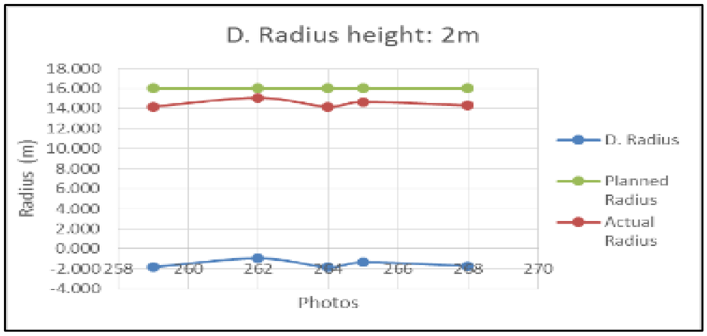



**Figure 71 Planned and actual radius estimation in different points at a height of 2 m in 5 different points, Test 2 - app1**

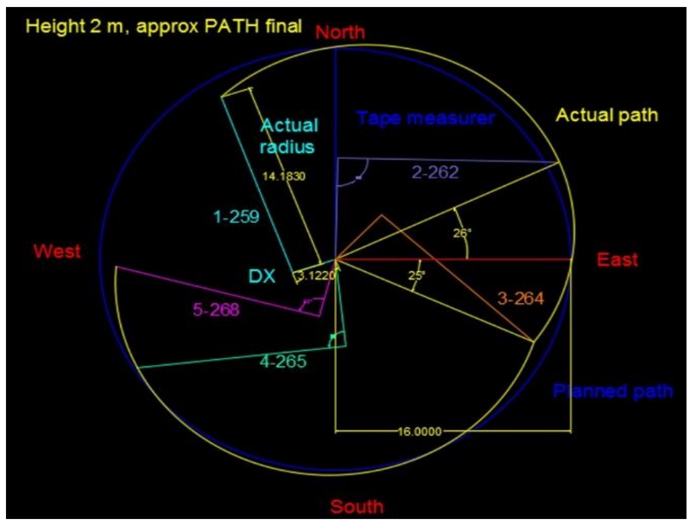



**Figure 72 Planned and actual path at a height of 2 m in Test 2 - app1, evaluation 3**

From Table 18, Figure 70 and Figure 71, it is possible to say for the height of 2 m in this mission that the error between the pole's center has an average of 5.79 m, with a maximum error of 7.639 m and a minimum of 3.122 m. For the radius difference, the average was 1.523 m, with a maximum difference of 1.848 m and a minimum of 0.912 m, which means that the average actual radius was 14.477 m, the maximum radius was 15.088 m and the minimum was 14.152 m.

Table 18 was created for a height of 2 m. The same table was also done for the heights of 4 m and 6 m and according to them, Table 19, Figure 73 and Figure 74 were generated to summarize and show the DX error and radius difference according to all the photos. The information given in Table 19 was classified for each height and according to that Table 20 was created.

**Table 19 DX and radius difference for all the photos analyzed in Test 2 - app 1**

| **Ref.** | **Id.** | **N.** | **Photo FHD0** | **DX(m)** | **Abs DX(m)** | **DY(m)** | **Photo frame height (m)** | **Act. Rad. (m)** | **Plan. Rad. (m)** | **Rad. diff. (m)** | **Abs. Rad. diff. (m)** | **Angle UAS - East (Deg)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2m height | 1 | 1 | 259 | -3.122 | 3.122 | 4.372 | 11.896 | 14.183 | 16.000 | -1.817 | 1.817 | 122.000 |
| | 2 | 2 | 262 | -7.639 | 7.639 | 4.505 | 12.655 | 15.088 | 16.000 | -0.912 | 0.912 | 26.000 |
| | 3 | 3 | 264 | -7.060 | 7.060 | 4.626 | 11.871 | 14.152 | 16.000 | -1.848 | 1.848 | -25.000 |
| | 4 | 4 | 265 | -6.655 | 6.655 | 5.027 | 12.300 | 14.664 | 16.000 | -1.336 | 1.336 | -149.000 |
| | 5 | 5 | 268 | -4.476 | 4.476 | 2.450 | 11.992 | 14.297 | 16.000 | -1.703 | 1.703 | -178.000 |
| 4m height | 6 | 1 | 283 | -2.931 | 2.931 | 5.355 | 14.205 | 16.935 | 16.000 | 0.935 | 0.935 | 160.000 |
| | 7 | 2 | 285 | -5.168 | 5.168 | 4.943 | 10.931 | 13.032 | 16.000 | -2.968 | 2.968 | 37.000 |
| | 8 | 3 | 286 | -2.640 | 2.640 | 5.236 | 11.155 | 13.299 | 16.000 | -2.701 | 2.701 | 3.000 |
| | 9 | 4 | 289 | -3.938 | 3.938 | 4.256 | 12.900 | 15.379 | 16.000 | -0.621 | 0.621 | -20.000 |
| | 10 | 5 | 290 | -4.830 | 4.830 | 5.642 | 13.556 | 16.161 | 16.000 | 0.161 | 0.161 | -163.000 |
| 6m height | 11 | 1 | 307 | 0.368 | 0.368 | 5.276 | 13.391 | 15.965 | 16.000 | -0.035 | 0.035 | 169.000 |
| | 12 | 2 | 311 | -2.830 | 2.830 | 5.426 | 11.319 | 13.495 | 16.000 | -2.505 | 2.505 | 96.000 |
| | 13 | 3 | 312 | -1.305 | 1.305 | | 11.398 | 13.589 | 16.000 | -2.411 | 2.411 | 23.000 |
| | 14 | 4 | 315 | -4.311 | 4.311 | 5.183 | 12.777 | 15.233 | 16.000 | -0.767 | 0.767 | -8.000 |
| | 15 | 5 | 316 | -4.163 | 4.163 | 4.350 | 12.384 | 14.764 | 16.000 | -1.236 | 1.236 | -89.000 |
| | 16 | 6 | 317 | -6.143 | 6.143 | 5.298 | 13.647 | 16.270 | 16.000 | 0.270 | 0.270 | -143.000 |
| **Aver.** | | | | | 4.224 | | | 14.782 | | | 1.389 | |
| **Std. dev.** | | | | | 2.024 | | | 1.159 | | | 0.932 | |
| **Coef. Var.** | | | | | 47.91% | | | 7.84% | | | 67.08% | |
| **Max.** | | | | | 7.639 | | | 16.935 | | | 2.968 | |
| **Min.** | | | | | 0.368 | | | 13.032 | | | 0.035 | |

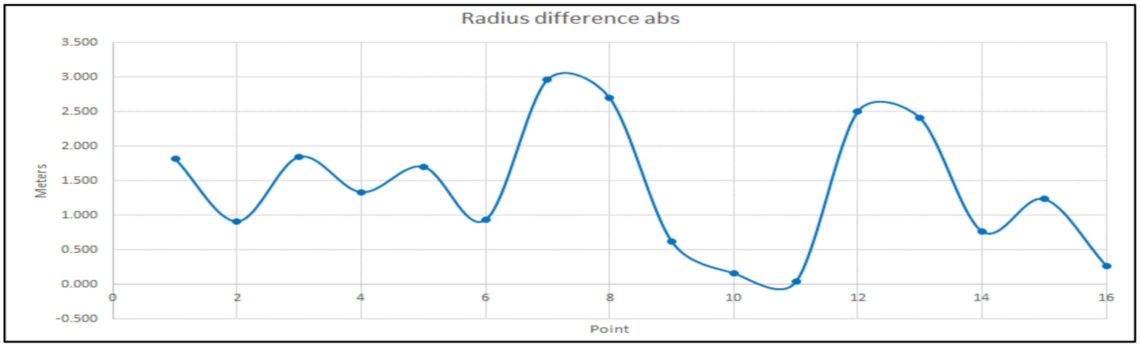



**Figure 73 Absolute radius difference for all the photos analyzed in Test 2 - app 1**

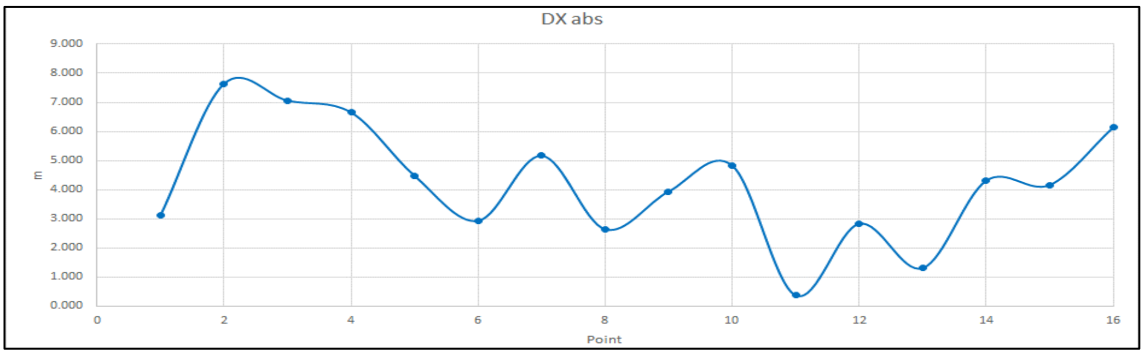



**Figure 74 Horizontal distance between the center of the picture and the pole position (DX abs) for all the photos analyzed in Test 2 - app 1**

**Table 20 Summary of planned and actual data and differences for each height from photos in Test 2 - app 1**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Planned Test 2 – app 1** | Point | 1 | 2 | 3 | | | | | |
| | Height (m) | 2.000 | 4.000 | 6.000 | | | | | |
| | Abs DX (m) | 0 | 0 | 0 | | | | | |
| | Radius (m) | 16.000 | 16.000 | 16.000 | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
| **Actual Test 2 – app 1** | Abs DX (m) | 5.790 | 3.910 | 3.187 | 4.296 | 1.344 | 31.29% | 5.790 | 3.187 |
| | Radius (m) | 14.477 | 15.118 | 14.886 | 14.827 | 0.325 | 2.19% | 15.118 | 14.477 |
| **Abs. diff. Test 2 – app 1** | Abs DX (m) | 5.790 | 3.910 | 3.187 | 4.296 | 1.344 | 31.29% | 5.790 | 3.187 |
| | Radius (m) | 1.523 | 0.882 | 1.114 | 1.173 | 0.325 | 27.68% | 1.523 | 0.882 |
| **Abs. diff. Test 2 – app 1(%)** | Abs DX (m) | 100.00% | 100.00% | 100.00% | 100.00% | 0.00% | 0.00% | 100.00% | 100.00% |
| | Radius (m) | 10.52% | 5.83% | 7.48% | 7.95% | 2.38% | 29.93% | 10.52% | 5.83% |

From Table 19, it can be said that the horizontal average error between the center of the photos and the pole for all the mission at a height between 2 m to 6 m was 4.224 m, with a maximum value of 7.639 m and minimum of 0.368 m. The average absolute radius difference from the photos was 1.389 m or 9% with respect to the planned radius (16 m), with a maximum value of 2.968 m and a minimum of 0.035 m. The radius had a range between 16.935 m and 13.032 m according to this table.

From Table 20, it is shown that in the height of 2 m the Abs DX had an average value of 5.790 m which was bigger than in the other heights and the radius had an average of 14.477 m which was lower than in the other points.

According to the evaluation 3 proposed in subchapter 3.3, the following is the percentage for the wrong focus:

$$Eq.\%\, wrong\ focus = \frac{\sum Option\ B\ photos}{\sum Option\ A\ photos + \sum Option\ B\ photos} \times 100\%$$

$$Eq.\%\, wrong\ focus = \frac{16}{0+16} \times 100\% = 100\%$$

It means that the center of the photos did not fit with the center of coordinates, and it is supported with the information provided in Table 19 in which the horizontal distance between the pole and the center of the images had an average of 4.224 m with a standard deviation of 2.024 m.

*4.2.2.5. 3D Model for Test 2 – app 1*

Figure 75 until Figure 79 show the 3D model for the flight of the UAV and its orientation with respect to the pole according to Figure 56, Figure 72 and the other ones that were done at different heights. In those graphics the height was considered constant in each step, the blue circumference is the planned path, the red figure is the actual path and the green lines show the actual yaw angle according to the GPS and UAV sensors (subchapter 4.2.3.3), the yellow figure is the actual path and the magenta lines show the UAV orientation from the photos (subchapter 4.2.3.4), the blue line indicates the tape measure that was used to reference the north.

Figure 80 and Figure 81 show a 3D model for the UAV flight according to the planned and actual paths drawn in Figure 75 until Figure 79.

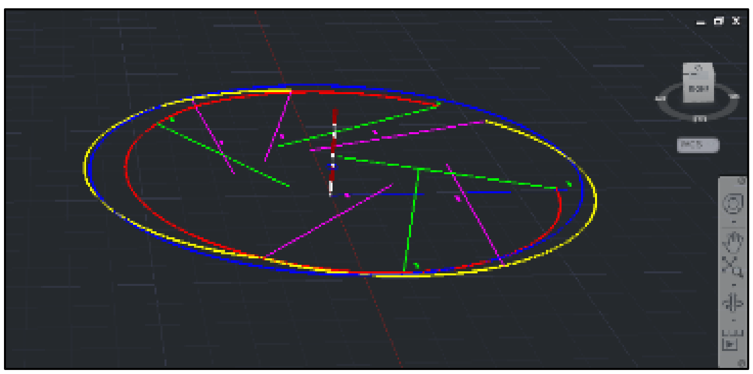


**Figure 75 3D model for the planned and actual path at a height of 2 m, Test 2 - app1**

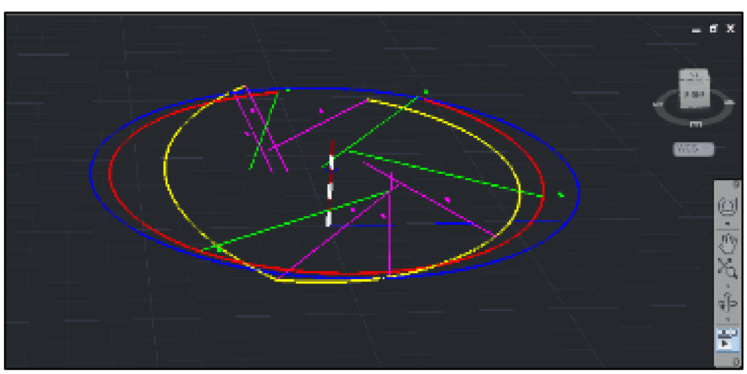


**Figure 76 3D model for the planned and actual path at a height of 4 m, Test 2 - app1**

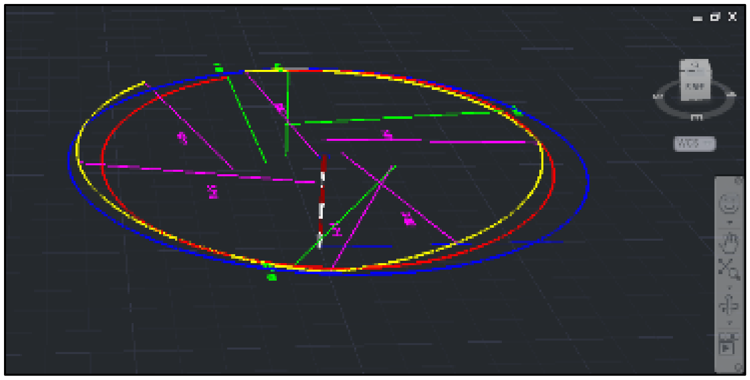


**Figure 77 3D model for the planned and actual path at a height of 6 m, Test 2 - app1**

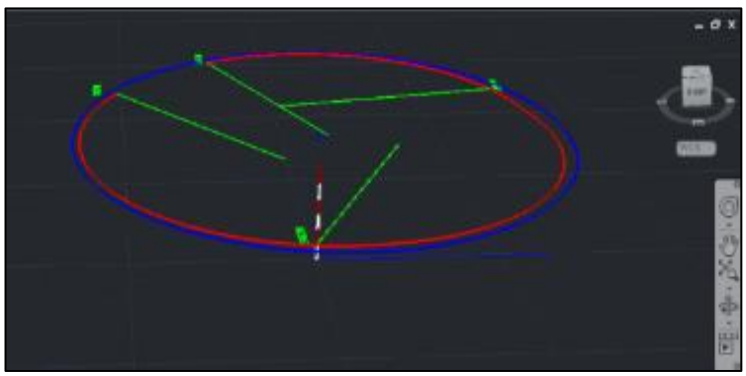


**Figure 78 3D model for the planned and actual path at a height of 8 m, Test 2 - app1**

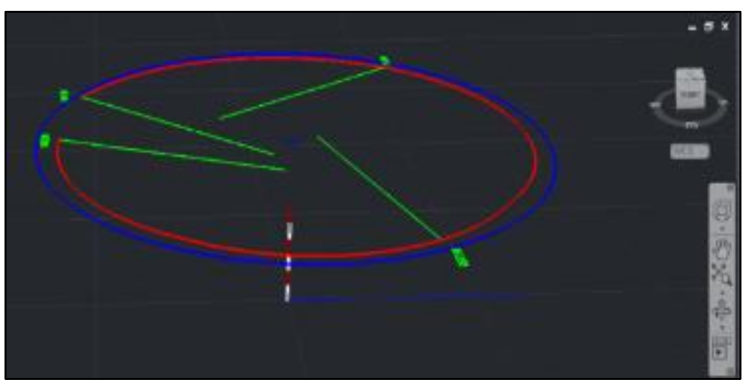


**Figure 79 3D model for the planned and actual path at a height of 10 m, Test 2 - app1**

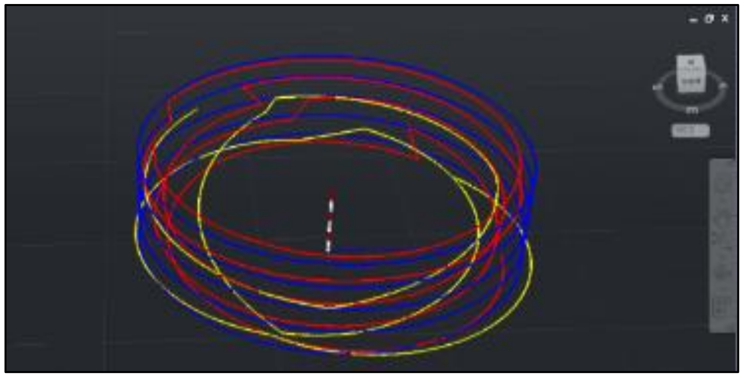


**Figure 80 3D model – view 1 for the planned and actual path, Test 2 - app1**

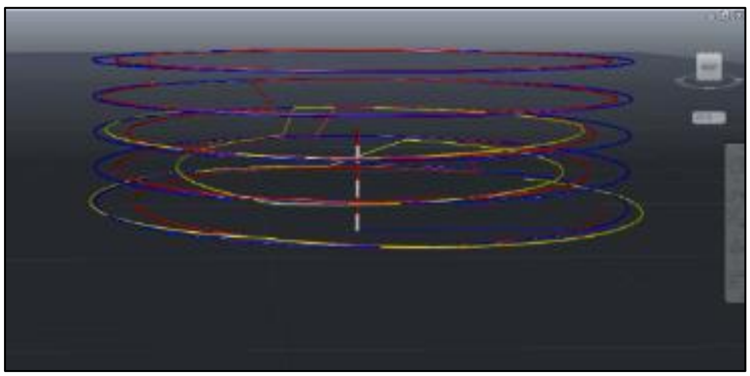


**Figure 81 3D model – view 2 for the planned and actual path, Test 2 - app1**

#### *4.2.2.6. Analysis of the mission*

After checking the information collected in subchapters 4.2.2.2, 4.2.2.3 and 4.2.2.4, the following can be mentioned:

- The actual path for the UAV was not circular as it was pretended in the mission planning and as it was stated in subchapter 4.2.1.6, which can be linked to factors related to the GPS accuracy in the UAV, the wind, etc.

- Although the accuracy in the SUAS-GPS may be of 5 m or less according to subchapter 2.8, for this work the evaluation 2 gives a good idea about the actual position and orientation during the UAV flight.
- From the evaluation 2, it can be said that the UAV had differences in its planned and actual flight. The actual height was on average 0.066 m or 1.93% lower than the planned one; the latitude had an average difference of 0.000002 DD or 0.269 m; the longitude had an average difference of 0.000002 DD or 0.229 m; the pitch angle had an absolute increment in each height step and its average was 3.557 degrees; the radius had an average of 15.119 m with a minimum value of 13.850 m (13% lower than the planned value) and a maximum of 16.412 m (2.5% bigger than the planned value); and the angle between the actual orientation and the planned objective had a difference of 14.859 degrees on average.
- From previous evaluations, it can be mentioned that the measurements done with photos in the evaluation 3 can have an error of 4.35 percent, which in a distance of 16 m represents an error of approximately 0.696 m (Appendix A.1.). However, the error in this analysis depends on factors such as the inclination of the camera with respect to the objective at the moment of taking the picture, the camera resolution, and the measurements done by the user.
- From the evaluation 3, it can be said that the center for the pictures in the UAV can have a difference with the center of coordinates for the mission of approximately 4.224 m with a maximum difference of 7.639 m and minimum

of 0.368 m. It is interesting to mention that according to the orientation of the UAV at the moment of taking the picture it was not focusing to a specific point but to a region as it was said in subchapter 4.2.2.4.

- From the evaluation 3, the average absolute radius actual radius difference was 1.389 m or 9% lower that the planned one, however, there was a point in which the difference between the actual and planned radius was 2.968 m or approximately 19%. This gives an idea about the risk of collision of the UAV with the structure to be inspected if it is not given a prudent distance to do the work when flying autonomously.
- Evaluation 2 and 3 show differences in the values of the actual path and yaw angle, however, they support the fact that the UAV did not fly exactly as it was expected and it had a deviation at the moment of focusing the objective.

#### *4.2.3. Test 1 - app 2, date 04-16-2016*

##### *4.2.3.1. Mission definition*

Values in Table 21 are the established parameters for this mission according to the latitude and longitude information taken from the mobile application “GPS Coordinates”. It should be mentioned that the last four or five digits in those app’s coordinates are not fixed which can induce an error which is less than 11.09 m in the latitude and 9.551 m in the longitude, according to the values from in subchapter 2.8.

**Table 21 Mobile application and parameters used in Test 1 – app 2**

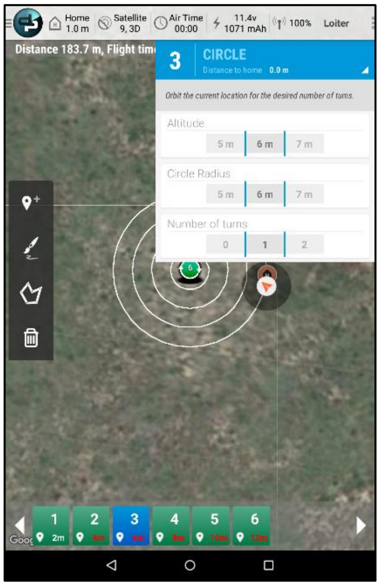
| | |
|---|---|
| **Mobile app used** | Drone Height Reduction |
| **Long X (DD)** | -96.43860183239443 |
| **Lat Y (DD)** | 30.632975982366506 |
| **Radius (m)** | 8 |
| **Con. Height (m)** | 4 |
| **Var. Height (m)** | 8 |
| **R. Reduction (m)** | 2 |
| **Interval** | 6 |
| **N. of turns** | 1 |

In Figure 82 .A. to .D. it can be observed how the mission is sent and verified in the UAV.

**A** **B**


**Figure 82 (A) Mission 1 sent with the Drone Height Reduction app. (B) First waypoint for the mission in Droidplanner 2. (C) Third waypoint for the mission in Droidplanner 2. (D) Last waypoint for the mission in Droidplanner 2.**

C




D

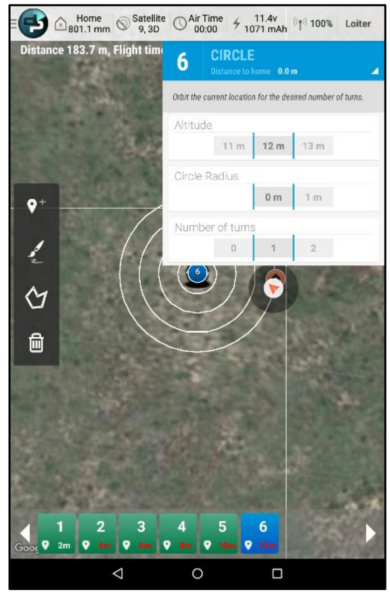



**Figure 82 Continued**

### *4.2.3.2. Evaluation 1*

According to the evaluation 1 proposed in subchapter 3.3., the app worked without any inconveniences for this mission.

### *4.2.3.3. Evaluation 2*

For this mission, an IRIS+ drone of 3DRobotics was used as it was said in subchapter 4.2.2.3. The information gathered was organized synchronizing the camera and the mobile device clocks (They had a difference of 31 seconds approximately) and separating the data when a change in the height of the images was identified. In subchapter C.1. (Appendix C) it can be found the information split per heights between 4 and 12 m, and one example is provided in Table 22 for a height of 2m.

**Table 22 Photos and coordinates were taken from a height of 2m in Test 1 - app 2**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9081 | 14:20:34 | 14:20:03 | 15 | -96.438514 | 30.632966 | 0.000 | -45.5 | 3.9 | -0.6 | Apr 16, 2016 2:20:03 PM |
| 2 | 9082 | 14:20:35 | 14:20:04 | 16 | -96.438516 | 30.632970 | 0.550 | -44.3 | 1.7 | -2.1 | Apr 16, 2016 2:20:04 PM |
| 3 | 9083 | 14:20:36 | 14:20:05 | 17 | -96.438519 | 30.632974 | 1.850 | -54.4 | 7.0 | -4.3 | Apr 16, 2016 2:20:05 PM |
| 4 | 9084 | 14:20:37 | 14:20:06 | 18 | -96.438523 | 30.632971 | 2.010 | -79.7 | 0.4 | -16.9 | Apr 16, 2016 2:20:06 PM |
| 5 | 9085 | 14:20:38 | 14:20:07 | 19 | -96.438539 | 30.632949 | 2.140 | -46.3 | 4.2 | -2.6 | Apr 16, 2016 2:20:07 PM |
| 6 | 9086 | 14:20:39 | 14:20:08 | 20 | -96.438549 | 30.632938 | 2.220 | -34.0 | 3.3 | -2.4 | Apr 16, 2016 2:20:08 PM |
| 7 | 9087 | 14:20:40 | 14:20:09 | 21 | -96.438571 | 30.632922 | 2.030 | -9.4 | -0.1 | -0.6 | Apr 16, 2016 2:20:09 PM |
| 8 | 9088 | 14:20:41 | 14:20:10 | 22 | -96.438597 | 30.632915 | 1.740 | 14.2 | -0.3 | -1.7 | Apr 16, 2016 2:20:10 PM |
| 9 | 9089 | 14:20:42 | 14:20:11 | 23 | -96.438624 | 30.632917 | 1.590 | 36.6 | -3.3 | -2.2 | Apr 16, 2016 2:20:11 PM |
| 10 | 9090 | 14:20:43 | 14:20:12 | 24 | -96.438639 | 30.632922 | 1.720 | 49.2 | -4.3 | -1.1 | Apr 16, 2016 2:20:12 PM |
| 11 | 9091 | 14:20:44 | 14:20:13 | 25 | -96.438662 | 30.632937 | 1.780 | 71.1 | -6.5 | -1.0 | Apr 16, 2016 2:20:13 PM |

**Table 22 Continued**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 9092 | 14:20:45 | 14:20:14 | 26 | -96.438671 | 30.632949 | 1.810 | 93.7 | -5.7 | -3.0 | Apr 16, 2016 2:20:14 PM |
| 13 | 9093 | 14:20:46 | 14:20:15 | 27 | -96.438681 | 30.632983 | 1.970 | 115.1 | -7.9 | -3.4 | Apr 16, 2016 2:20:15 PM |
| 14 | 9094 | 14:20:47 | 14:20:16 | 28 | -96.438674 | 30.633009 | 2.040 | 136.3 | -7.2 | -4.1 | Apr 16, 2016 2:20:16 PM |
| 15 | 9095 | 14:20:48 | 14:20:17 | 29 | -96.438656 | 30.633030 | 2.030 | 157.7 | -7.5 | -5.0 | Apr 16, 2016 2:20:17 PM |
| 16 | 9096 | 14:20:49 | 14:20:18 | 30 | -96.438644 | 30.633037 | 2.000 | 168.1 | -4.7 | -6.5 | Apr 16, 2016 2:20:18 PM |
| 17 | 9097 | 14:20:50 | 14:20:19 | 31 | -96.438619 | 30.633046 | 1.910 | -170.9 | -5.3 | -6.8 | Apr 16, 2016 2:20:19 PM |
| 18 | 9098 | 14:20:51 | 14:20:20 | 32 | -96.438590 | 30.633044 | 1.870 | -152.7 | -3.1 | -6.4 | Apr 16, 2016 2:20:20 PM |
| 19 | 9099 | 14:20:52 | 14:20:21 | 33 | -96.438564 | 30.633034 | 1.830 | -123.2 | -1.1 | -6.3 | Apr 16, 2016 2:20:21 PM |
| 20 | 9100 | 14:20:53 | 14:20:22 | 34 | -96.438545 | 30.633019 | 1.830 | -112.1 | -1.0 | -5.3 | Apr 16, 2016 2:20:22 PM |
| 21 | 9101 | 14:20:54 | 14:20:23 | 35 | -96.438529 | 30.632989 | 1.840 | -85.4 | 2.2 | 10.9 | Apr 16, 2016 2:20:23 PM |
| 22 | 9102 | 14:20:55 | 14:20:24 | 36 | -96.438526 | 30.632984 | 2.070 | -86.3 | 2.4 | 8.2 | Apr 16, 2016 2:20:24 PM |

With this information Figure 83 for the actual path and the planned center was developed at a height of 2m.

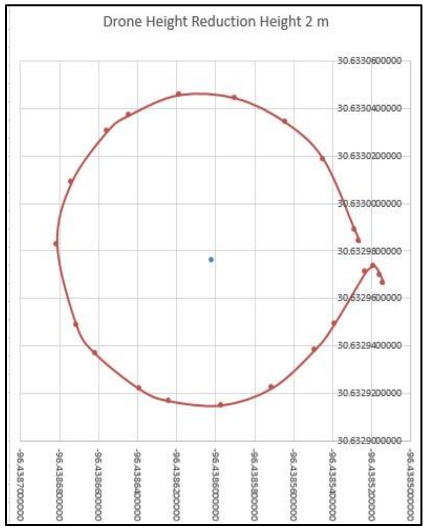



**Figure 83 Actual path and planned center at a height of 2 m in Test 1 – app 2**

Figure 83 was modified in AutoCAD in order to obtain the center of coordinates for the actual path graphically (taken from a green circumference that was almost symmetrical to the actual path), the planned path (blue circumference), an average of the radius (pink lines) according to four representative points in Figure 84 (index 20, 25, 30 and 34), the estimated yaw angle with respect to the north and according to the UAV orientation and the planned center (pink angles), and the actual yaw angle according to the value read from the UAV (Green adjacent lines to the representative points).

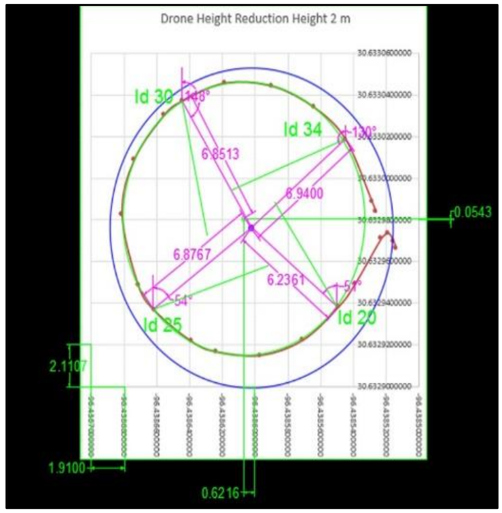



**Figure 84 Planned and actual path at a height of 2 m in Test 1 - app 2, evaluation 2**

The estimated yaw angle and actual radius read from Figure 84 for each representative point can be observed in Table 23. The actual yaw angle was taken according to the data in Table 22 and the planned radius was given as a parameter for the mission. This information was used to do Figure 85 and Figure 86.

**Table 23 Planned and actual yaw angle and radius according to the UAV-GPS data at a height of 2 m in Test 1 - app 2**

| N. | Index | Est. Yaw (Deg) | Act. Yaw (Deg) | Yaw diff. (Deg) | Abs Yaw diff. (Deg) | Planned radius (m) | Actual Radius (m) | Radius diff. (m) | Abs radius diff. (m) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 20 | -51.000 | -33.966 | 17.034 | 17.034 | 8.000 | 6.236 | -1.764 | 1.764 |
| 2 | 25 | 54.000 | 71.093 | 17.093 | 17.093 | 8.000 | 6.877 | -1.123 | 1.123 |
| 3 | 30 | 148.000 | 168.092 | 20.092 | 20.092 | 8.000 | 6.851 | -1.149 | 1.149 |
| 4 | 34 | -130.000 | -112.132 | 17.868 | 17.868 | 8.000 | 6.940 | -1.060 | 1.060 |
| **Aver.** | | | | | 18.022 | | 6.726 | | 1.274 |
| **Std. dev.** | | | | | 1.431 | | 0.329 | | 0.329 |
| **Coef. Var.** | | | | | 7.94% | | 4.89% | | 25.80% |
| **Max.** | | | | | 20.092 | | 6.940 | | 1.764 |
| **Min.** | | | | | 17.034 | | 6.236 | | 1.060 |

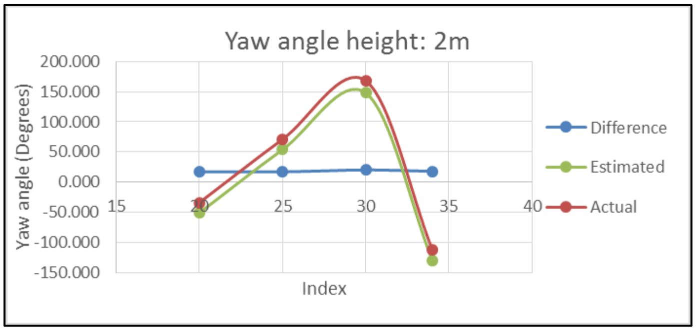



**Figure 85 Yaw angle according to the UAV-GPS at a height of 2 m in Test 1 - app 2**

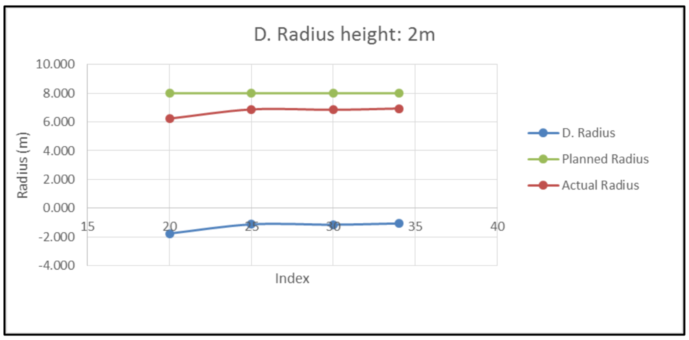



**Figure 86 Radius according to the UAV-GPS at a height of 2 m in Test 1 - app2**

From Table 23 and Figure 85 it can be seen that the UAV is not looking to the center of the pole and the actual orientation of the UAV can have a difference of 18.022 degrees on average with respect to it. For the actual radius, Table 23 and Figure 86 show a difference of 1.274 m on average between the actual and planned path which was not constant thorough the height.

The same analysis was done for heights of 4 m, 6 m, 8 m, 10 m and 12 m. Table 24 shows the actual and planned radius and yaw angle for all the representative points in the mission, and Figure 87 and Figure 88 show the absolute variation of the radius and the yaw angle.

**Table 24 Planned and actual yaw angle and radius according to the UAV-GPS data for all the representative points in Test 1 - app 2**

| Ref. | Id | N. | Index | Est. Yaw (Deg) | Act. Yaw (Deg) | Yaw diff. (Deg) | Abs. Yaw diff. (Deg) | Planned radius (m) | Actual Radius (m) | Radius diff. (m) | Abs radius diff. (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2m height | 1 | 1 | 20 | -51.000 | -33.966 | 17.034 | 17.034 | 8.000 | 6.236 | -1.764 | 1.764 |
| | 2 | 2 | 25 | 54.000 | 71.093 | 17.093 | 17.093 | 8.000 | 6.877 | -1.123 | 1.123 |
| | 3 | 3 | 30 | 148.000 | 168.092 | 20.092 | 20.092 | 8.000 | 6.851 | -1.149 | 1.149 |
| | 4 | 4 | 34 | -130.000 | -112.132 | 17.868 | 17.868 | 8.000 | 6.940 | -1.060 | 1.060 |
| 4m height | 5 | 1 | 40 | -78.000 | -67.595 | 10.405 | 10.405 | 8.000 | 6.427 | -1.573 | 1.573 |
| | 6 | 2 | 45 | 13.000 | 38.768 | 25.768 | 25.768 | 8.000 | 6.659 | -1.341 | 1.341 |
| | 7 | 3 | 50 | 110.000 | 135.704 | 25.704 | 25.704 | 8.000 | 7.137 | -0.863 | 0.863 |
| | 8 | 4 | 55 | -140.000 | -119.065 | 20.935 | 20.935 | 8.000 | 6.379 | -1.621 | 1.621 |
| 6m height | 9 | 1 | 65 | -34.000 | -11.134 | 22.866 | 22.866 | 6.000 | 5.179 | -0.821 | 0.821 |
| | 10 | 2 | 69 | 56.000 | 75.356 | 19.356 | 19.356 | 6.000 | 5.288 | -0.712 | 0.712 |
| | 11 | 3 | 73 | 138.000 | 160.705 | 22.705 | 22.705 | 6.000 | 5.556 | -0.444 | 0.444 |
| | 12 | 4 | 77 | -140.000 | -93.798 | 46.202 | 46.202 | 6.000 | 5.001 | -0.999 | 0.999 |
| 8m height | 13 | 1 | 82 | -100.000 | -93.109 | 6.891 | 6.891 | 4.000 | 3.143 | -0.857 | 0.857 |
| | 14 | 2 | 87 | -27.000 | 1.288 | 28.288 | 28.288 | 4.000 | 3.273 | -0.727 | 0.727 |
| | 15 | 3 | 92 | 80.000 | 111.278 | 31.278 | 31.278 | 4.000 | 3.644 | -0.356 | 0.356 |
| | 16 | 4 | 97 | -170.000 | -148.478 | 21.522 | 21.522 | 4.000 | 3.871 | -0.129 | 0.129 |
| 10m height | 17 | 1 | 101 | -152.000 | -130.907 | 21.093 | 21.093 | 2.000 | 1.801 | -0.199 | 0.199 |
| | 18 | 2 | 106 | -87.000 | -35.025 | 51.975 | 51.975 | 2.000 | 0.701 | -1.299 | 1.299 |
| | 19 | 3 | 111 | 23.000 | 73.951 | 50.951 | 50.951 | 2.000 | 1.881 | -0.119 | 0.119 |
| | 20 | 4 | 116 | 151.000 | 174.138 | 23.138 | 23.138 | 2.000 | 1.366 | -0.634 | 0.634 |
| 12m height | 21 | 1 | 119 | 162.000 | -176.752 | 21.248 | 21.248 | 0.000 | 1.856 | 1.856 | 1.856 |
| | 22 | 2 | 125 | -77.000 | -78.338 | -1.338 | 1.338 | 0.000 | 0.913 | 0.913 | 0.913 |
| | 23 | 3 | 133 | 19.000 | 78.586 | 59.586 | 59.586 | 0.000 | 2.090 | 2.090 | 2.090 |
| | 24 | 4 | 137 | 115.000 | 150.484 | 35.484 | 35.484 | 0.000 | 1.561 | 1.561 | 1.561 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aver.** | | | | | | | 25.784 | | | | 1.009 |
| **Std. dev.** | | | | | | | 14.139 | | | | 0.553 |
| **Coef. Var.** | | | | | | | 54.84% | | | | 54.86% |
| **Max.** | | | | | | | 59.586 | | | | 2.090 |
| **Min.** | | | | | | | 1.338 | | | | 0.119 |

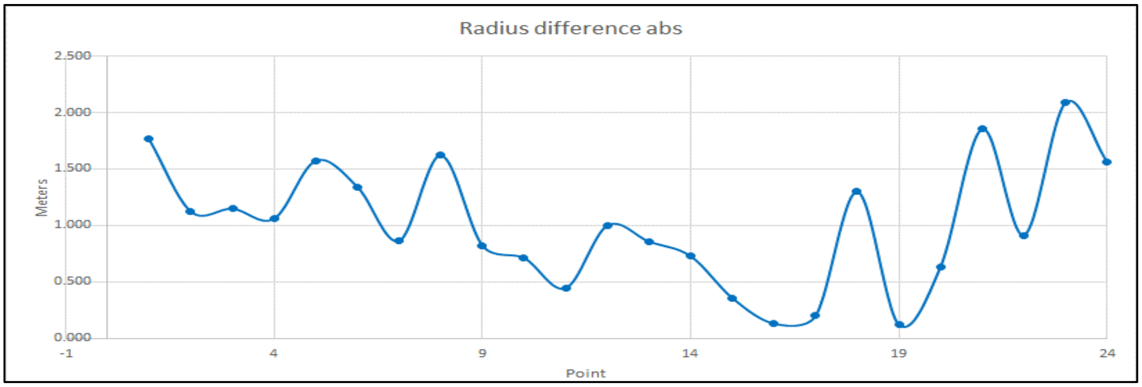



**Figure 87 Absolute radius difference according to the UAV-GPS data for all the representative points in Test 1 - app 2**

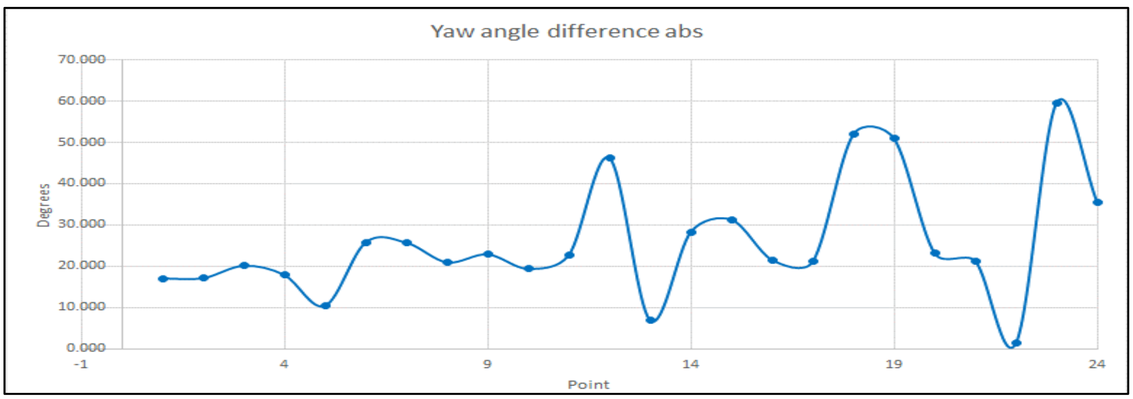



**Figure 88 Absolute yaw angle according to the UAV-GPS data for all the representative points in Test 1 - app 2**

According to Table 24 and the Figure 87, it can be seen that the actual radius is in average lower than the planned one except in the last step (12 m height) and their difference is approximately 1.009 m. In the last step the largest difference between the actual and planned radius was observed, with a value of 2.090 m, which is interesting because at that point it seems that the UAV was flying a path with a radius similar to the one at a height of 10 m. In the heights between 2 and 10 m, there were points in which the actual radius had a minimum difference of 0.119 m and maximum of 1.764 m (points 111 and 20). Table 24 and Figure 88 indicate that in general there was a difference between the actual orientation of the UAV with respect to the pole location which was in average 25.784 degrees, with a maximum difference of 59.586 and a minimum difference of 1.338 degrees (points with index 133 and 125).

Table 25 summarizes the data collected for each height according to the evaluation 2 and Figure 89 to Figure 93 show the actual average and planned height, latitude, longitude, pitch angle and radius in 6 different levels in height.

**Table 25 Summary of planned and actual data and differences for each height according to the UAV-GPS in Test 1 - app2**

| | Point | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| **Planned Test 1 – app 2** | Height (m) | 2.000 | 4.000 | 6.000 | 8.000 | 10.000 | 12.000 |
| | Lat (DD) | 30.632976 | 30.632976 | 30.632976 | 30.632976 | 30.632976 | 30.632976 |
| | Long (DD) | -96.438602 | -96.438602 | -96.438602 | -96.438602 | -96.438602 | -96.438602 |
| | Pitch angle (degrees) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Radius (m) | 8.000 | 8.000 | 6.000 | 4.000 | 2.000 | 0.000 |
| **Actual Test 1 – app 2** | Height (m) | 1.765 | 3.906 | 5.902 | 7.998 | 9.876 | 11.796 |
| | Lat (DD) | 30.632981 | 30.632978 | 30.632977 | 30.632979 | 30.632976 | 30.632975 |
| | Long (DD) | -96.438607 | -96.438607 | -96.438603 | -96.438605 | -96.438605 | -96.438606 |
| | Pitch angle (degrees) | -1.491 | -0.692 | -1.217 | 0.173 | 1.154 | 1.527 |
| | Radius (m) | 6.726 | 6.650 | 5.256 | 3.483 | 1.437 | 1.605 |

| | | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
|---|---|---|---|---|---|---|
| **Actual Test 1 – app 2** | Height (m) | | | | | |
| | Lat (DD) | 30.632978 | 0.000002 | 0.00% | 30.632981 | 30.632975 |
| | Long (DD) | -96.438605 | 0.000001 | 0.00% | -96.438603 | -96.438607 |
| | Pitch angle (degrees) | -0.091 | 1.251 | -1374.74% | 1.527 | -1.491 |
| | Radius (m) | | | | 6.726 | 1.437 |

| | Point | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| **Abs. diff. Test 1 – app 2** | Height (m) | 0.235 | 0.094 | 0.098 | 0.002 | 0.124 | 0.204 |
| | Lat (DD) | 0.000005 | 0.000002 | 0.000002 | 0.000003 | 0.000000 | 0.000001 |
| | Lat (m) | 0.504 | 0.277 | 0.168 | 0.324 | 0.024 | 0.084 |
| | Long (DD) | 0.000005 | 0.000006 | 0.000002 | 0.000003 | 0.000003 | 0.000004 |
| | Long (m) | 0.475 | 0.534 | 0.153 | 0.266 | 0.275 | 0.357 |
| | Pitch angle (degrees) | 1.491 | 0.692 | 1.217 | 0.173 | 1.154 | 1.527 |
| | Radius (m) | 1.274 | 1.350 | 0.744 | 0.517 | 0.563 | 1.605 |

**Table 25 Continued**

| | | Ave. | Std. dev. | Coef. Var. | Max. | Min. |
|---|---|---|---|---|---|---|
| **Abs. diff. Test 1 – app 2** | Height (m) | 0.126 | 0.084 | 66.43% | 0.235 | 0.002 |
| | Lat (DD) | 0.000002 | 0.000002 | 76.10% | 0.000005 | 0.000000 |
| | Lat (m) | 0.230 | 0.175 | 76.10% | 0.504 | 0.024 |
| | Long (DD) | 0.000004 | 0.000001 | 41.37% | 0.000006 | 0.000002 |
| | Long (m) | 0.343 | 0.142 | 41.37% | 0.534 | 0.153 |
| | Pitch angle (degrees) | 1.043 | 0.521 | 49.97% | 1.527 | 0.173 |
| | Radius (m) | 1.009 | 0.459 | 45.47% | 1.605 | 0.517 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Abs. diff. Test 1 – app 2 (%)** | Point | 1 | 2 | 3 | 4 | 5 | 6 |
| | Height (m) | 11.75% | 2.35% | 1.63% | 0.03% | 1.24% | 1.70% |
| | Lat (DD) | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Long (DD) | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Pitch angle (degrees) | - | - | - | - | - | - |
| | Radius (m) | 15.92% | 16.87% | 12.40% | 12.93% | 28.14% | - |

| | | Ave. | Std. dev. | Coef. Var. | Max. | Min. |
|---|---|---|---|---|---|---|
| **Abs. diff. Test 1 – app 2 (%)** | Height (m) | 3.12% | 4.30% | 137.97% | 11.75% | 0.03% |
| | Lat (DD) | 0.00% | 0.00% | 76.10% | 0.00% | 0.00% |
| | Long (DD) | 0.00% | 0.00% | 41.37% | 0.00% | 0.00% |
| | Pitch angle (degrees) | - | - | - | - | - |
| | Radius (m) | 17.25% | 6.38% | 36.95% | 28.14% | 12.40% |

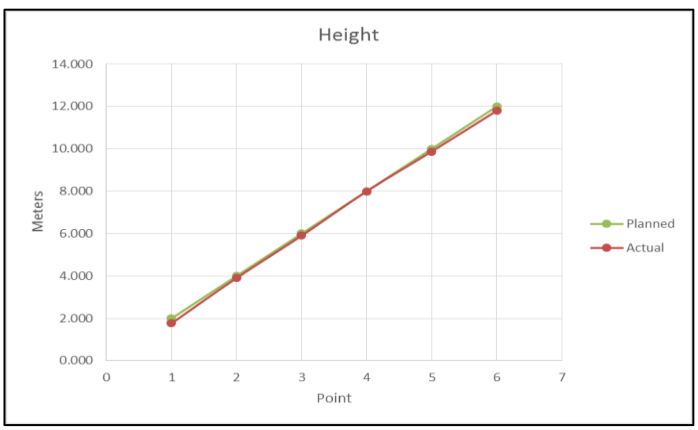



**Figure 89 Actual average and planned height for each point according to the UAV-GPS in Test 1 - app 2**

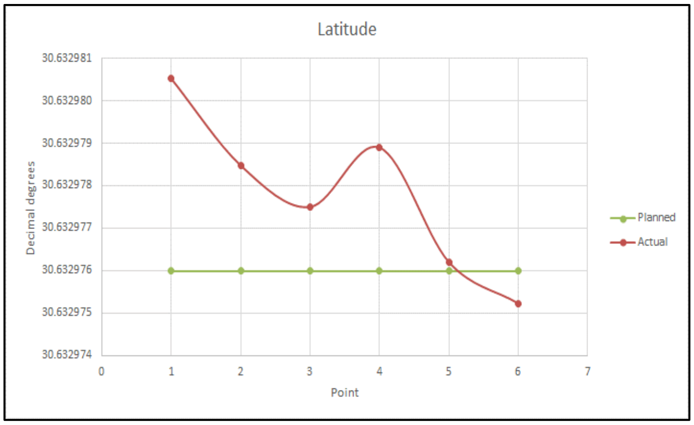



**Figure 90 Actual average and planned latitude for each point according to the UAV-GPS in Test 1 - app 2**

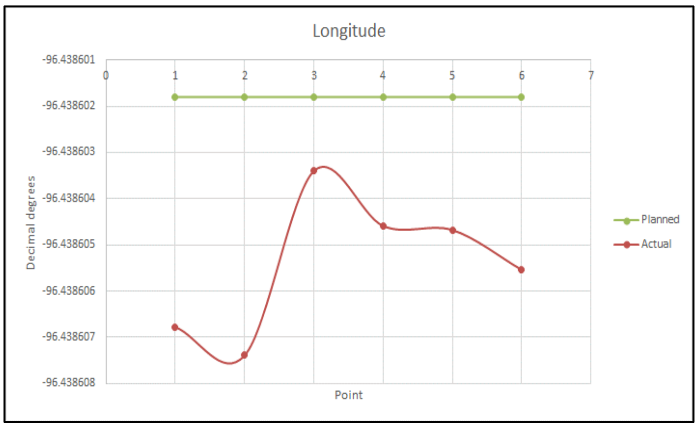



**Figure 91 Actual average and planned longitude for each point according to the UAV-GPS in Test 1 - app 2**

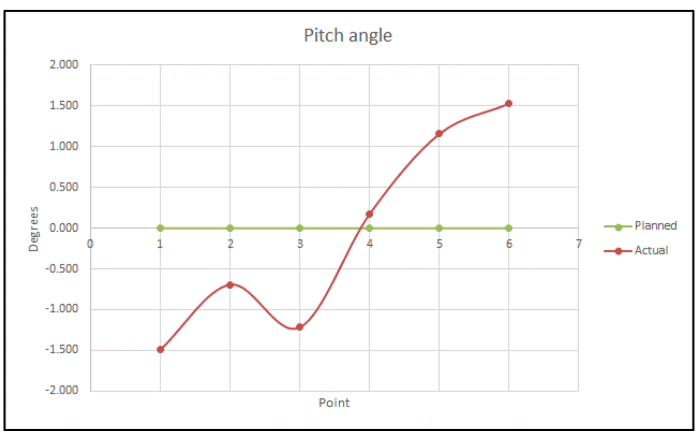



**Figure 92 Actual average and planned pitch angle for each point according to the UAV-GPS in Test 1 - app 2**

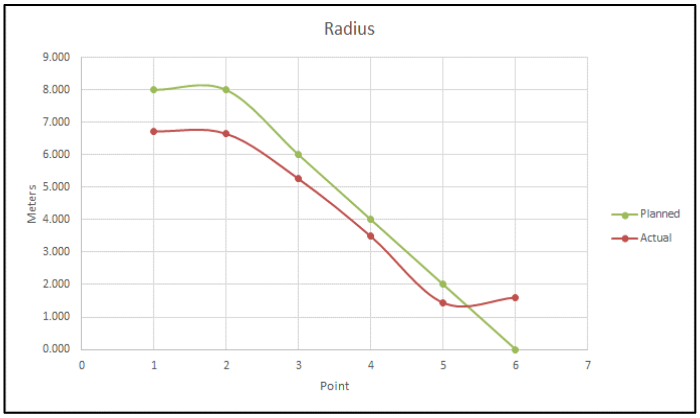



**Figure 93 Actual average and planned radius for each point according to the UAV-GPS in Test 1 - app 2**

From Table 25 it can be observed that the error between the planned and actual path in each mission step is on average 0.126 m or 3.12% in height, 0.230 m for the latitude, 0.343 m for the longitude, 1.043 degrees for the pitch angle, and approximately 17.25% for the radius.

*4.2.3.4. Evaluation 3*

Photos between a height of 2 m and 6 m with 2 m increments were taken each second in order to do the evaluation 3 proposed in subchapter 3.3.

As it was mentioned in subchapter 4.2.1.4 and 4.2.2.4, the photos of this process were used to do an actual flight path reconstruction in order to test the accuracy between the real and the planned path according to the objective 2 of this research mentioned in subchapter 1.4, in order to complement and compare the information obtained in the evaluation 2 in subchapter 4.2.3.3.

A calibration photo (photo GOPR7782) was taken at a distance of 7.6 m in order to have a reference of the frame height when the second section of the pole has a height of 1 m (Figure 94 and Figure 95).

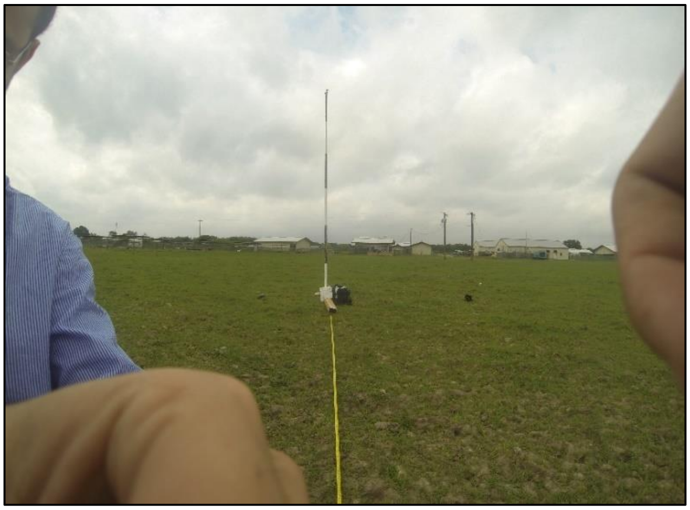


**Figure 94 Calibration photo GOPR7782**

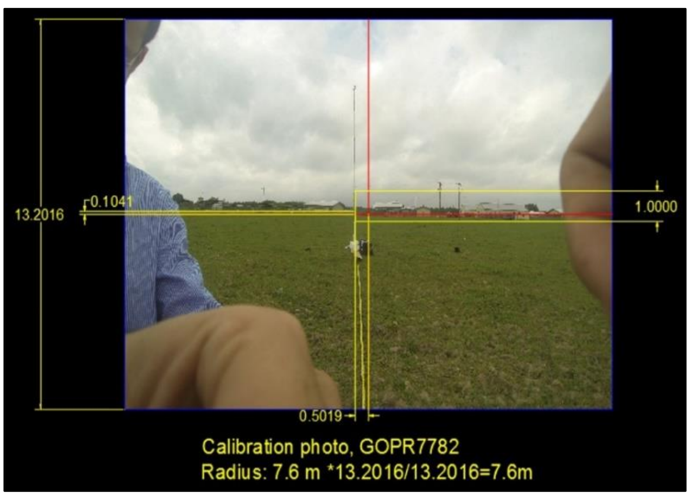



**Figure 95 Calibration photo GOPR7782 with measurements**

Approximately 64 photos were taken between a height of 2 m and 6 m and according to the results in subchapter 4.2.1.4., the inclination when the UAV took the pictures was omitted in the calculations.

For this evaluation at least 4 pictures in different quadrants (considering the actual path circumference for each height as planar) were examined as it is shown in Figure 96 in order to obtain the distance between the center of the photo and the pole (DX) and the height of the frame in order to estimate the radius (Figure 97). With that information it was possible to develop Table 26 which gives information about the average, standard deviation, coefficient of variation, maximum and minimum values of absolute DX, actual radius, difference between planned and actual radius and the angle difference between consecutive photos. This data was used to draw an approximate path of the UAV when it was doing the mission at a height of 2 m (Figure 100); the position of the UAV with respect to the tape that was oriented looking to the magnetic north was measured from the drawing and was utilized to build the column “Angle UAS - East (Degrees)” in Table 26.

**Figure 96 Photo G0159087 at a height of 2 m**

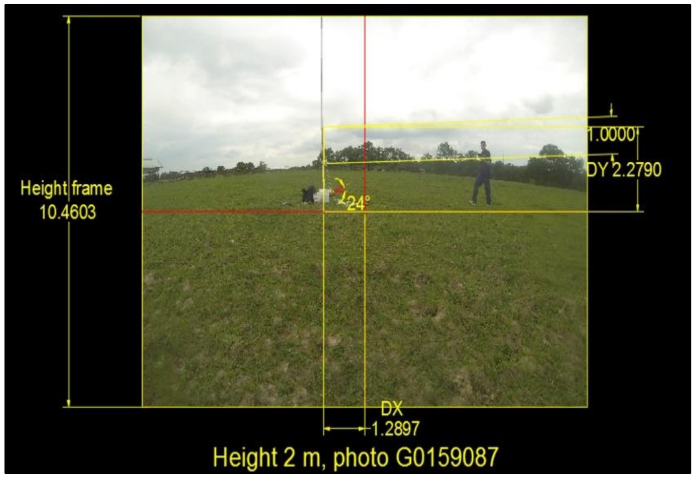



**Figure 97 G0159087 at a height of 2 m with measurements**

**Table 26 Measurements for 7 photos which were taken at a height of 2 m in Test 1 - app2**

| N. | Photo G015 - | DX(m) | Abs DX(m) | DY(m) | Photo frame height (m) | Actual Radius (m) | Planned radius (m) | Radius diff. (m) | Abs radius diff. (m) | Angle UAS-East (Degrees) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9081 | -5.658 | 5.658 | 1.308 | 11.769 | 6.775 | 8.000 | -1.225 | 1.225 | 32.000 |
| 2 | 9087 | -1.290 | 1.290 | 2.279 | 10.460 | 6.022 | 8.000 | -1.978 | 1.978 | -12.000 |
| 3 | 9088 | -1.160 | 1.160 | 2.330 | 11.099 | 6.390 | 8.000 | -1.610 | 1.610 | -103.000 |
| 4 | 9093 | -2.652 | 2.652 | 2.736 | 14.080 | 8.106 | 8.000 | 0.106 | 0.106 | -166.000 |
| 5 | 9097 | -3.456 | 3.456 | 2.424 | 12.324 | 7.095 | 8.000 | -0.905 | 0.905 | -200.000 |
| 6 | 9099 | -3.010 | 3.010 | 2.088 | 10.818 | 6.228 | 8.000 | -1.772 | 1.772 | -326.000 |
| 7 | 9102 | -2.242 | 2.242 | 0.769 | 11.212 | 6.455 | 8.000 | -1.545 | 1.545 | -349.000 |
| **Aver.** | | | 2.781 | | | 6.724 | | | 1.306 | |
| **Std. dev.** | | | 1.524 | | | 0.704 | | | 0.636 | |
| **Coef. Var.** | | | 54.82% | | | 10.47% | | | 48.70% | |
| **Max.** | | | 5.658 | | | 8.106 | | | 1.978 | |
| **Min.** | | | 1.160 | | | 6.022 | | | 0.106 | |

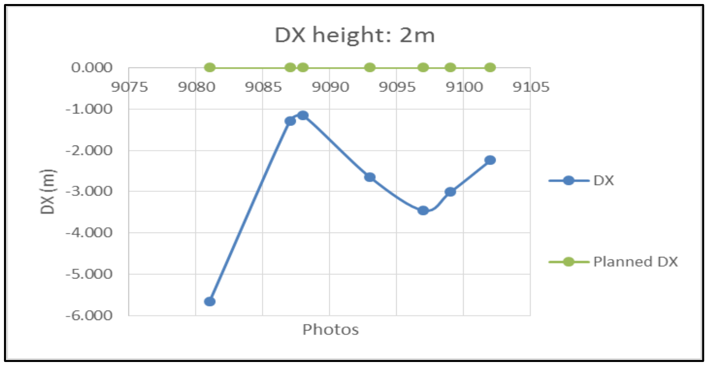



**Figure 98 Horizontal distance (DX) between the center of the photo and the pole at a height of 2 m in 7 different points, Test 1 - app2**

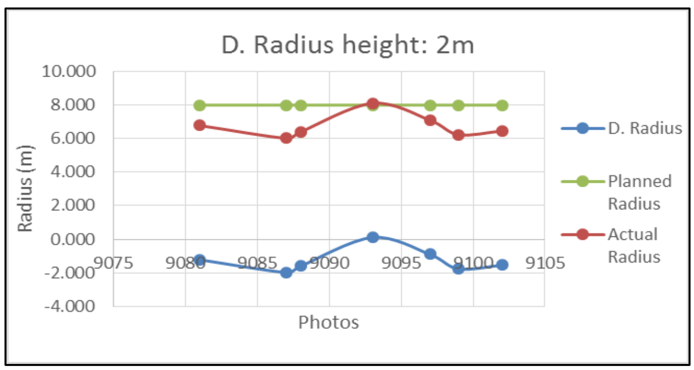



**Figure 99 Planned and actual radius estimation in different points at a height of 2 m in 7 different points, Test 1 - app2**

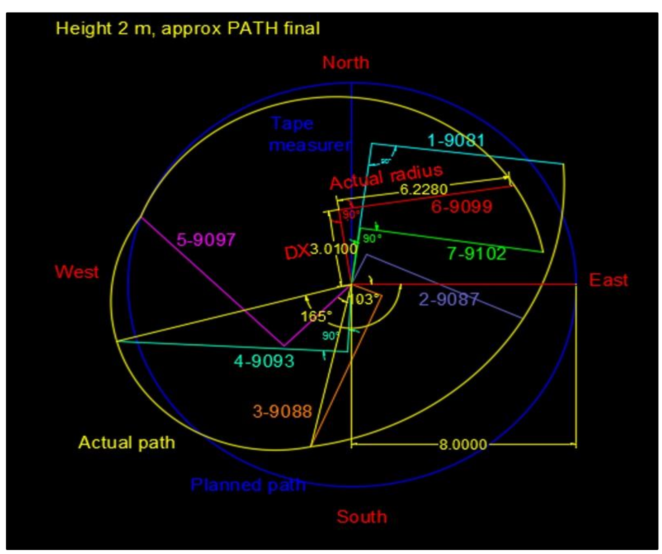



**Figure 100 Planned and actual path at a height of 2 m in Test 1 - app2, evaluation 3**

From Table 26, Figure 98 and Figure 99, it is possible to say for the height of 2 m in this mission that the error between the pole's center has an average of 2.781 m, with a maximum error of 5.658 m and a minimum of 1.160 m. For the radius difference, the average was 1.306 m, with a maximum difference of 1.978 m and a minimum of 0.106 m, which means that the average actual radius was 6.724 m, the maximum radius was 8.106 m and the minimum was 6.022 m.

Table 26 was created for a height of 2 m. The same table was also done for the heights of 4 m and 6 m and according to them, Table 27, Figure 101 and Figure 102 were generated, which summarize and show the DX error and radius difference according to all the photos. The information given in Table 27 was classified for each height and from the results Table 28 was created.

**Table 27 DX and radius difference for all the photos analyzed in Test 1 - app 2**

| Ref. | Id. | N. | Photo G015- | DX(m) | Abs DX(m) | DY(m) | Photo frame height (m) | Act. Rad. (m) | Plan. Rad. (m) | Rad. diff. (m) | Abs. Rad. diff. (m) | Angle UAS - East (Deg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2m height | 1 | 1 | 9081 | -5.658 | 5.658 | 1.308 | 11.769 | 6.775 | 8.000 | -1.225 | 1.225 | 32.000 |
| | 2 | 2 | 9087 | -1.290 | 1.290 | 2.279 | 10.460 | 6.022 | 8.000 | -1.978 | 1.978 | -12.000 |
| | 3 | 3 | 9088 | -1.160 | 1.160 | 2.330 | 11.099 | 6.390 | 8.000 | -1.610 | 1.610 | -103.000 |
| | 4 | 4 | 9093 | -2.652 | 2.652 | 2.736 | 14.080 | 8.106 | 8.000 | 0.106 | 0.106 | -166.000 |
| | 5 | 5 | 9097 | -3.456 | 3.456 | 2.424 | 12.324 | 7.095 | 8.000 | -0.905 | 0.905 | -200.000 |
| | 6 | 6 | 9099 | -3.010 | 3.010 | 2.088 | 10.818 | 6.228 | 8.000 | -1.772 | 1.772 | -326.000 |
| | 7 | 7 | 9102 | -2.242 | 2.242 | 0.769 | 11.212 | 6.455 | 8.000 | -1.545 | 1.545 | -349.000 |
| 4m height | 8 | 1 | 9103 | -2.512 | 2.512 | 2.827 | 11.503 | 6.622 | 8.000 | -1.378 | 1.378 | 43.000 |
| | 9 | 2 | 9110 | -2.156 | 2.156 | 1.542 | 10.778 | 6.205 | 8.000 | -1.795 | 1.795 | -64.000 |
| | 10 | 3 | 9117 | -4.619 | 4.619 | 2.151 | 12.253 | 7.054 | 8.000 | -0.946 | 0.946 | -160.000 |
| | 11 | 4 | 9119 | -3.764 | 3.764 | 3.382 | 11.686 | 6.727 | 8.000 | -1.273 | 1.273 | -280.000 |
| | 12 | 5 | 9122 | -5.927 | 5.927 | 0.975 | 9.079 | 5.227 | 8.000 | -2.773 | 2.773 | -320.000 |
| 6m height | 13 | 1 | 9125 | -3.594 | 3.594 | 2.152 | 10.702 | 6.161 | 6.000 | 0.161 | 0.161 | 69.000 |
| | 14 | 2 | 9130 | -1.508 | 1.508 | 1.355 | 7.709 | 4.438 | 6.000 | -1.562 | 1.562 | -24.000 |
| | 15 | 3 | 9136 | -2.075 | 2.075 | 1.230 | 10.062 | 5.793 | 6.000 | -0.207 | 0.207 | -147.000 |

**Table 27 Continued**

| Ref. | Id. | N. | Photo G015- | DX(m) | Abs DX(m) | DY(m) | Photo frame height (m) | Act. Rad. (m) | Plan. Rad. (m) | Rad. diff. (m) | Abs. Rad. diff. (m) | Angle UAS - East (Deg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6m height | 16 | 4 | 9139 | -2.569 | 2.569 | 2.275 | 10.384 | 5.978 | 6.000 | -0.022 | 0.022 | -187.000 |
| | 17 | 5 | 9142 | -4.727 | 4.727 | 2.086 | 8.038 | 4.627 | 6.000 | -1.373 | 1.373 | -282.000 |
| **Aver.** | | | | | 3.113 | | | | | | 1.214 | |
| **Std. dev.** | | | | | 1.445 | | | | | | 0.752 | |
| **Coef. Var.** | | | | | 46.41% | | | | | | 61.95% | |
| **Max.** | | | | | 5.927 | | | | | | 2.773 | |
| **Min.** | | | | | 1.160 | | | | | | 0.022 | |

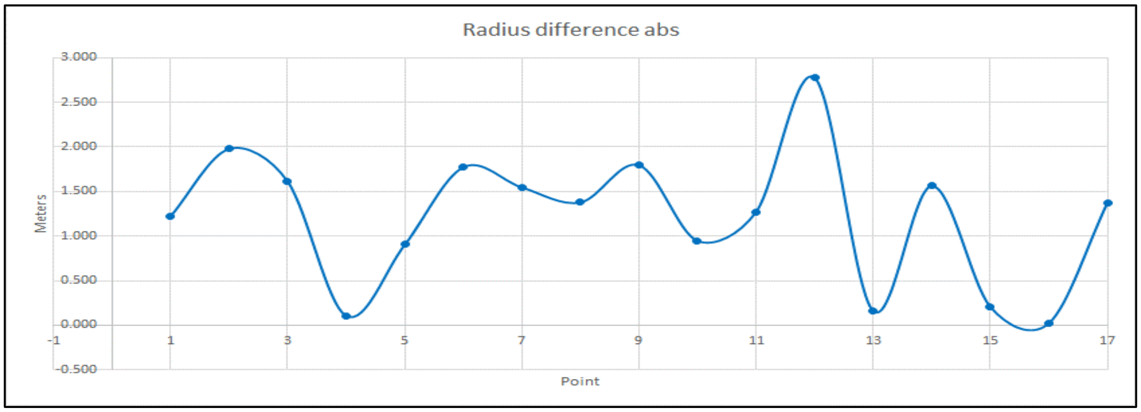



**Figure 101 Absolute radius difference for all the photos analyzed in Test 1 - app 2**

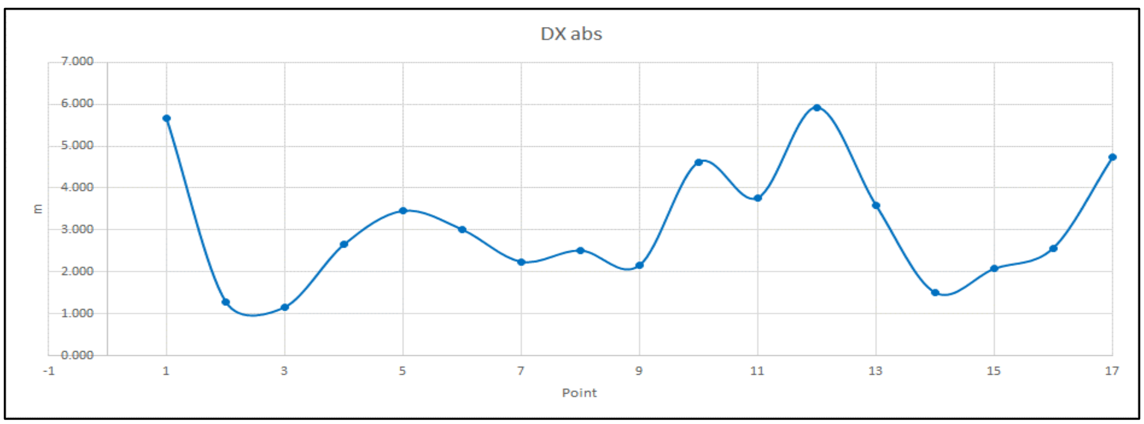



**Figure 102 Horizontal distance between the center of the picture and the pole position (DX abs) for all the photos analyzed in Test 1 - app 2**

**Table 28 Summary of planned and actual data and differences for each height from photos in Test 1 - app 2**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Planned Test 1 – app 2** | Path number | 1 | 2 | 3 | | | | | |
| | Height (m) | 2.000 | 4.000 | 6.000 | | | | | |
| | Abs DX (m) | 0 | 0 | 0 | | | | | |
| | Radius (m) | 8.000 | 8.000 | 6.000 | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
| **Actual Test 1 – app 2** | Abs DX (m) | 2.781 | 3.796 | 2.895 | 3.157 | 0.556 | 17.61% | 3.796 | 2.781 |
| | Radius (m) | 6.724 | 6.367 | 5.399 | 6.164 | 0.685 | 11.12% | 6.724 | 5.399 |
| **Abs. diff. Test 1 – app 2** | Abs DX (m) | 2.781 | 3.796 | 2.895 | 3.157 | 0.556 | 17.61% | 3.796 | 2.781 |
| | Radius (m) | 1.276 | 1.633 | 0.601 | 1.170 | 0.524 | 44.82% | 1.633 | 0.601 |
| **Abs. diff. Test 1 – app 2(%)** | Abs DX (m) | 100.00% | 100.00% | 100.00% | 100.00% | 0.00% | 0.00% | 100.00% | 100.00% |
| | Radius (m) | 18.97% | 25.65% | 11.12% | 18.58% | 7.27% | 39.13% | 25.65% | 11.12% |

From Table 27, it can be said that the horizontal average error between the center of the photos and the pole for all the mission at a height among 2 m and 6 m was 3.113 m, with a maximum value of 5.927 m and minimum of 1.160 m. The average absolute radius difference from the photos was 1.214 m with respect to the planned radius, with a maximum value of 2.773 m and a minimum of 0.022 m.

From Table 28, it is shown that at a height of 4 m the Abs DX had an average value of 3.796 m which was bigger than in the other heights and the radius difference had an average of 1.633 m which was bigger than in the other points.

According to the evaluation 3 proposed in subchapter 3.3, the following is the percentage for the wrong focus:

$$Eq.\%\ wrong\ focus = \frac{\sum Option\ B\ photos}{\sum Option\ A\ photos + \sum Option\ B\ photos} \times 100\%$$

$$Eq.\%\ wrong\ focus = \frac{17}{0 + 17} \times 100\% = 100\%$$

It means that the center of the photos did not fit with the center of coordinates, and it is supported with the information provided in Table 27 in which the horizontal distance between the pole and the center of the images had an average of 3.113 m with a standard deviation of 1.445 m.

*4.2.3.5. 3D Model for Test 1 – app 2*

Figure 103 until Figure 108 show the 3D model for the flight of the UAV and its orientation with respect to the pole according to Figure 84, Figure 100 and the other ones that were done at different heights. In those graphics the height was considered constant in each step, the blue circumference is the planned path, the red figure is the actual path and the green lines show the actual yaw angle according to the GPS and UAV sensors (subchapter 4.2.3.3), the yellow figure is the actual path and the magenta lines show the UAV orientation from the photos (subchapter 4.2.3.4), the blue line indicates the tape measure that was used to reference the north.

Figure 109 and Figure 110 show a 3D model for the UAV flight according to the planned and actual paths drawn in Figure 103 until Figure 108.

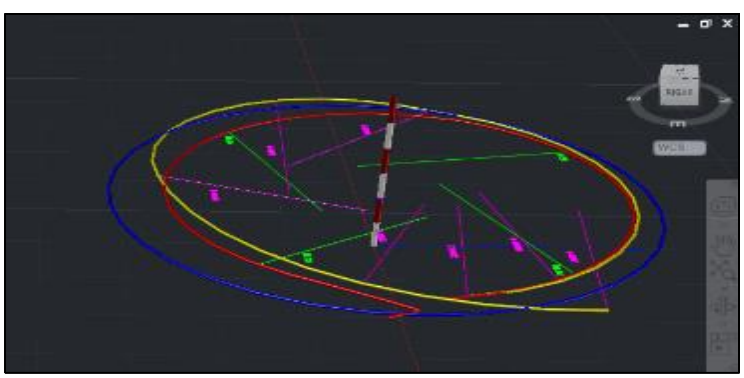


**Figure 103 3D model for the planned and actual path at a height of 2 m, Test 1 - app 2**

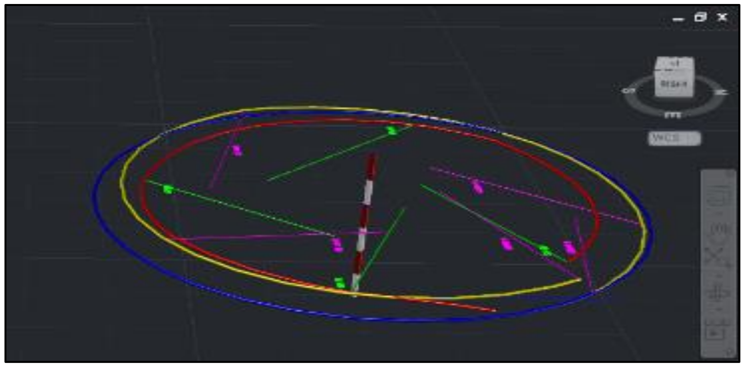


**Figure 104 3D model for the planned and actual path at a height of 4 m, Test 1 - app 2**

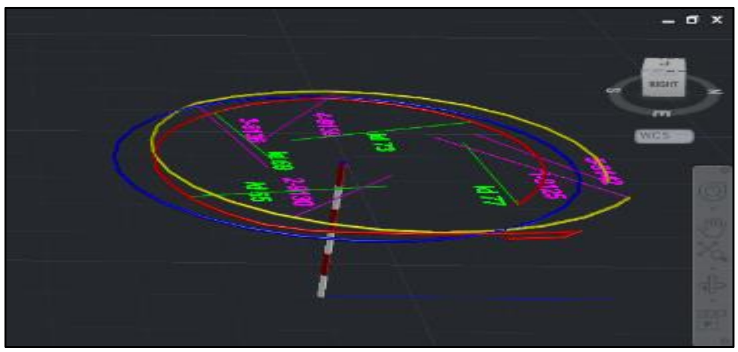


**Figure 105 3D model for the planned and actual path at a height of 6 m, Test 1 - app 2**

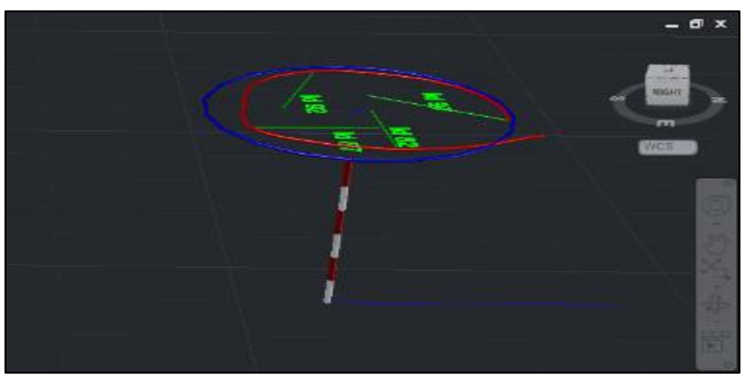


**Figure 106 3D model for the planned and actual path at a height of 8 m, Test 1 - app 2**

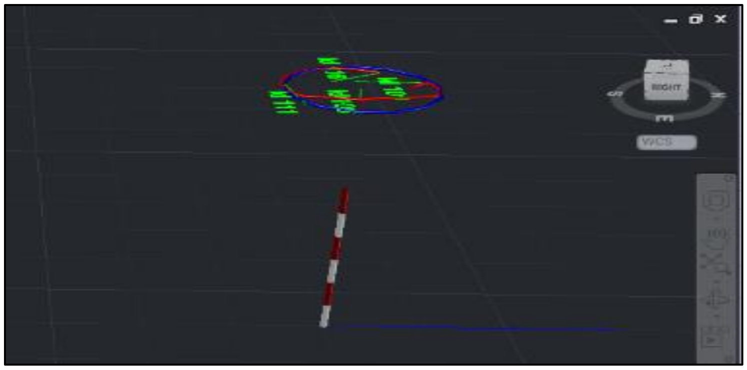


**Figure 107 3D model for the planned and actual path at a height of 10 m, Test 1 - app 2**

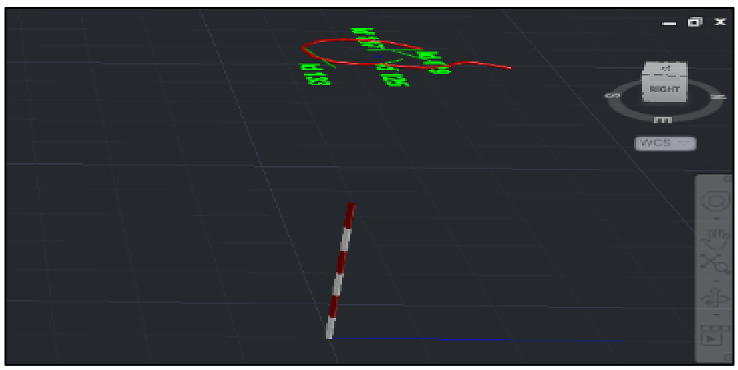


**Figure 108 3D model for the planned and actual path at a height of 12 m, Test 1 – app 2**

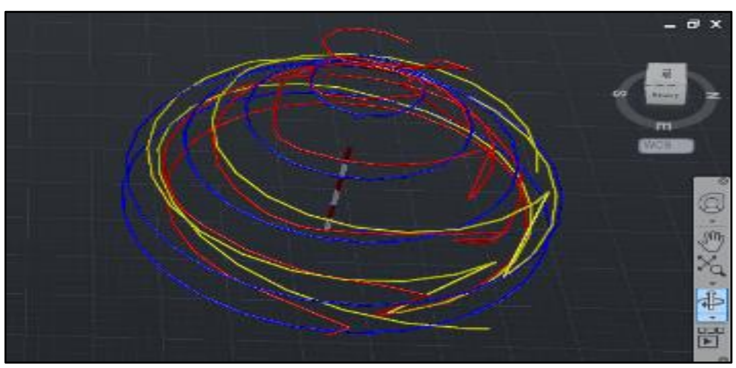


**Figure 109 3D model – view 1 for the planned and actual path, Test 1 – app 2**

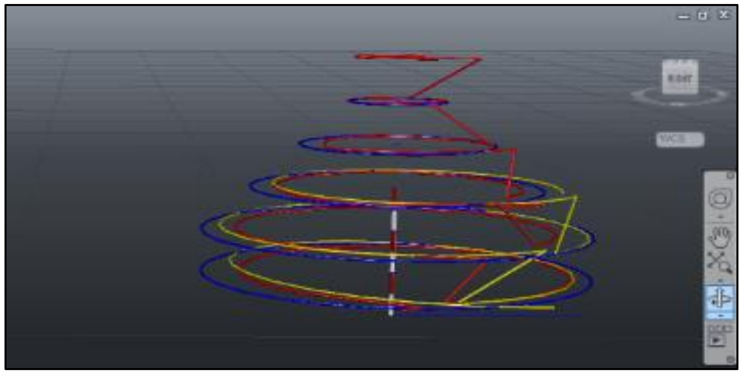


**Figure 110 3D model – view 2 for the planned and actual path, Test 1 – app 2**

### *4.2.3.6. Analysis of the mission*

After checking the information collected in subchapters 4.2.3.2, 4.2.3.3 and 4.2.3.4, the following can be mentioned:

- The actual path for the UAV was not circular as it was pretended in the mission planning and as it was stated in subchapters 4.2.1.6 and 4.2.2.6, which can be linked to factors related to the GPS accuracy in the UAV, the wind, etc.
- As it was mentioned in subchapter 4.2.2.6, for this work evaluation 2 gives a good idea about the actual position and orientation during the UAV flight.
- From evaluation 2, it can be said that the UAV had differences in its planned and actual flight. The actual height was on average 0.126 m or 3.12% lower than the planned one; the latitude had a difference of 0.000002 DD or 0.230 m on average; the longitude had a difference of 0.000004 DD or 0.343 m on average; the pitch angle had positive and negative values in each height step and its average was 1.043 degrees; the radius difference had an average of 1.009 m with a minimum value of 0.119 m and a maximum of 2.090 m; and

the angle between the actual orientation and the planned objective had a difference of 25.784 degrees on average.

- From previous evaluations, it can be mentioned that the measurements done with photos in evaluation 3 can have an error of 4.35 percent, which in a distance of 8 m represent an error of approximately 0.348 m (Appendix A.1.). However, the error in this analysis depends on factors such as the inclination of the camera with respect to the objective at the moment of taking the picture, the camera resolution, and the measurements done by the user.
- From evaluation 3, it can be said that the center for the pictures in the UAV can have a difference with the center of coordinates for the mission of approximately 3.113 m with a maximum difference of 5.927 m and minimum of 1.160 m. It is interesting to mention that according to the orientation of the UAV at the moment of taking the picture it was not focusing to a specific point but to a region as it was said in subchapter 4.2.3.4.
- From evaluation 3, the average absolute actual and planned radius difference was 1.214 m, however, there was a point in which the difference between the actual and planned radius was 2.773 m or approximately 35%. This gives an idea about the risk of collision of the UAV with the structure to be inspected when flying autonomously if it is not given a prudent distance to do the work.
- The evaluation number 3 for this test has shown in the last step (height of 12 m) and when the planned radius is “0”, the UAV tried to follow an actual path with a similar radius to the one in the previous step (height of 10 m).

- As it was said in subchapter 4.2.2.6, the evaluation 2 and 3 show differences in the values of the actual path and yaw angle, however, they support the fact that the UAV did not flight exactly as it was expected and it had a deviation at the moment of focusing the objective.

### *4.2.4. Test 2 - app 2, date 04-16-2016*

#### *4.2.4.1. Mission definition*

In Table 29 can be found the established parameters for this mission according to the latitude and longitude information taken from the mobile application "GPS Coordinates". It should be mentioned that the last four or five digits in those app's coordinates are not fixed which can induce an error in the mission lower than 11.09 m in the latitude and 9.551 m in the longitude, according to the values from in subchapter 2.8.

**Table 29 Mobile application and parameters used in Test 2 – app 2**

| | |
|---|---|
| **Mobile app used** | Drone Height Reduction |
| **Long X (DD)** | -96.43860183239443 |
| **Lat Y (DD)** | 30.632975982366506 |
| **Radius (m)** | 16 |
| **Con. Height (m)** | 4 |
| **Var. Height (m)** | 8 |
| **R. Reduction (m)** | 4 |
| **Interval** | 6 |
| **N. of turns** | 1 |

In Figure 111 .A. to .D. it can be observed how the mission is sent and verified in the UAV.

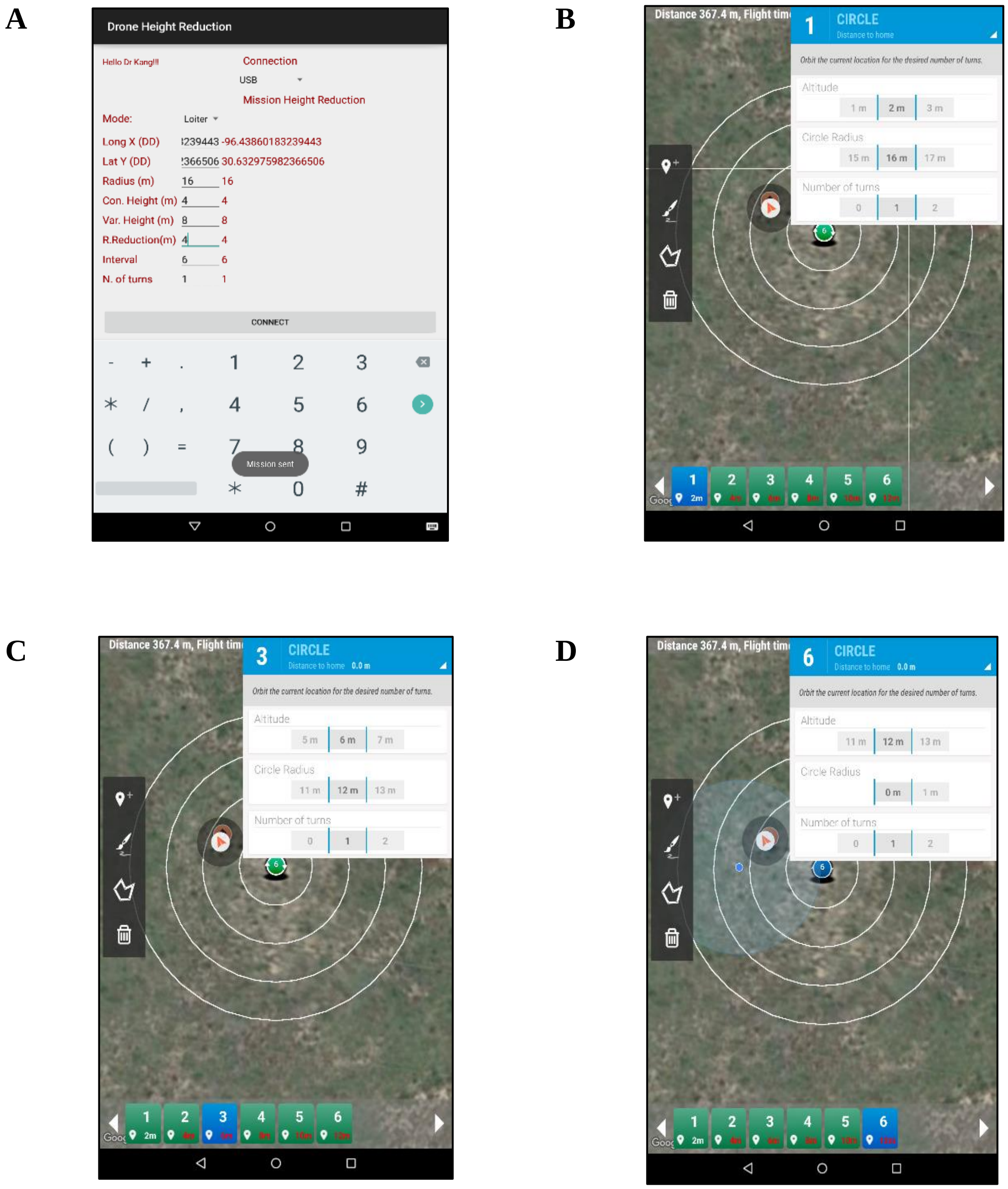



**Figure 111 (A) Mission 2 sent with the Drone Height Reduction app. (B) First waypoint for the mission in Droidplanner 2. (C) Third waypoint for the mission in Droidplanner 2. (D) Last waypoint for the mission in Droidplanner 2.**

### *4.2.4.2. Evaluation 1*

According to evaluation 1 proposed in subchapter 3.3., the app worked without any inconveniences for this mission.

#### *4.2.4.3. Evaluation 2*

For this mission, an IRIS+ drone of 3DRobotics was used as it was said in subchapters 4.2.2.3 and 4.2.3.3. The information gathered was organized synchronizing the camera and the mobile device clocks (They had a difference of 36 seconds approximately as it is mentioned in the subchapter 4.2.2.3) and separating the data when a change in the height of the images was identified. In subchapter D.1. (Appendix D) it can be found the information split at height steps between 4 and 12 m, and one example is provided in Table 30 for a height of 2m.

**Table 30 Photos and coordinates were taken from a height of 2m in Test 2 - app 2**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 128 | 14:51:38 | 14:51:02 | 39 | -96.438479 | 30.633055 | 1.830 | -113.6 | -1.7 | -5.0 | Apr 16, 2016 2:51:02 PM |
| 2 | | | | 40 | -96.438452 | 30.633024 | 1.740 | -104.5 | -2.7 | -4.6 | Apr 16, 2016 2:51:03 PM |
| 3 | 129 | 14:51:40 | 14:51:04 | 41 | -96.438437 | 30.632992 | 1.750 | -87.7 | -3.0 | -5.3 | Apr 16, 2016 2:51:04 PM |
| 4 | | | | 42 | -96.438435 | 30.632956 | 1.780 | -69.9 | -1.6 | -4.7 | Apr 16, 2016 2:51:05 PM |
| 5 | 130 | 14:51:42 | 14:51:06 | 43 | -96.438447 | 30.632921 | 1.820 | -52.4 | -2.4 | -6.1 | Apr 16, 2016 2:51:06 PM |
| 6 | | | | 44 | -96.438456 | 30.632907 | 1.840 | -34.8 | -0.3 | -5.4 | Apr 16, 2016 2:51:07 PM |
| 7 | 131 | 14:51:44 | 14:51:08 | 45 | -96.438505 | 30.632867 | 1.900 | -17.9 | -0.8 | -4.8 | Apr 16, 2016 2:51:08 PM |
| 8 | | | | 46 | -96.438524 | 30.632857 | 1.870 | -9.2 | -1.9 | -4.1 | Apr 16, 2016 2:51:09 PM |

**Table 30 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 132 | 14:51:46 | 14:51:10 | 47 | -96.438594 | 30.632843 | 1.820 | 16.4 | -3.0 | -3.8 | Apr 16, 2016 2:51:10 PM |
| 10 | | | | 48 | -96.438620 | 30.632844 | 1.880 | 33.4 | -2.5 | -3.5 | Apr 16, 2016 2:51:11 PM |
| 11 | 133 | 14:51:48 | 14:51:12 | 49 | -96.438662 | 30.632855 | 1.810 | 50.2 | -4.0 | -5.0 | Apr 16, 2016 2:51:12 PM |
| 12 | | | | 50 | -96.438701 | 30.632876 | 1.830 | 67.6 | -3.8 | -5.3 | Apr 16, 2016 2:51:13 PM |
| 13 | 134 | 14:51:50 | 14:51:14 | 51 | -96.438731 | 30.632908 | 1.860 | 85.5 | -3.7 | -4.8 | Apr 16, 2016 2:51:14 PM |
| 14 | | | | 52 | -96.438749 | 30.632945 | 1.930 | 95.3 | -4.5 | -5.9 | Apr 16, 2016 2:51:15 PM |
| 15 | 135 | 14:51:52 | 14:51:16 | 53 | -96.438752 | 30.632986 | 1.980 | 112.2 | -4.9 | -5.8 | Apr 16, 2016 2:51:16 PM |
| 16 | | | | 54 | -96.438749 | 30.633004 | 1.980 | 129.3 | -4.9 | -6.6 | Apr 16, 2016 2:51:17 PM |
| 17 | 136 | 14:51:54 | 14:51:18 | 55 | -96.438720 | 30.633057 | 1.960 | 145.3 | -3.2 | -7.4 | Apr 16, 2016 2:51:18 PM |
| 18 | | | | 56 | -96.438691 | 30.633082 | 1.940 | 162.1 | -3.1 | -9.0 | Apr 16, 2016 2:51:19 PM |
| 19 | 137 | 14:51:56 | 14:51:20 | 57 | -96.438650 | 30.633100 | 1.940 | 179.1 | -4.3 | -8.9 | Apr 16, 2016 2:51:20 PM |
| 20 | | | | 58 | -96.438629 | 30.633104 | 1.980 | -164.9 | -2.2 | -9.6 | Apr 16, 2016 2:51:21 PM |
| 21 | 138 | 14:51:58 | 14:51:22 | 59 | -96.438585 | 30.633106 | 1.920 | -160.4 | 1.5 | 7.7 | Apr 16, 2016 2:51:22 PM |
| 22 | | | | 60 | -96.438561 | 30.633110 | 1.820 | -160.9 | -3.6 | 9.5 | Apr 16, 2016 2:51:23 PM |

With this information Figure 112 was developed for the actual path and the planned center at a height of 2m.

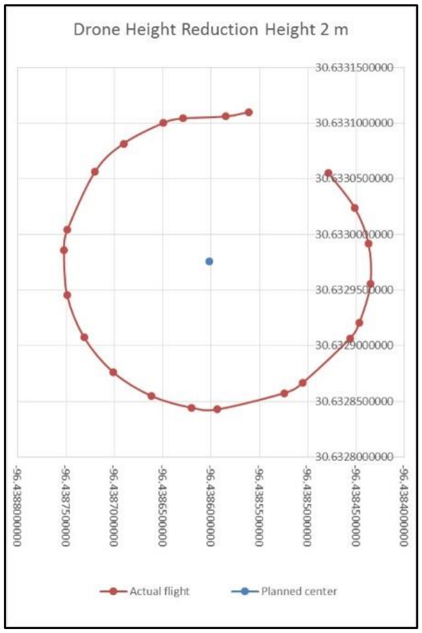



**Figure 112 Actual path and planned center at a height of 2 m in Test 2 – app 2**

Figure 112 was modified in AutoCAD in order to obtain the center of coordinates for the actual path graphically (taken from a green ellipse that was almost symmetrical to the actual path), the planned path (blue circumference), an average of the radius (pink lines) according to four representative points in Figure 113 (index 39, 45, 52 and 60), the estimated yaw angle with respect to the north and according to the UAV orientation and the planned center (pink angles), and the actual yaw angle according to the value read from the UAV (Green adjacent lines to the representative points).

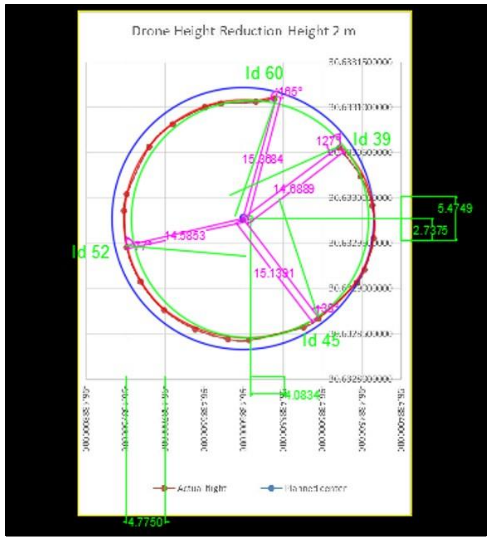



**Figure 113 Planned and actual path at a height of 2 m in Test 2 - app 2, evaluation 2**

The estimated yaw angle and actual radius read from Figure 113 for each representative point can be observed in Table 31. The actual yaw angle was taken according to the data in Table 30 and the planned radius was given as a parameter for the mission. This information was used to create Figure 114 and Figure 115.

**Table 31 Planned and actual yaw angle and radius according to the UAV-GPS data at a height of 2 m in Test 2 - app 2**

| N. | Index | Est. Yaw (Deg) | Act. Yaw (Deg) | Yaw diff. (Deg) | Abs Yaw diff. (Deg) | Planned radius (m) | Actual Radius (m) | Radius diff. (m) | Abs radius diff. (m) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 39 | -127.000 | -113.624 | 13.376 | 13.376 | 16.000 | 14.689 | -1.311 | 1.311 |
| 2 | 45 | -38.000 | -17.858 | 20.142 | 20.142 | 16.000 | 15.139 | -0.861 | 0.861 |
| 3 | 52 | 77.000 | 95.254 | 18.254 | 18.254 | 16.000 | 14.585 | -1.415 | 1.415 |
| 4 | 60 | -165.000 | -160.897 | 4.103 | 4.103 | 16.000 | 15.368 | -0.632 | 0.632 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Aver.** | | | | | 13.969 | | 14.945 | | 1.055 |
| **Std. dev.** | | | | | 7.168 | | 0.371 | | 0.371 |
| **Coef. Var.** | | | | | 51.32% | | 2.48% | | 35.14% |
| **Max.** | | | | | 20.142 | | 15.368 | | 1.415 |
| **Min.** | | | | | 4.103 | | 14.585 | | 0.632 |

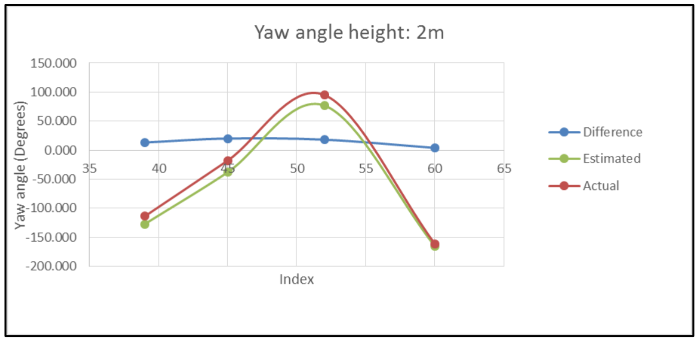



**Figure 114 Yaw angle according to the UAV-GPS at a height of 2 m in Test 2 - app 2**

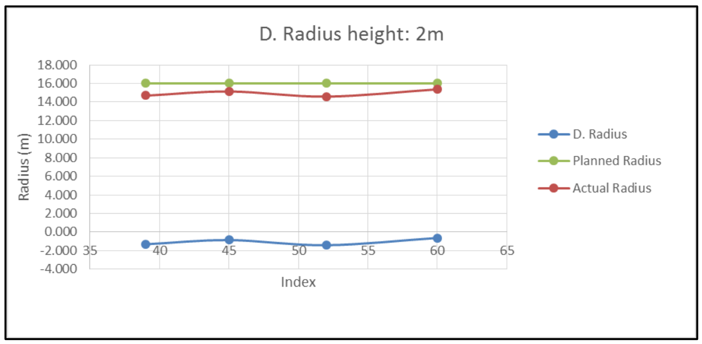



**Figure 115 Radius according to the UAV-GPS at a height of 2 m in Test 2 - app2**

From Table 31 and Figure 114 it can be seen that the UAV is not looking to the center of the pole and the actual orientation of the UAV can have a difference of 13.969 degrees in average with respect to it. For the actual radius, Table 31 and Figure 115 show a difference of 1.055 m in average between the actual and planned path which was not constant in all the height.

The same analysis was done for heights of 4 m, 6 m, 8 m, 10 m and 12 m. Table 32 shows the actual and planned radius and yaw angle for all the representative points in the mission, and Figure 116 and Figure 117 show the absolute variation of the radius and the yaw angle.

**Table 32 Planned and actual yaw angle and radius according to the UAV-GPS data for all the representative points in Test 2 - app 2**

| Ref. | Id | N. | Index | Est. Yaw (Deg) | Act. Yaw (Deg) | Yaw diff. (Deg) | Abs. Yaw diff. (Deg) | Planned radius (m) | Actual Radius (m) | Radius diff. (m) | Abs radius diff. (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2m height | 1 | 1 | 39 | -127.000 | -113.624 | 13.376 | 13.376 | 16.000 | 14.689 | -1.311 | 1.311 |
| | 2 | 2 | 45 | -38.000 | -17.858 | 20.142 | 20.142 | 16.000 | 15.139 | -0.861 | 0.861 |
| | 3 | 3 | 52 | 77.000 | 95.254 | 18.254 | 18.254 | 16.000 | 14.585 | -1.415 | 1.415 |
| | 4 | 4 | 60 | -165.000 | -160.897 | 4.103 | 4.103 | 16.000 | 15.368 | -0.632 | 0.632 |
| 4m height | 5 | 1 | 63 | -178.000 | -172.808 | 5.192 | 5.192 | 16.000 | 14.910 | -1.090 | 1.090 |
| | 6 | 2 | 69 | -95.000 | -80.291 | 14.709 | 14.709 | 16.000 | 14.684 | -1.317 | 1.317 |
| | 7 | 3 | 77 | 21.000 | 50.766 | 29.766 | 29.766 | 16.000 | 13.765 | -2.235 | 2.235 |
| | 8 | 4 | 85 | 153.000 | 177.518 | 24.518 | 24.518 | 16.000 | 13.655 | -2.345 | 2.345 |
| 6m height | 9 | 1 | 92 | 178.000 | -174.146 | 7.854 | 7.854 | 12.000 | 10.844 | -1.156 | 1.156 |
| | 10 | 2 | 98 | -77.000 | -53.907 | 23.093 | 23.093 | 12.000 | 10.800 | -1.200 | 1.200 |
| | 11 | 3 | 104 | 31.000 | 50.621 | 19.621 | 19.621 | 12.000 | 10.420 | -1.580 | 1.580 |
| | 12 | 4 | 111 | 151.000 | -153.371 | 55.629 | 55.629 | 12.000 | 10.880 | -1.120 | 1.120 |
| 8m height | 13 | 1 | 114 | 148.000 | -179.707 | 32.293 | 32.293 | 8.000 | 8.975 | 0.975 | 0.975 |
| | 14 | 2 | 119 | -131.000 | -110.944 | 20.056 | 20.056 | 8.000 | 7.658 | -0.342 | 0.342 |
| | 15 | 3 | 126 | 10.000 | 29.465 | 19.465 | 19.465 | 8.000 | 7.418 | -0.582 | 0.582 |
| | 16 | 4 | 132 | 135.000 | 174.650 | 39.650 | 39.650 | 8.000 | 7.279 | -0.721 | 0.721 |
| 10m height | 17 | 1 | 135 | 135.000 | 139.572 | 4.572 | 4.572 | 4.000 | 4.996 | 0.996 | 0.996 |
| | 18 | 2 | 140 | -135.000 | -113.217 | 21.783 | 21.783 | 4.000 | 3.457 | -0.543 | 0.543 |
| | 19 | 3 | 146 | -9.000 | 16.549 | 25.549 | 25.549 | 4.000 | 3.764 | -0.236 | 0.236 |
| | 20 | 4 | 152 | 117.000 | 130.751 | 13.751 | 13.751 | 4.000 | 3.578 | -0.422 | 0.422 |
| 12m height | 21 | 1 | 155 | 114.000 | 114.661 | 0.661 | 0.661 | 0.000 | 3.951 | 3.951 | 3.951 |
| | 22 | 2 | 160 | -156.000 | -136.164 | 19.836 | 19.836 | 0.000 | 3.360 | 3.360 | 3.360 |
| | 23 | 3 | 166 | -28.000 | -17.802 | 10.198 | 10.198 | 0.000 | 3.365 | 3.365 | 3.365 |
| | 24 | 4 | 174 | 99.000 | 110.451 | 11.451 | 11.451 | 0.000 | 3.514 | 3.514 | 3.514 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aver.** | | | | | | | 18.980 | | | | 1.469 |
| **Std. dev.** | | | | | | | 12.258 | | | | 1.083 |
| **Coef. Var.** | | | | | | | 64.59% | | | | 73.72% |
| **Max.** | | | | | | | 55.629 | | | | 3.951 |
| **Min.** | | | | | | | 0.661 | | | | 0.236 |

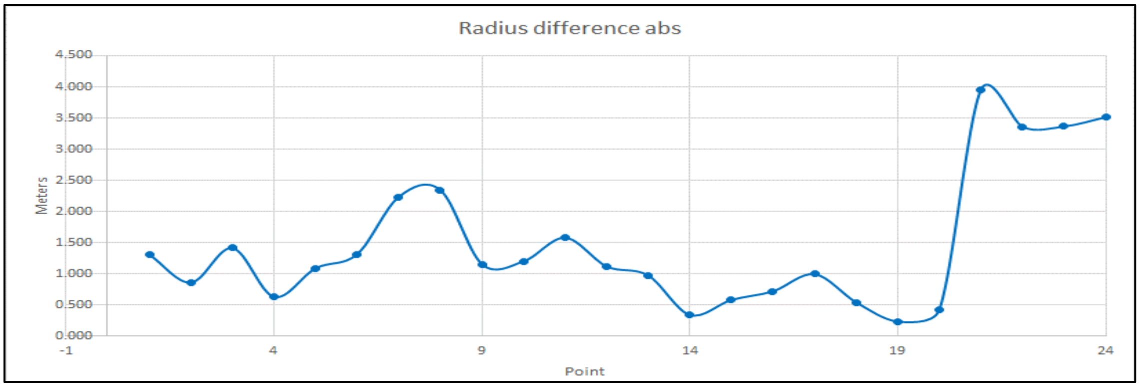



**Figure 116 Absolute radius difference according to the UAV-GPS data for all the representative points in Test 2 - app 2**

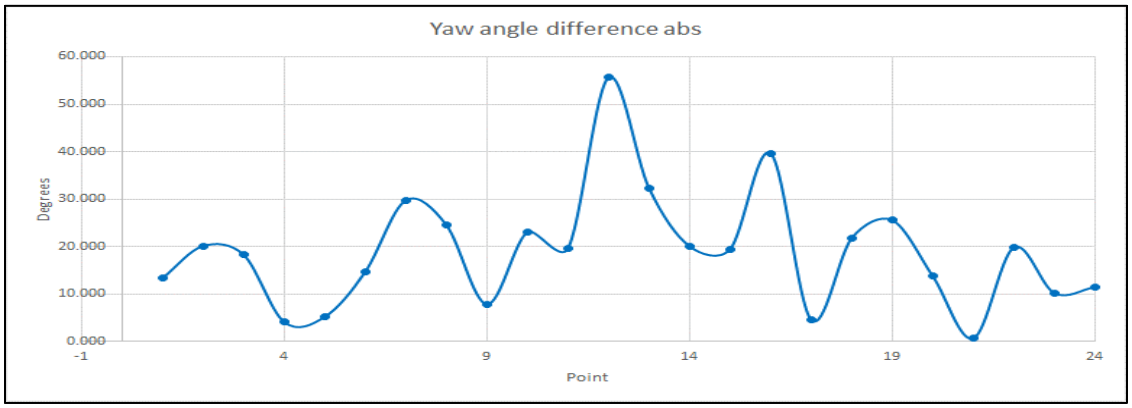



**Figure 117 Absolute yaw angle according to the UAV-GPS data for all the representative points in Test 2 - app 2**

According to Table 32 and Figure 116, it can be seen that the actual radius is on average lower than the planned one except in the last step (12 m height) and their difference is approximately 1.469 m. In the last step the largest difference between the actual and planned radius was observed and its value was 3.951 m, which is interesting because at that point it seems that the UAV was following a path with a radius similar to the one at a height of 10 m as it happened in Test 1 – app 2 (subchapter 4.2.3.3). In the heights between 2 and 10 m, there were points in which the actual radius had a minimum difference of 0.236 m and maximum of 2.345 m (points 146 and 85). Table 32 and Figure

117 indicate that in general there was a difference between the actual orientation of the UAV with respect to the pole location which was on average 18.980 degrees, with a maximum difference of 55.629 and a minimum difference of 0.661 degrees (points with index 111 and 155).

Table 33 summarizes the data collected for each height according to evaluation 2 and Figure 118 to Figure 122 show the actual average and planned height, latitude, longitude, pitch angle and radius at 6 different height levels.

**Table 33 Summary of planned and actual data and differences for each height according to the UAV-GPS in Test 2 - app2**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Planned Test 2 – app 2** | Path number | 1 | 2 | 3 | 4 | 5 | 6 |
| | Height (m) | 2.000 | 4.000 | 6.000 | 8.000 | 10.000 | 12.000 |
| | Lat (DD) | 30.632976 | 30.632976 | 30.632976 | 30.632976 | 30.632976 | 30.632976 |
| | Long (DD) | -96.438602 | -96.438602 | -96.438602 | -96.438602 | -96.438602 | -96.438602 |
| | Pitch angle (degrees) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | Radius (m) | 16.000 | 16.000 | 12.000 | 8.000 | 4.000 | 0.000 |
| **Actual Test 2 – app 2** | Height (m) | 1.872 | 3.993 | 6.017 | 7.965 | 10.013 | 12.018 |
| | Lat (DD) | 30.632975 | 30.632974 | 30.632980 | 30.632981 | 30.632978 | 30.632978 |
| | Long (DD) | -96.438593 | -96.438606 | -96.438604 | -96.438605 | -96.438606 | -96.438606 |
| | Pitch angle (degrees) | -2.503 | -1.838 | -2.768 | -2.503 | -0.640 | -0.742 |
| | Radius (m) | 14.945 | 14.253 | 10.736 | 7.833 | 3.949 | 3.547 |

| | | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
|---|---|---|---|---|---|---|
| **Actual Test 2 – app 2** | Height (m) | | | | | |
| | Lat (DD) | 30.632978 | 0.000003 | 0.00% | 30.632981 | 30.632974 |
| | Long (DD) | -96.438603 | 0.000005 | 0.00% | -96.438593 | -96.438606 |
| | Pitch angle (degrees) | -1.832 | 0.937 | -51.12% | -0.640 | -2.768 |
| | Radius (m) | | | | 14.945 | 3.547 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Abs. diff. Test 2 – app 2** | Point | 1 | 2 | 3 | 4 | 5 | 6 |
| | Height (m) | 0.128 | 0.007 | 0.017 | 0.035 | 0.013 | 0.018 |
| | Lat (DD) | 0.000001 | 0.000002 | 0.000004 | 0.000005 | 0.000002 | 0.000002 |
| | Lat (m) | 0.109 | 0.268 | 0.468 | 0.543 | 0.271 | 0.253 |
| | Long (DD) | 0.000009 | 0.000004 | 0.000002 | 0.000003 | 0.000004 | 0.000004 |
| | Long (m) | 0.864 | 0.402 | 0.205 | 0.307 | 0.372 | 0.371 |

**Table 33 Continued**

| Abs. diff. Test 2 – app 2 | Point | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| | Pitch angle (degrees) | 2.503 | 1.838 | 2.768 | 2.503 | 0.640 | 0.742 |
| | Radius (m) | 1.055 | 1.747 | 1.264 | 0.167 | 0.051 | 3.547 |

| | | Ave. | Std. dev. | Coef. Var. | Max. | Min. |
|---|---|---|---|---|---|---|
| Abs. Diff. Test 2 – app 2 | Height (m) | 0.036 | 0.046 | 126.55% | 0.128 | 0.007 |
| | Lat (DD) | 0.000003 | 0.000001 | 49.74% | 0.000005 | 0.000001 |
| | Lat (m) | 0.319 | 0.159 | 49.74% | 0.543 | 0.109 |
| | Long (DD) | 0.000004 | 0.000002 | 54.38% | 0.000009 | 0.000002 |
| | Long (m) | 0.420 | 0.228 | 54.38% | 0.864 | 0.205 |
| | Pitch angle (degrees) | 1.832 | 0.937 | 51.12% | 2.768 | 0.640 |
| | Radius (m) | 1.305 | 1.277 | 97.83% | 3.547 | 0.051 |

| Abs. diff. Test 2 – app 2 (%) | Point | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| | Height (m) | 6.41% | 0.18% | 0.28% | 0.43% | 0.13% | 0.15% |
| | Lat (DD) | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Long (DD) | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Pitch angle (degrees) | - | - | - | - | - | - |
| | Radius (m) | 6.59% | 10.92% | 10.53% | 2.09% | 1.28% | |

| | | Ave. | Std. dev. | Coef. Var. | Max. | Min. |
|---|---|---|---|---|---|---|
| Abs. diff. Test 2 – app 2 (%) | Height (m) | 1.26% | 2.52% | 199.57% | 6.41% | 0.13% |
| | Lat (DD) | 0.00% | 0.00% | 49.74% | 0.00% | 0.00% |
| | Long (DD) | 0.00% | 0.00% | 54.38% | 0.00% | 0.00% |
| | Pitch angle (degrees) | - | - | - | - | - |
| | Radius (m) | 6.28% | 4.53% | 72.13% | 10.92% | 1.28% |

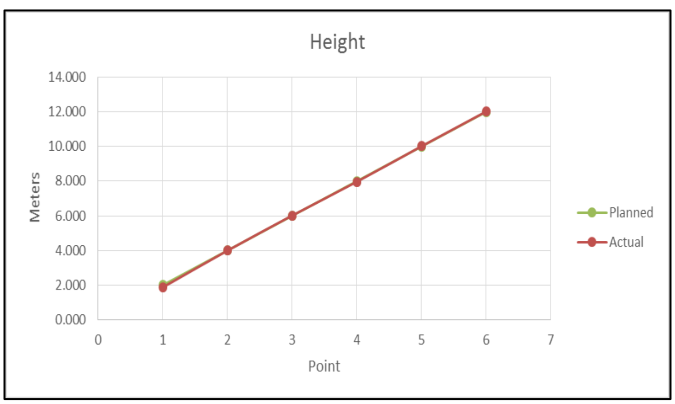



**Figure 118 Actual average and planned height for each point according to the UAV-GPS in Test 2 - app 2**

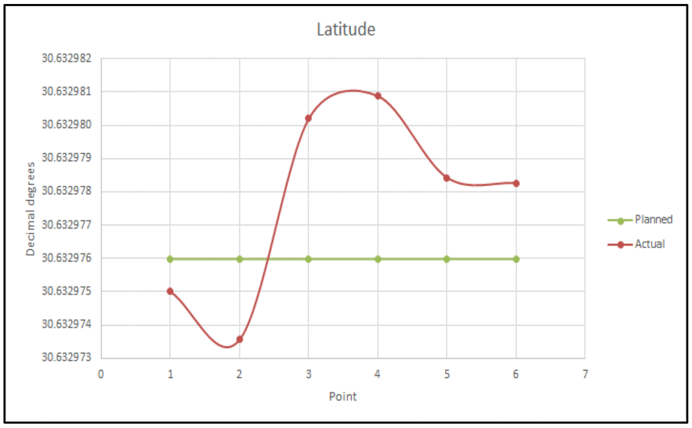



**Figure 119 Actual average and planned latitude for each point according to the UAV-GPS in Test 2 - app 2**

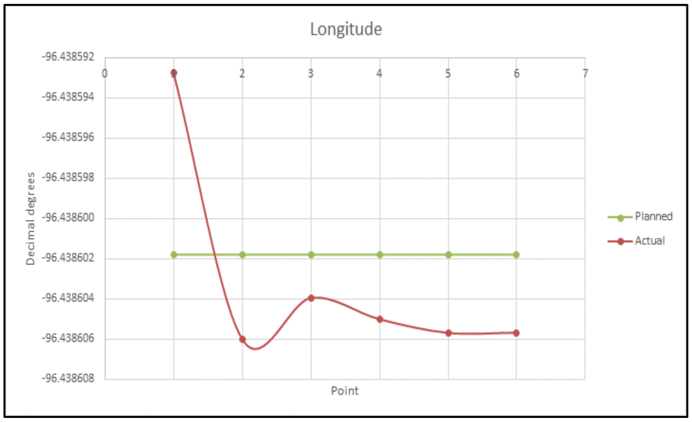



**Figure 120 Actual average and planned longitude for each point according to the UAV-GPS in Test 2 - app 2**

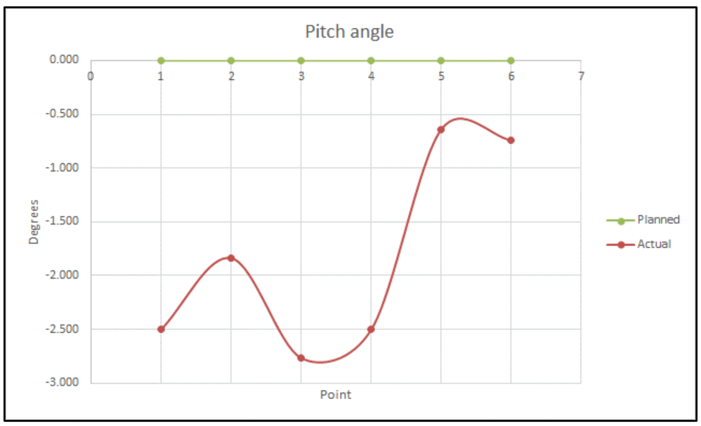



**Figure 121 Actual average and planned pitch angle for each point according to the UAV-GPS in Test 2 - app 2**

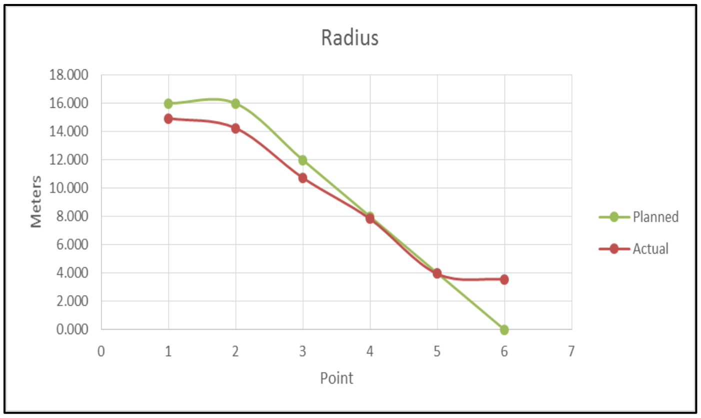



**Figure 122 Actual average and planned radius for each point according to the UAV-GPS in Test 2 - app 2**

From Table 33, it can be observed that the error between the planned and actual path in each mission step is on average 0.036 m or 1.26% at height, 0.319 m for the latitude, 0.420 m for the longitude, 1.832 degrees for the pitch angle, and approximately 6.28% for the radius.

### *4.2.4.4. Evaluation 3*

Photos between a height of 2 m and 6 m with 2 m increments were taken each second in order to do the evaluation 3 proposed in subchapter 3.3.

Such as it is mentioned in subchapters 4.2.1.4, 4.2.2.4 and 4.2.3.4, the photos of this process were used to do an actual flight path reconstruction in order to test the accuracy between the real and the planned path according to objective 2 of this research mentioned in subchapter 1.4, in order to complement and compare the information obtained in evaluation 2 in subchapter 4.2.4.3.

The same camera in subchapter 4.2.2.4 was used and for that reason, the calibration photo FHD0031 was employed for the images' analysis.

Approximately 34 photos were taken between a height of 2 m and 6 m and according to the results in subchapter 4.2.1.4, the inclination when the UAV took the pictures was omitted in the calculations.

For this evaluation at least 4 pictures in different quadrants (considering the actual path circumference for each height as the plane) were examined as it is shown in the image Figure 123 in order to obtain the distance between the center of the photo and the pole (DX) and the height of the frame in order to estimate the radius (Figure 124). With that information was possible to develop Table 34 which gives information about the average, standard deviation, coefficient of variation, maximum and minimum values of absolute DX, actual radius, difference between planned and actual radius and the angle difference between consecutive photos. This data was used to draw an approximate path of the UAV when it was doing the mission at a 2 m height (Figure 127); the position of the UAV with respect to the tape that was oriented looking to the magnetic north was measured from the drawing and was utilized to build the column “Angle UAS - East (Degrees)” in Table 34.

**Figure 123 Photo FHD0131 at a height of 2 m**

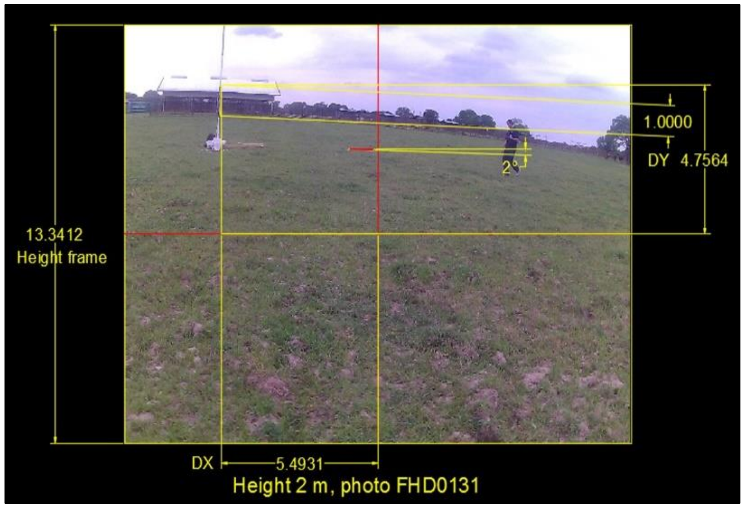



**Figure 124 FHD0131 at a height of 2 m with measurements**

**Table 34 Measurements for 5 photos which were taken at a height of 2 m in Test 2 - app2**

| N. | Photo FHD0- | DX(m) | Abs DX(m) | DY(m) | Photo frame height (m) | Actual Radius (m) | Planned radius (m) | Radius diff. (m) | Abs radius diff. (m) | Angle UAS-East (Degrees) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 128 | 1.544 | 1.544 | 3.118 | 10.701 | 12.758 | 16.000 | -3.242 | 3.242 | 43.000 |
| 2 | 131 | -5.493 | 5.493 | 4.756 | 13.341 | 15.906 | 16.000 | -0.094 | 0.094 | 17.000 |
| 3 | 133 | -6.593 | 6.593 | 4.826 | 13.115 | 15.635 | 16.000 | -0.365 | 0.365 | -32.000 |
| 4 | 134 | -7.330 | 7.330 | 4.848 | 12.740 | 15.189 | 16.000 | -0.811 | 0.811 | -141.000 |
| 5 | 138 | -4.514 | 4.514 | 2.532 | 11.223 | 13.380 | 16.000 | -2.620 | 2.620 | -202.000 |
| **Aver.** | | | 5.095 | | | 14.574 | | | 1.426 | |
| **Std. dev.** | | | 2.255 | | | 1.414 | | | 1.414 | |
| **Coef. Var.** | | | 44.27% | | | 9.70% | | | 99.14% | |
| **Max.** | | | 7.330 | | | 15.906 | | | 3.242 | |
| **Min.** | | | 1.544 | | | 12.758 | | | 0.094 | |

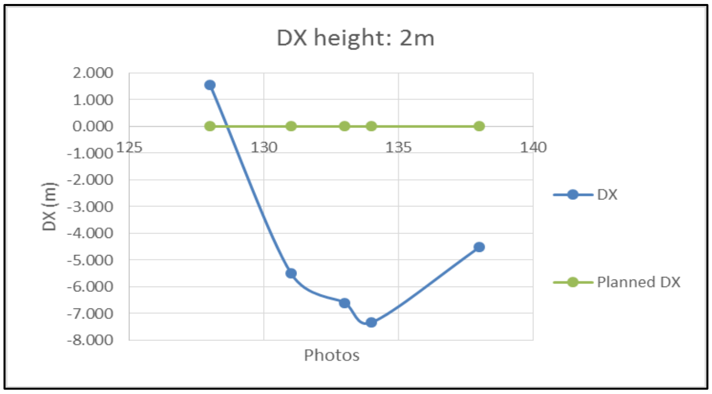



**Figure 125 Horizontal distance (DX) between the center of the photo and the pole at a height of 2 m in 5 different points, Test 2 - app2**

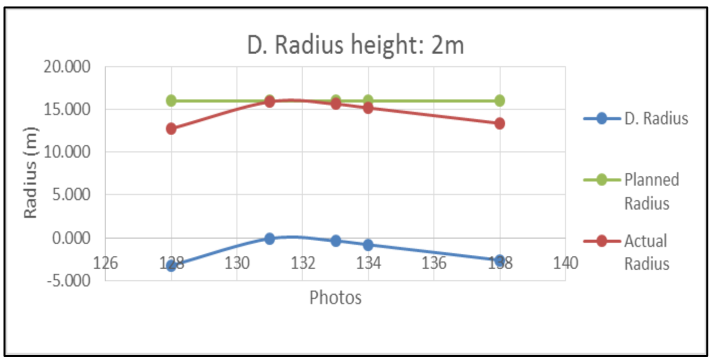



**Figure 126 Planned and actual radius estimation in different points at a height of 2 m in 5 different points, Test 2 - app2**

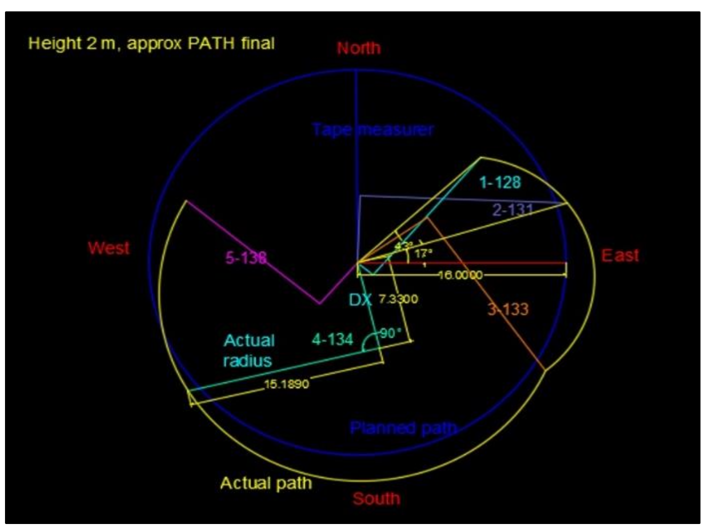



**Figure 127 Planned and actual path at a height of 2 m in Test 2 - app2, evaluation 3**

From Table 34, Figure 125 and Figure 126, it is possible to say for the height of 2 m in this mission that the error between the pole's center has an average of 5.095 m, with a maximum error of 7.330 m and a minimum of 1.544 m. For the radius difference, the average was 1.426 m, with a maximum difference of 3.242 m and a minimum of 0.094 m, which means that the average actual radius was 14.574 m, the maximum radius was 15.906 m and the minimum was 12.758 m.

Table 34 was created for a height of 2 m. The same table was also done for the heights of 4 m and 6 m and according to them, Table 35, Figure 128 and Figure 129 were generated, which summarize and show the DX error and radius difference according to all the photos. The information given in Table 35 was classified for each height and according to that Table 36 was created.

**Table 35 DX and radius difference for all the photos analyzed in Test 2 - app 2**

| Ref. | Id. | N. | Photo FHD0- | DX(m) | Abs DX (m) | DY (m) | Photo frame height (m) | Act. Rad. (m) | Plan. Rad. (m) | Rad. diff. (m) | Abs. Rad. diff. (m) | Angle UAS - East (Deg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2m height | 1 | 1 | 128 | 1.544 | 1.544 | 3.118 | 10.701 | 12.758 | 16.000 | -3.242 | 3.242 | 43.000 |
| | 2 | 2 | 131 | -5.493 | 5.493 | 4.756 | 13.341 | 15.906 | 16.000 | -0.094 | 0.094 | 17.000 |
| | 3 | 3 | 133 | -6.593 | 6.593 | 4.826 | 13.115 | 15.635 | 16.000 | -0.365 | 0.365 | -32.000 |
| | 4 | 4 | 134 | -7.330 | 7.330 | 4.848 | 12.740 | 15.189 | 16.000 | -0.811 | 0.811 | -141.000 |
| | 5 | 5 | 138 | -4.514 | 4.514 | 2.532 | 11.223 | 13.380 | 16.000 | -2.620 | 2.620 | -202.000 |
| 4m height | 8 | 1 | 140 | -3.921 | 3.921 | 2.329 | 12.787 | 15.245 | 16.000 | -0.755 | 0.755 | 159.000 |
| | 9 | 2 | 142 | -3.772 | 3.772 | 3.558 | 10.701 | 12.758 | 16.000 | -3.242 | 3.242 | 28.000 |
| | 10 | 3 | 144 | -5.285 | 5.285 | 3.633 | 11.781 | 14.045 | 16.000 | -1.955 | 1.955 | 13.000 |
| | 11 | 4 | 146 | -7.877 | 7.877 | 5.229 | 13.708 | 16.343 | 16.000 | 0.343 | 0.343 | -97.000 |
| 6m height | 13 | 1 | 153 | 2.751 | 2.751 | 3.626 | 8.898 | 10.608 | 12.000 | -1.392 | 1.392 | 130.000 |
| | 14 | 2 | 155 | 2.985 | 2.985 | 3.401 | 8.387 | 9.999 | 12.000 | -2.001 | 2.001 | 23.000 |

**Table 35 Continued**

| Ref. | Id. | N. | Photo FHD0- | DX(m) | Abs DX (m) | DY (m) | Photo frame height (m) | Act. Rad. (m) | Plan. Rad. (m) | Rad. diff. (m) | Abs. Rad. diff. (m) | Angle UAS - East (Deg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6m height | 15 | 3 | 157 | 3.575 | 3.575 | 3.099 | 9.413 | 11.222 | 12.000 | -0.778 | 0.778 | -28.000 |
| | 16 | 4 | 159 | 6.306 | 6.306 | 0.000 | 10.194 | 12.154 | 12.000 | 0.154 | 0.154 | -129.000 |
| **Aver.** | | | | | 4.765 | | | | | | 1.366 | |
| **Std. dev.** | | | | | 1.905 | | | | | | 1.137 | |
| **Coef. Var.** | | | | | 39.99% | | | | | | 83.29% | |
| **Max.** | | | | | 7.877 | | | | | | 3.242 | |
| **Min.** | | | | | 1.544 | | | | | | 0.094 | |

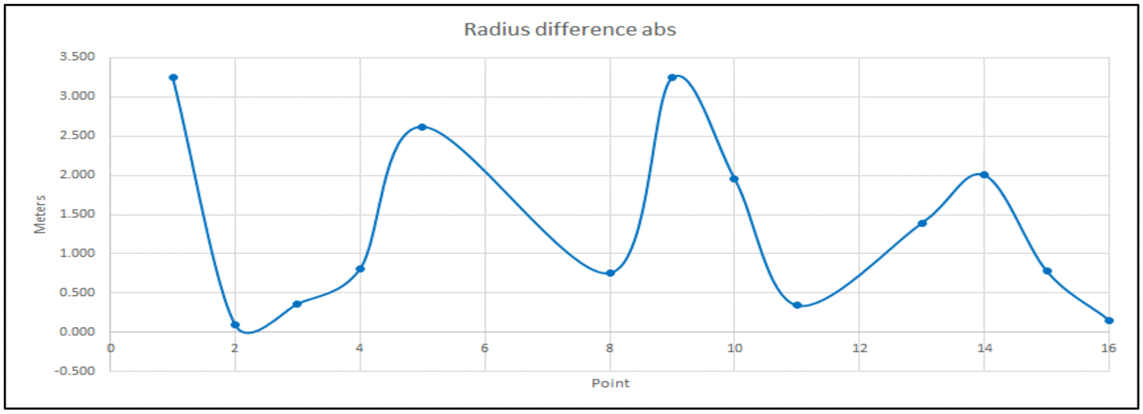



**Figure 128 Absolute radius difference for all the photos analyzed in Test 2 - app 2**

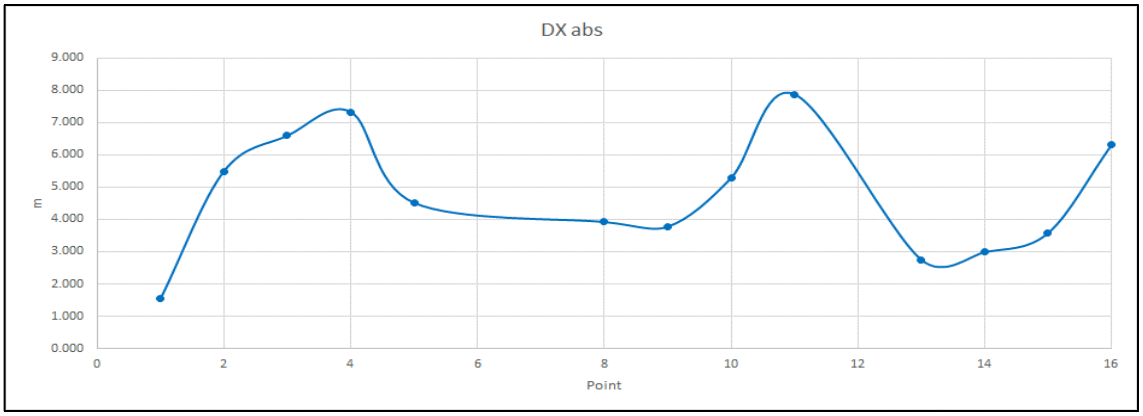



**Figure 129 Horizontal distance between the center of the picture and the pole position (DX abs) for all the photos analyzed in Test 2 - app 2**

**Table 36 Summary of planned and actual data and differences for each height from photos in Test 2 - app 2**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Planned Test 2 – app 2** | Path number | 1 | 2 | 3 | | | | | |
| | Height (m) | 2.000 | 4.000 | 6.000 | | | | | |
| | DX (m) | 0 | 0 | 0 | | | | | |
| | Radius (m) | 16.000 | 16.000 | 12.000 | **Ave.** | **Std. dev.** | **Coef. Var.** | **Max.** | **Min.** |
| **Actual Test 2 – app 2** | DX (m) | 5.095 | 5.214 | 3.904 | 4.737 | 0.724 | 15.29% | 5.214 | 3.904 |
| | Radius (m) | 14.574 | 14.598 | 10.996 | 13.389 | 2.073 | 15.48% | 14.598 | 10.996 |
| **Abs. diff. Test 2 – app 2** | DX (m) | 5.095 | 5.214 | 3.904 | 4.737 | 0.724 | 15.29% | 5.214 | 3.904 |
| | Radius (m) | 1.426 | 1.402 | 1.004 | 1.278 | 0.237 | 18.55% | 1.426 | 1.004 |
| **Abs. diff. Test 2 – app 2(%)** | DX (m) | 100.00% | 100.00% | 100.00% | 100.00% | 0.00% | 0.00% | 100.00% | 100.00% |
| | Radius (m) | 9.79% | 9.60% | 9.13% | 9.51% | 0.34% | 3.55% | 9.79% | 9.13% |

From Table 35, it can be said that the horizontal average error between the center of the photos and the pole for all the mission at a height among 2 m and 6 m was 4.765 m, with a maximum number of 7.877 m and minimum of 1.544 m. The average absolute radius difference from the photos was 1.366 m with respect to the planned radius, with a maximum value of 3.242 m and a minimum of 0.094 m.

From Table 36, it is shown that in the height of 4 m the Abs DX had an average value of 5.214 m which was bigger than in the other heights and the radius difference in the height of 2 m had an average of 1.426 m which was bigger than in the other points.

According to the evaluation 3 proposed in subchapter 3.3, the following is the percentage for the wrong focus:

$$Eq.\%\, wrong\ focus = \frac{\sum Option\ B\ photos}{\sum Option\ A\ photos + \sum Option\ B\ photos} \times 100\%$$

$$Eq.\%\, wrong\ focus = \frac{16}{0 + 16} \times 100\% = 100\%$$

It means that the center of the photos did not fit with the center of coordinates, and it is supported with the information provided in Table 35 in which the horizontal distance between the pole and the center of the images had an average of 4.765 m with a standard deviation of 1.905 m.

*4.2.4.5. 3D Model for Test 2 – app 2*

Figure 130 until Figure 135 show the 3D model for the flight of the UAV and its orientation with respect to the pole according to Figure 113, Figure 127 and the other ones that were done at different heights. In those graphics the height was considered constant in each step, the blue circumference is the planned path, the red figure is the actual path and the green lines show the actual yaw angle according to the GPS and UAV sensors (subchapter 4.2.4.3), the yellow figure is the actual path and the magenta lines show the UAV orientation from the photos (subchapter 4.2.4.4), the blue line indicates the tape measure that was used to reference the north.

Figure 136 and Figure 137 show a 3D model for the UAV flight according to the planned and actual paths drawn in Figure 130 until Figure 135.

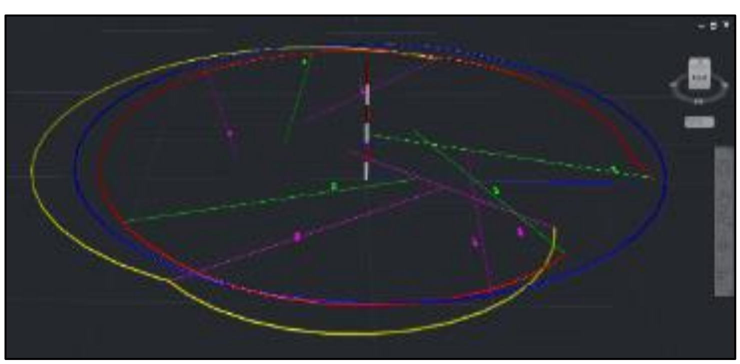


**Figure 130 3D model for the planned and actual path at a height of 2 m, Test 2 - app 2**

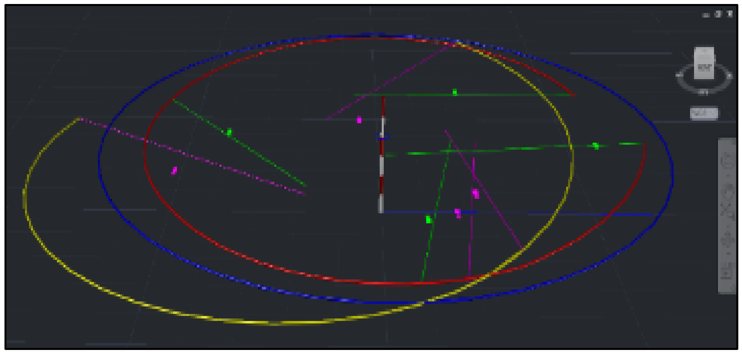


**Figure 131 3D model for the planned and actual path at a height of 4 m, Test 2 - app 2**

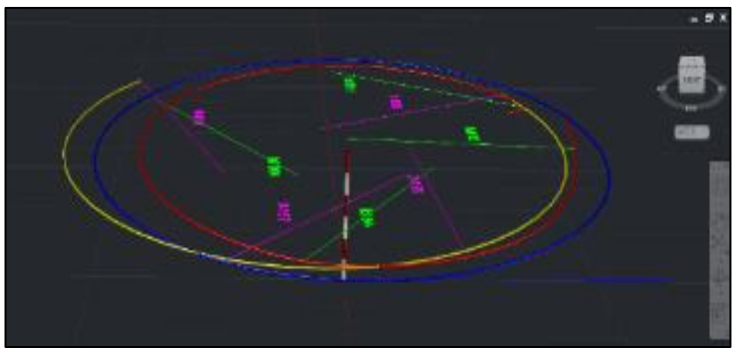


**Figure 132 3D model for the planned and actual path at a height of 6 m, Test 2 - app 2**

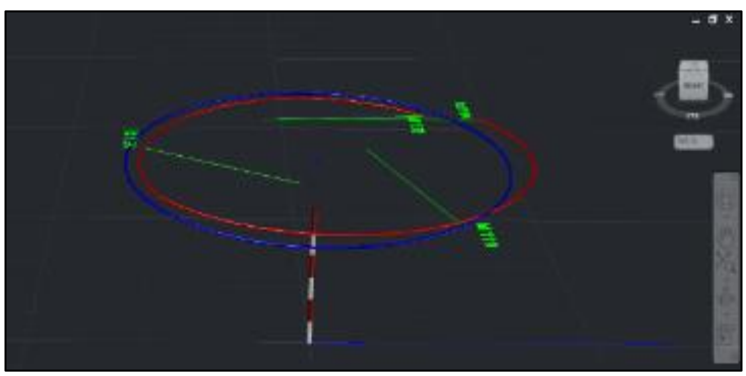


**Figure 133 3D model for the planned and actual path at a height of 8 m, Test 2 - app 2**

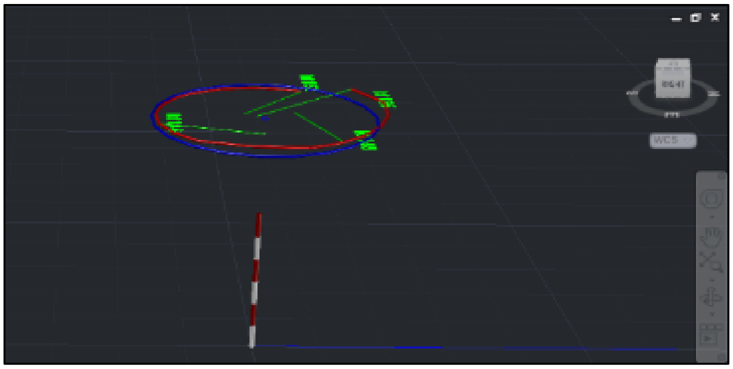


**Figure 134 3D model for the planned and actual path at a height of 10 m, Test 2 - app 2**

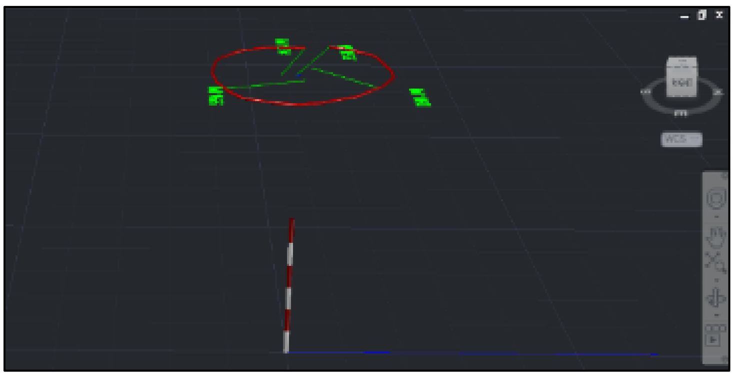


**Figure 135 3D model for the planned and actual path at a height of 12 m, Test 2 – app 2**

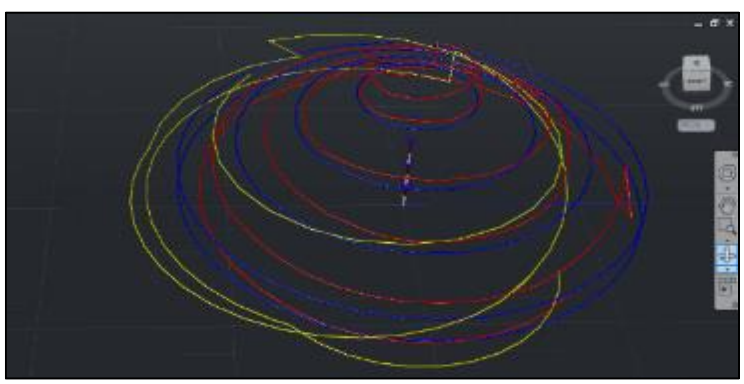


**Figure 136 3D model – view 1 for the planned and actual path, Test 2 – app 2**

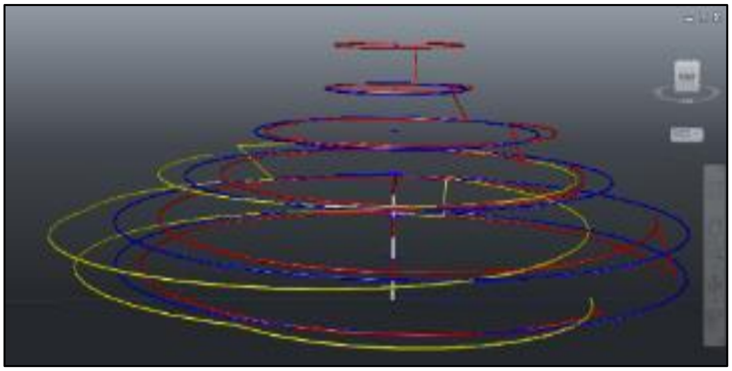


**Figure 137 3D model – view 2 for the planned and actual path, Test 2 – app 2**

#### *4.2.4.6. Analysis of the mission*

After checking the information collected in subchapters 4.2.4.2, 4.2.4.3 and 4.2.4.4, the following can be mentioned:

- The actual path for the UAV was not circular as it was pretended in the mission planning and as it was stated in subchapters 4.2.1.6, 4.2.2.6 and 4.2.3.6, which can be related to factors related to the GPS accuracy in the UAV, the wind, etc.
- As it was mentioned in subchapters 4.2.2.6 and 4.2.3.6, for this work the evaluation 2 gives a good idea about the actual position and orientation during the UAV flight.
- From evaluation 2, it can be said that the UAV had differences in its planned and actual flight. The actual height was 0.036 m or 1.26% on average lower than the planned one; the latitude had a difference of 0.000003 DD or 0.319 m on average; the longitude had a difference of 0.000004 DD or 0.420 m on average; the pitch angle had negative values in each height step and its average was 1.832 degrees; the radius difference had an average of 1.469 m with a

minimum value of 0.236 m and a maximum of 3.951 m; and the angle between the actual orientation and the planned objective had a difference of 18.980 degrees on average.

- From previous evaluations, it can be mentioned that the measurements done with photos in evaluation 3 can have an error of 4.35 percent, which in a distance of 8 m represents an error of approximately 0.348 m (Appendix A.1.). However, the error in this analysis depends on factors such as the inclination of the camera with respect to the objective at the moment of taking the picture, the camera resolution, and the measurements done by the user.
- From evaluation 3, it can be said that the center for the pictures in the UAV can have a difference with the center of coordinates for the mission of approximately 4.765 m with a maximum difference of 7.877 m and minimum of 1.544 m. It is interesting to mention that according to the orientation of the UAV at the moment of taking the picture it was not focusing to a specific point but to a region as it was said in subchapter 4.2.4.4.
- From evaluation 3, the average absolute planned and actual radius difference was 1.366 m, however, there was a point in which the difference between the actual and planned radius was 3.242 m or approximately 20%. This gives an idea about the risk of collision of the UAV with the structure to be inspected when flying autonomously if it is not given a prudent distance to do the work.
- As it was mentioned in subchapter 4.2.3.6, the results of evaluation number 3 for this test revealed in the last step (height of 12 m) and when the planned

radius is “0” an actual path with a similar radius to the one in the previous step (height of 10 m).

- As it was said in subchapters 4.2.2.6 and 4.2.3.6, evaluations 2 and 3 show differences in the values of the actual path and yaw angle, however, they support the fact that the UAV did not fly exactly as it was expected and it had a deviation at the moment of focusing the objective.

### *4.3. Analysis summary*

Table 37 summarizes the results of the missions for each application according to evaluation 2 and 3 done in subchapter 4.2.

**Table 37 Summary of missions' results for each mobile application**

| | | **Application 1: Structure_Scan_Coordinates** | | **Application 2: Drone Height Reduction** | |
|---|---|---|---|---|---|
| | | **Test 1** | **Test 2** | **Test 1** | **Test 2** |
| **Evaluation 2** | Latitude difference (DD) - Absolute average | No data | 0.000002 | 0.000002 | 0.000003 |
| | Latitude difference (m) - Absolute average | No data | 0.269 | 0.230 | 0.319 |
| | Latitude difference (m) - Absolute max | No data | 0.432 | 0.504 | 0.543 |
| | Latitude difference (m) - Absolute min | No data | 0.042 | 0.024 | 0.109 |
| | Longitude difference (DD) - Absolute average | No data | 0.000002 | 0.000004 | 0.000004 |
| | Longitude difference (m) - Absolute average | No data | 0.229 | 0.343 | 0.420 |
| | Longitude difference (m) - Absolute max | No data | 0.654 | 0.534 | 0.864 |
| | Longitude difference (m) - Absolute min | No data | 0.057 | 0.153 | 0.205 |
| | Altitude difference (m) - Absolute average | No data | 0.066 | 0.126 | 0.036 |
| | Altitude difference (m) - Absolute max | No data | 0.128 | 0.235 | 0.128 |
| | Altitude difference (m) - Absolute min | No data | 0.029 | 0.002 | 0.007 |
| | Radius difference (m) - Absolute average | No data | 0.922 | 1.009 | 1.469 |
| | Radius difference (m) - Absolute max | No data | 2.150 | 2.090 | 3.951 |
| | Radius difference (m) - Absolute min | No data | 0.140 | 0.119 | 0.236 |
| | Yaw angle difference (Degrees)- Absolute average | No data | 14.859 | 25.784 | 18.980 |
| | Yaw angle difference (Degrees) - Absolute max | No data | 22.321 | 59.586 | 55.629 |
| | Yaw angle difference (Degrees) - Absolute min | No data | 1.893 | 1.338 | 0.661 |
| | Pitch angle difference (Degrees) - Absolute average | No data | 3.557 | 1.043 | 1.832 |
| | Pitch angle difference (Degrees) - Absolute max | No data | 4.315 | 1.527 | 2.768 |
| | Pitch angle difference (Degrees) - Absolute min | No data | 2.725 | 0.173 | 0.640 |

**Table 37 Continued**

| | | Application 1: Structure_Scan_Coordinates | | Application 2: Drone Height Reduction | |
|---|---|---|---|---|---|
| | | **Test 1** | **Test 2** | **Test 1** | **Test 2** |
| **Evaluation 3** | Eq.% wrong focus | 100% | 100% | 100% | 100% |
| | Radius difference (m) - Absolute average | 0.713 | 1.389 | 1.214 | 1.366 |
| | Radius difference (m) - Absolute max | 2.202 | 2.968 | 2.773 | 3.242 |
| | Radius difference (m) - Absolute min | 0.051 | 0.035 | 0.022 | 0.094 |
| | DX (m) - Absolute average | 1.975 | 4.224 | 3.113 | 4.765 |
| | DX (m) - Absolute max | 4.382 | 7.639 | 5.927 | 7.877 |
| | DX (m) - Absolute min | 0.540 | 0.368 | 1.160 | 1.544 |

From this table, it is possible to say for all the missions that the difference in latitude and longitude had average range between 0.000002 and 0.000004 DD or 0.2302 and 0.420 m, the average altitude difference had an interval between 0.036 and 0.120 m, the radius difference had a possible minimum value of 0.022 m and a possible maximum value of 3.951 m, the yaw angle difference was between 0.661 and 59.586 degrees, the average pitch angle was in a range between 1.043 and 3.557 degrees, and the average horizontal distance between the center of the picture and the center of the pole (DX) was between 0.368 and 7.877 m.

# 5. CONCLUSION

This chapter reviews the objectives of this study, summarizes the work done and mentions its limitations. Significance and recommendations for future work are also given.

## *5.1. Review of research goal and objectives*

The goal of this research was to evaluate the possibility of using autonomous missions in SUAS for monitoring cylindrical buildings and two objectives were set. One was to develop two mobile applications for sUAV autonomous flights and the second was to test the apps' stability and UAV path accuracy in order to mitigate malfunctions or accidents when they are applied for cylindrical building inspections.

The objectives were met according to the methodology and results of this research, nevertheless, for the inspections of structures with SUAS, it is still necessary to improve the accuracy between the planned and actual path because the flight is highly influenced by the devices' characteristics and environmental factors.

## *5.2. Summary of SUAS current state*

UAS have been implemented since the early 1900s in the military field, however, with the progress in navigation systems, mobile devices and other technologies, they started to be used in other contexts. For construction and visual monitoring, they represent an opportunity to facilitate the inspection of structures in comparison with traditional methods in which crews work at height and use equipment such as cranes.

SUAS can be controlled manually or autonomously. The first option gives some freedom to the pilot in order to fly the device near to the structure, nonetheless, this person must have a lot of experience in order to avoid a collision and must be aware about the battery lifetime for the mission, which can have a range between 20 to 25 minutes on average depending on the type of UAV used.

Autonomous missions are another option to fly SUAS depending on their GPS and flight controller, however, configuration in commercial applications for those missions are not the most adequate in particular works and they can affect the flight accuracy.

### *5.3. Summary of findings*

Two applications for sUAV autonomous flights were developed for Android mobile devices such as tablets and smartphones in order to use them for inspections in cylindrical buildings and provide solutions to some current limitations in existing commercial applications related to the necessity of an internet connection to download the site's map, accuracy in the waypoints selected and camera's focus point during the flight.

One of the apps is called Structure_Scan_Coordinates and it can be used for cylindrical buildings with constant radius, while the second app called Drone Height Reduction can be used for complex buildings in which a section is cylindrical and their top is a cone. Taking some differences in the code used for each app into consideration, in the first app, the UAV has a pitch angle with a higher absolute value in each height step, while in the second app this value can be similar for each height step.

A third app called Coord_readerv2 was also developed for Android in order to have a program that saves the coordinates and the orientation during the drone flight in a

“.txt” file according to the information collected by telemetry between the UAV and the Android device. The development of this app was essential in order to measure the accuracy between the UAV’s planned and actual flight path which was one of the objectives of this work.

According to the outcomes of some analysis performed in this research, it can be said that the actual and planned center of coordinates for the UAV missions did not have a big difference because it was less than 0.5 m in longitude and latitude, and for the height, it was 0.126 m on average.

However, at the moment of taking pictures the results were different because the UAV’s yaw angle had a variation with respect to the photo objective until 60 degrees approximately, which means that this objective was not in the center of the images taken by the drone. It was also verified in each mission measuring the horizontal distance between the center of coordinates and the center of the photo, and its variation in the pictures was from some centimeters to 7.877 meters.

In the case of the radius, the results of this research show that it is not constant as it is wanted when the mission is planned, and the variation in its actual value can be from some centimeters to 3.951 meters, and that could be more in other works considering the GPS horizontal accuracy.

*5.4. Summary of discussion and results*

The results of the missions and the tests demonstrated that the apps worked. However, the planned and actual path show some differences, mainly in the radius and orientation because the flight is highly influenced by distinct variables such as the parameters sent to the SUAS with the mobiles applications, the UAV's GPS, the UAV's flight controller, the wind and the weather.

It is still recommended to be very cautious when flying an UAV autonomously in order to avoid any collision of the device with the structure to be inspected and to possibly use very high resolution cameras in order to take photos of the points of interest or to implement additional devices such as proximity sensors which can work with the UAV's internal flight controller avoiding flights too close to the structure.

### *5.5. Limitations*

This research was restricted to the following:

- Commercial apps that can be developed, analyzed and compared in the 3DRobotics drones or those that work with Pixhawk as autopilot.
- Apps were programmed for devices that use Android as the operating system and they depend on the existing programming objects, classes and methods that were used in the code.
- Apps and the flight of the SUAS were tested on a pole that gives an idea about the feasibility of its use on other structures.
- The results in this research are based on the flight and analysis of four different autonomous missions.
- Accuracy in the flight depended mainly on the GPS, weather conditions, battery capacity and SUAS characteristics.

*5.6. Significance*

The results of this work gave an idea about the feasibility of using autonomous flights in SUAS to facilitate the visual inspection of cylindrical structures which will be represented in time and money savings, and reduction of accidents.

New knowledge was also generated in order to allow other students to use open source code platforms in a drone to develop more sophisticated applications to solve construction and engineering problems economically.

*5.7. Recommendations for future research*

Future work on this topic may be related to the following:

- To develop better mobile applications which can be used in structures with different geometry.
- To continue progressing in the UAV's internal flight controller technology in order to have more accuracy in autonomous missions or to implement additional devices or sensors which can improve the UAV's flight.
- To evaluate if the current resolution in cameras can mitigate the effect of the distance that should be considered at the moment of flying an UAV near a structure.
- To research other uses that could be implemented for UAVs and robotics in the construction industry such as works at height in order to avoid the risk that workers have when they carry out their work under those conditions.

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APPENDIX A

*Data collected and other analysis Test 1 - app 1, date 02 -20-2016*

## *A.1. Error estimation in the photo measurements*

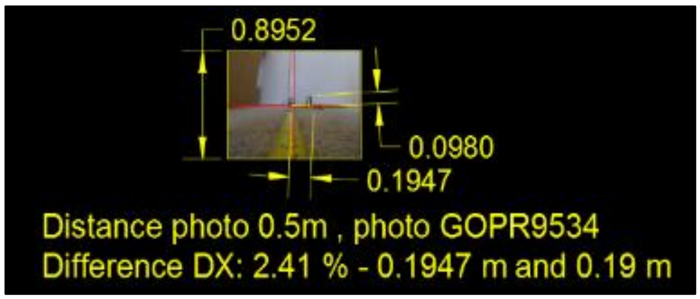



**Figure 138 Calibration photo GOPR9534 with a camera distance of 0.5 m and horizontal displacement of 0.19 m. The horizontal difference between the photo and actual measure is 2.41% approx.**

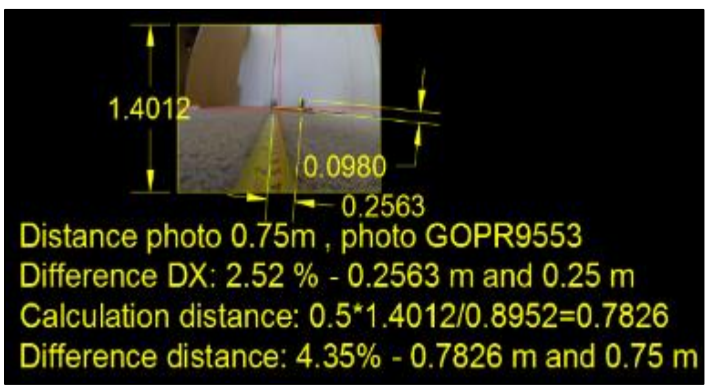



**Figure 139 Photo GOPR9553 with a camera distance of 0.75 m and horizontal displacement of 0.25 m. The horizontal difference between the photo and actual measure is 2.52% and the distance difference between the calculation and the actual measure is 4.35% approx.**

## *A.2. Data evaluation 3*

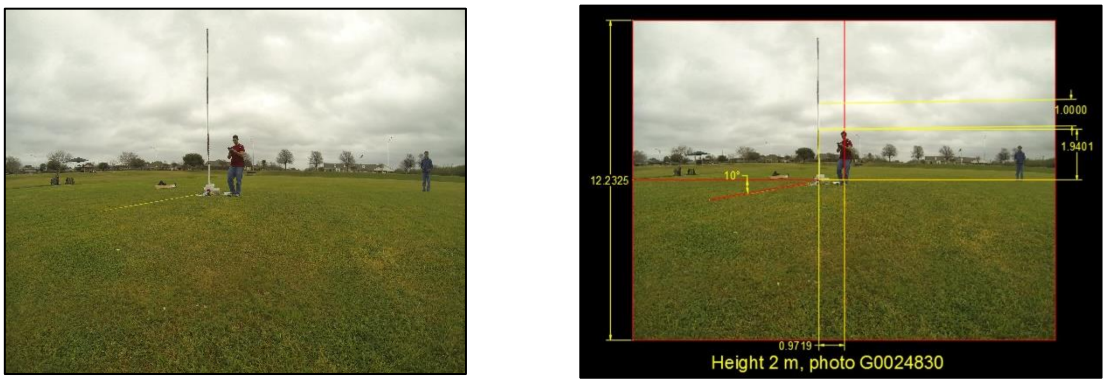



**Figure 140 Photo G0024830 at a height of 2 m with measurements**

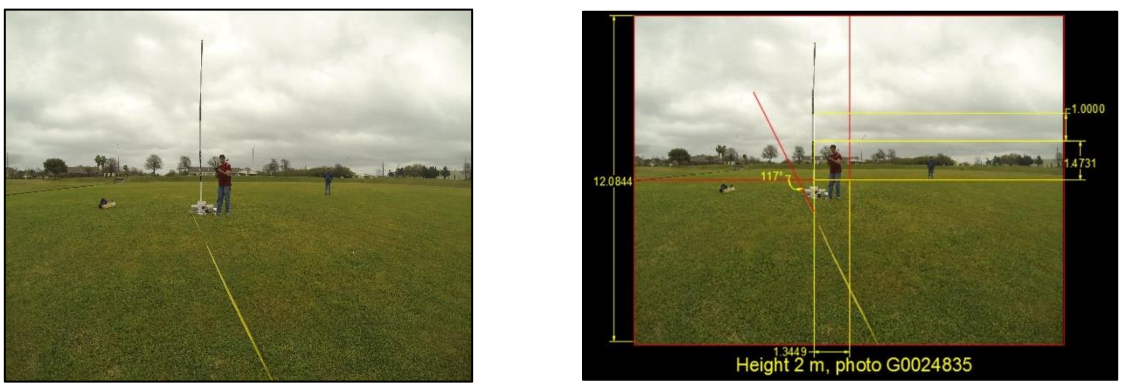



**Figure 141 Photo G0024835 at a height of 2 m with measurements**

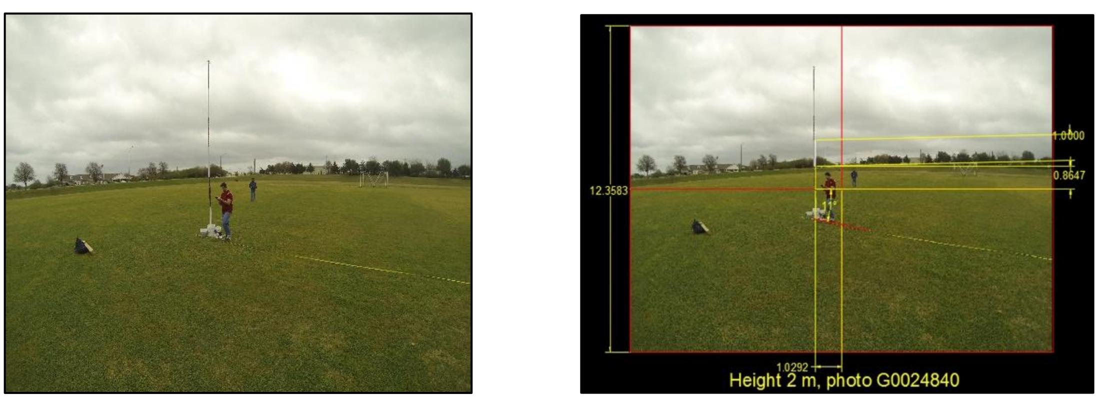



**Figure 142 Photo G0024840 at a height of 2 m with measurements**

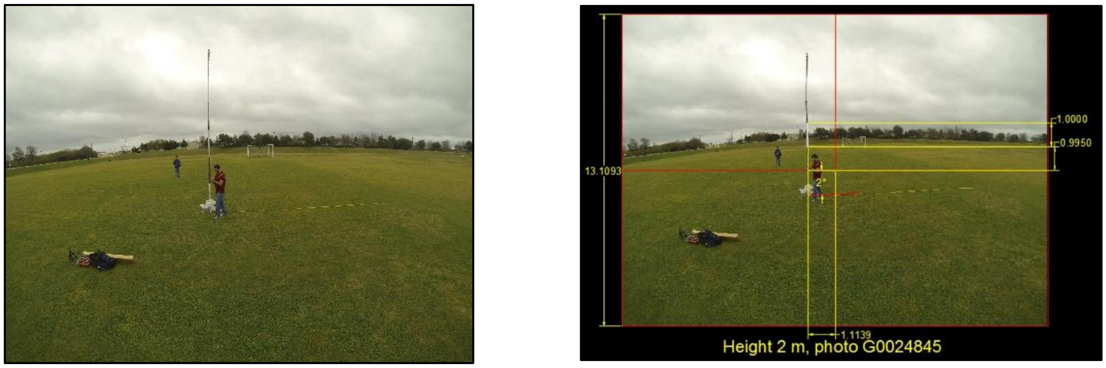



**Figure 143 Photo G0024845 at a height of 2 m with measurements**

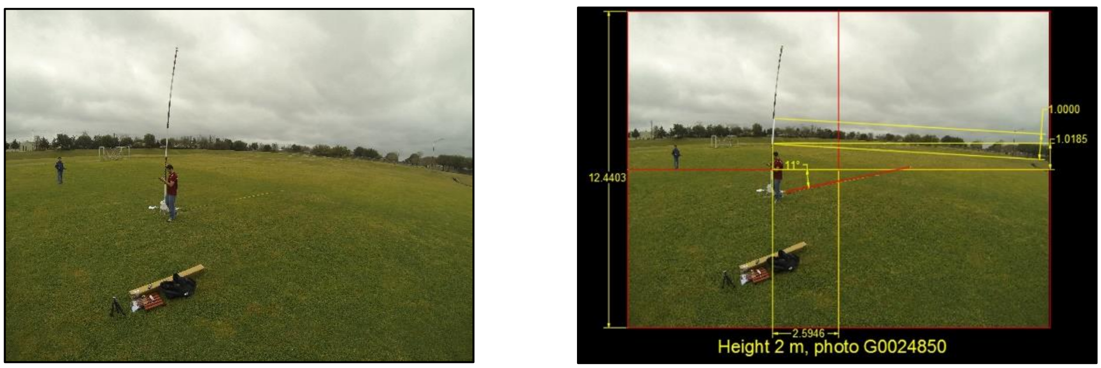



**Figure 144 Photo G0024850 at a height of 2 m with measurements**

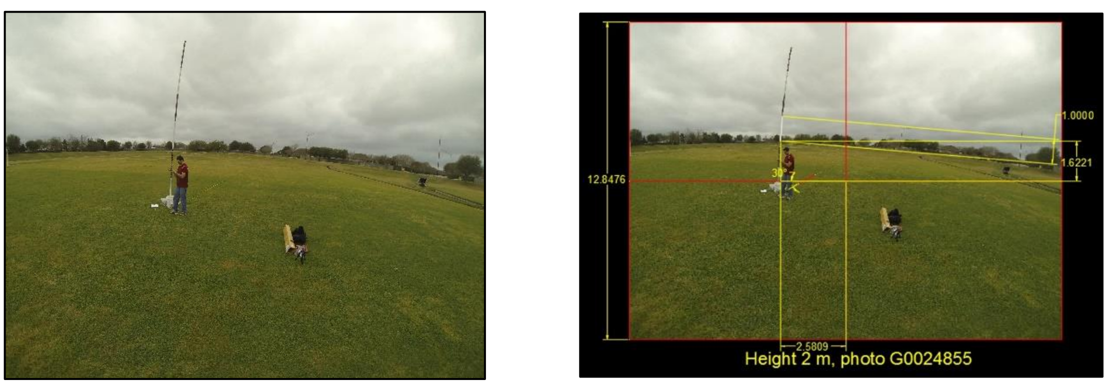



**Figure 145 Photo G0024855 at a height of 2 m with measurements**

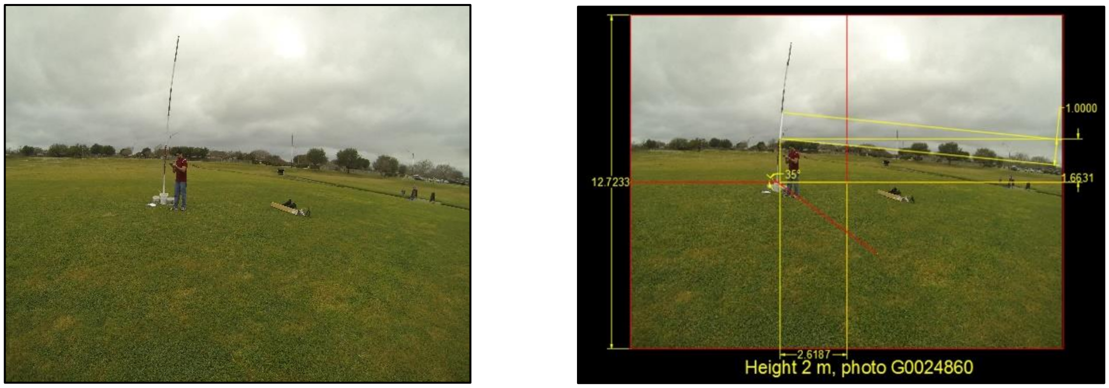



**Figure 146 Photo G0024860 at a height of 2 m with measurements**

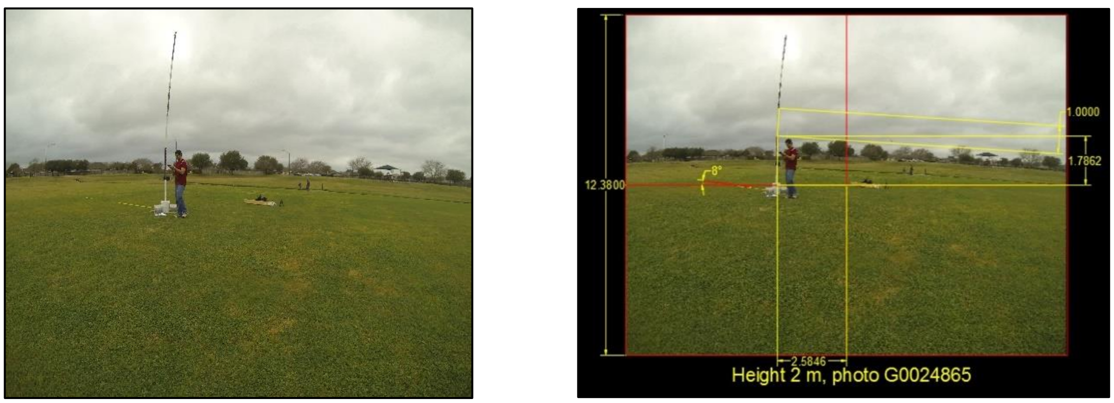



**Figure 147 Photo G0024865 at a height of 2 m with measurements**

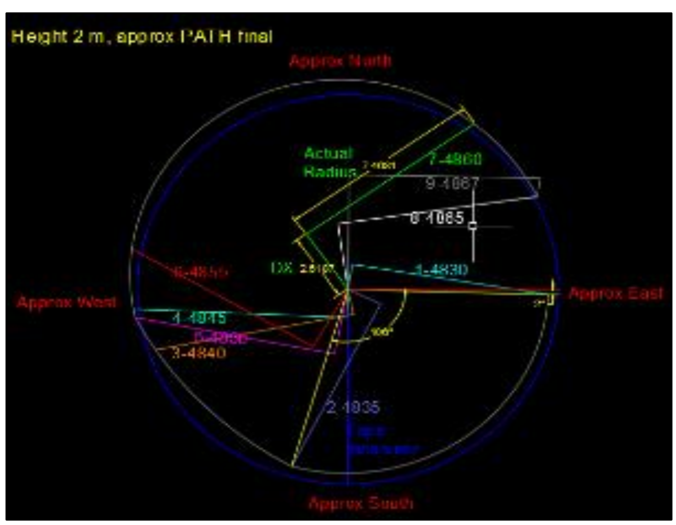



**Figure 148 Planned and actual path at a height of 2 m in Test 1 - app1, evaluation 3**

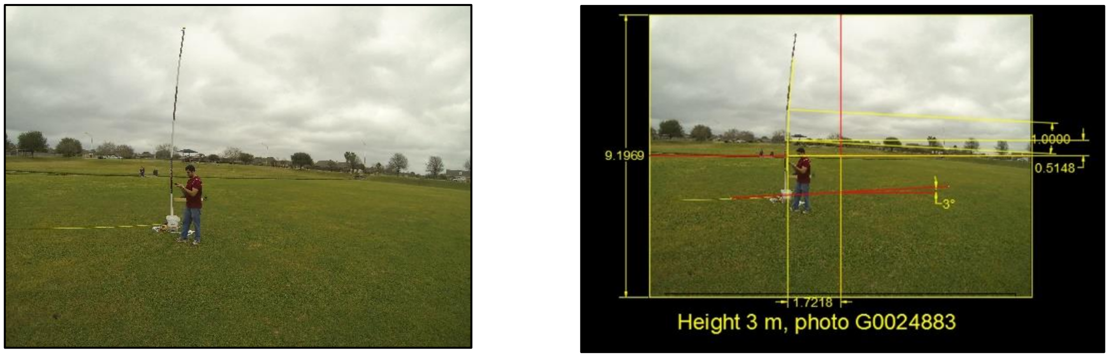



**Figure 149 Photo G0024883 at a height of 3 m with measurements**

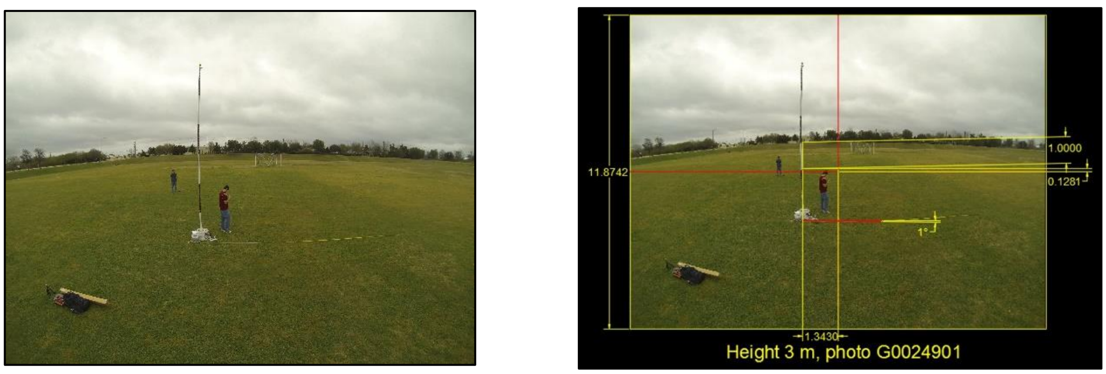



**Figure 150 Photo G0024901 at a height of 3 m with measurements**

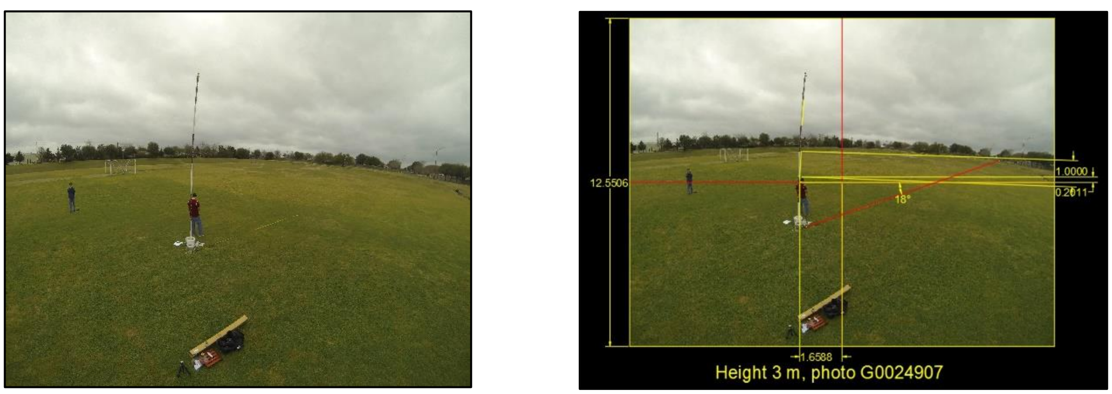



**Figure 151 Photo G0024907 at a height of 3 m with measurements**

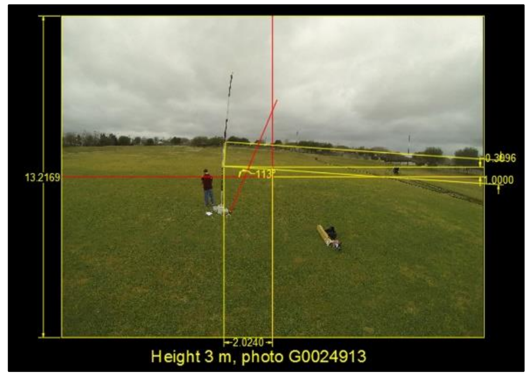



**Figure 152 Photo G0024913 at a height of 3 m with measurements**

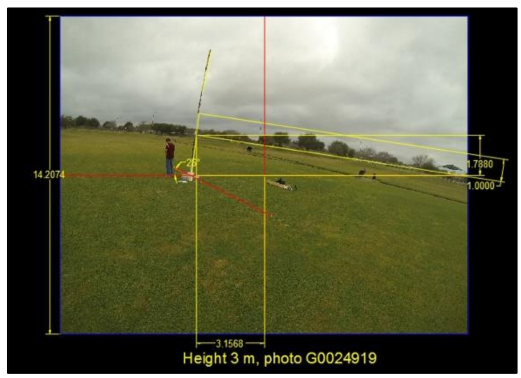
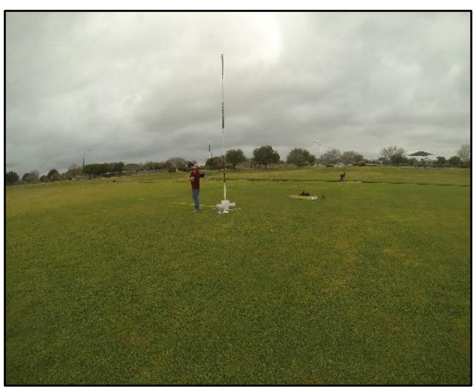



**Figure 153 Photo G0024919 at a height of 3 m with measurements**



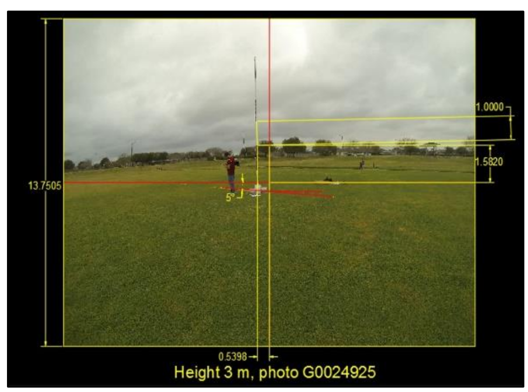



**Figure 154 Photo G0024925 at a height of 3 m with measurements**

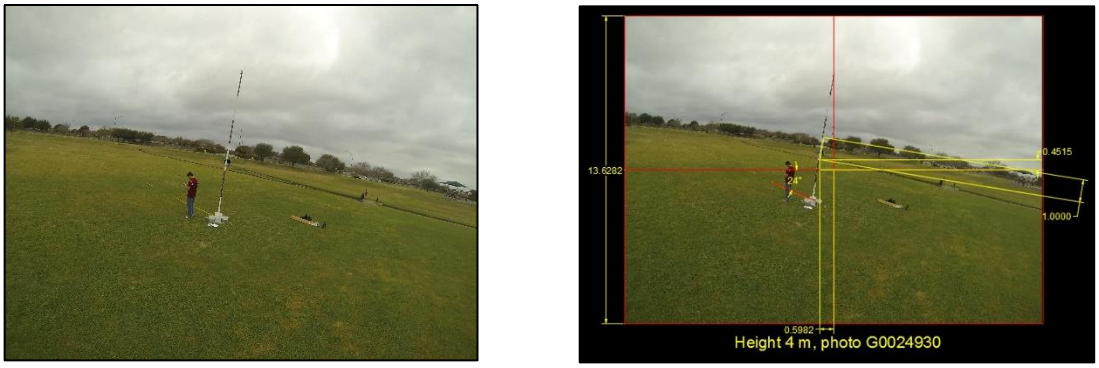



**Figure 155 Photo G0024930 at a height of 4 m with measurements**

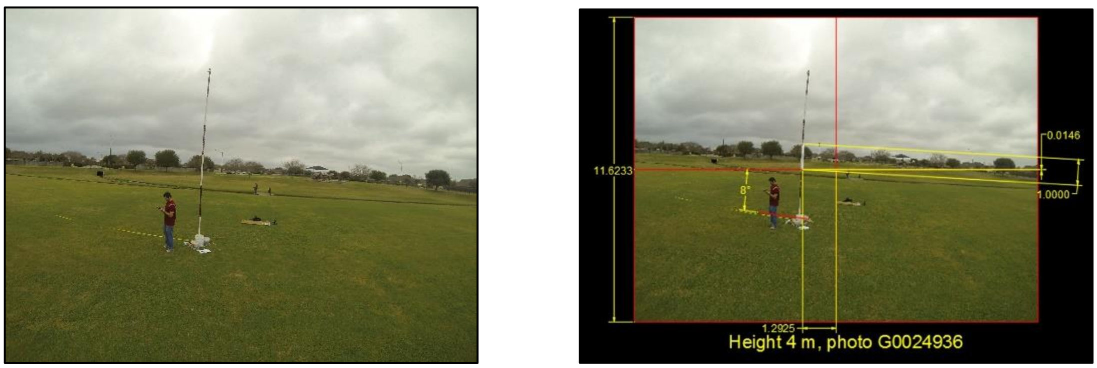



**Figure 156 Photo G0024936 at a height of 4 m with measurements**

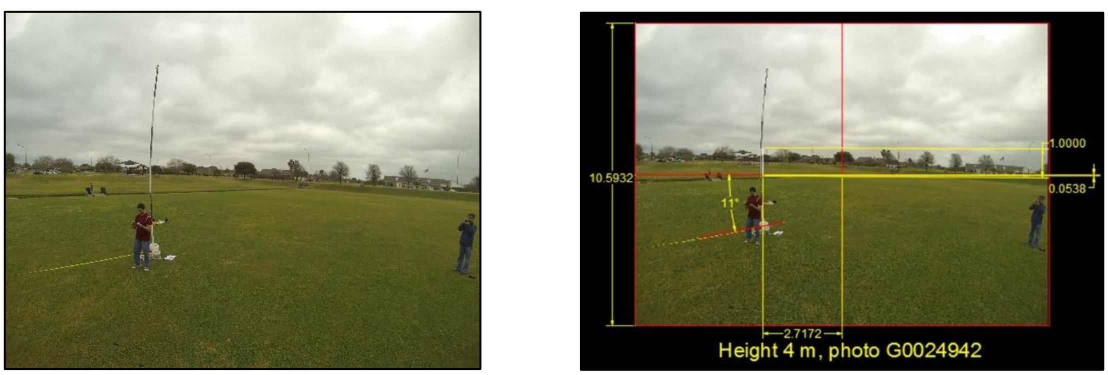



**Figure 157 Photo G0024942 at a height of 4 m with measurements**

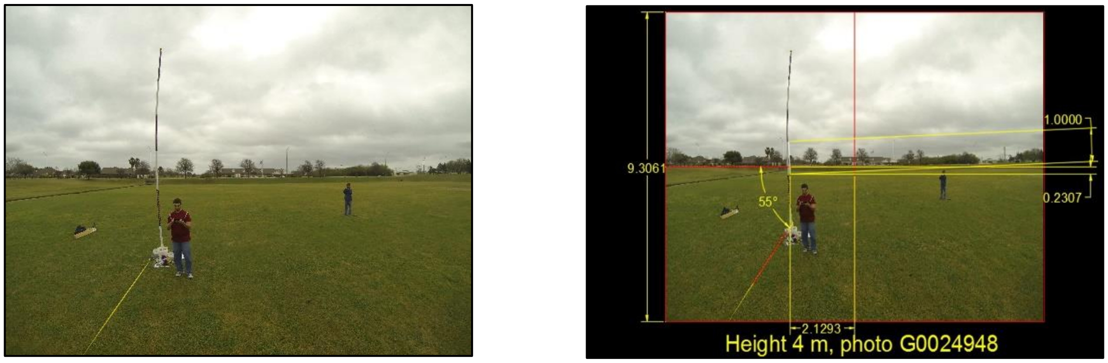



**Figure 158 Photo G0024948 at a height of 4 m with measurements**

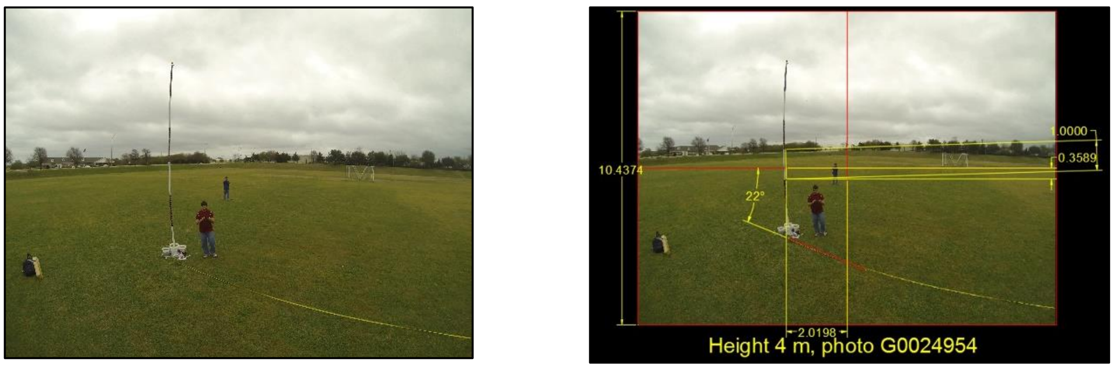



**Figure 159 Photo G0024954 at a height of 4 m with measurements**

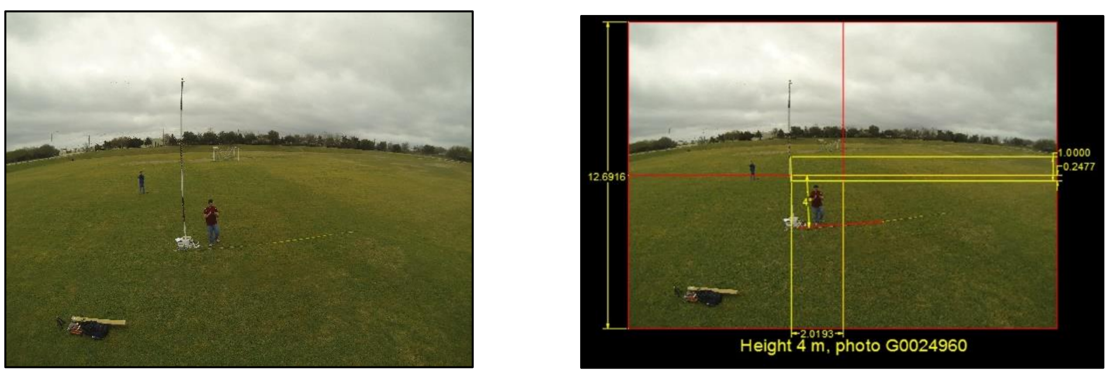



**Figure 160 Photo G0024960 at a height of 4 m with measurements**

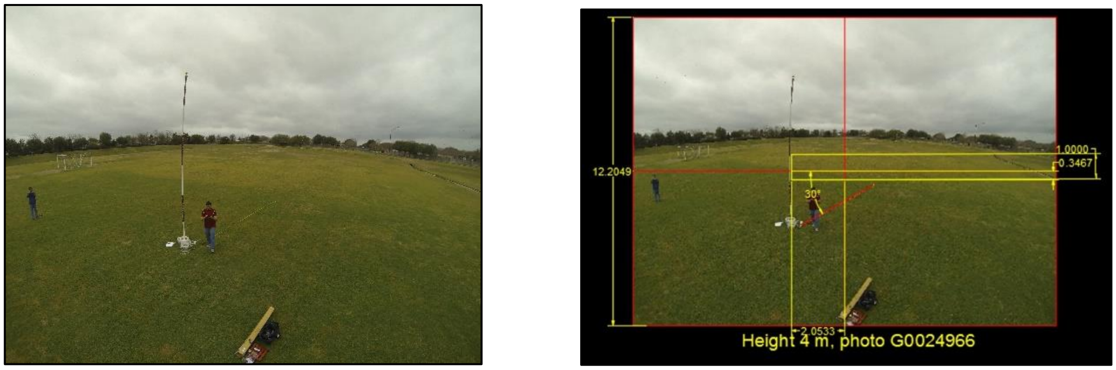



**Figure 161 Photo G0024966 at a height of 4 m with measurements**

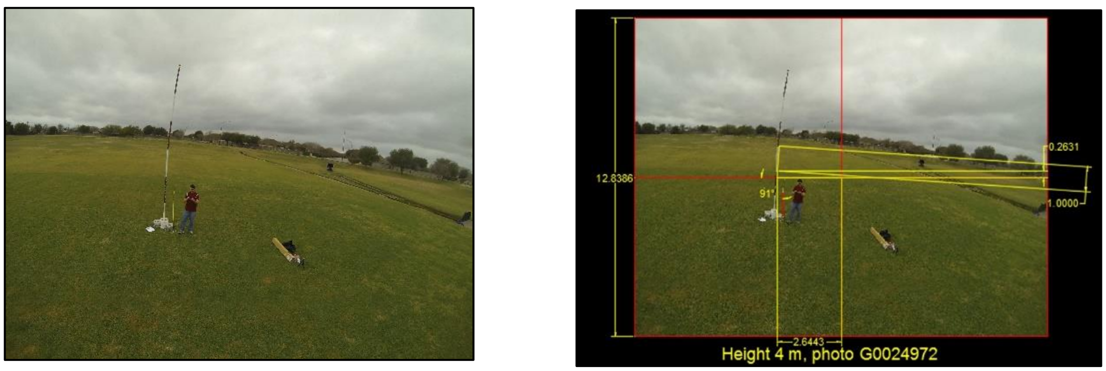



**Figure 162 Photo G0024972 at a height of 4 m with measurements**

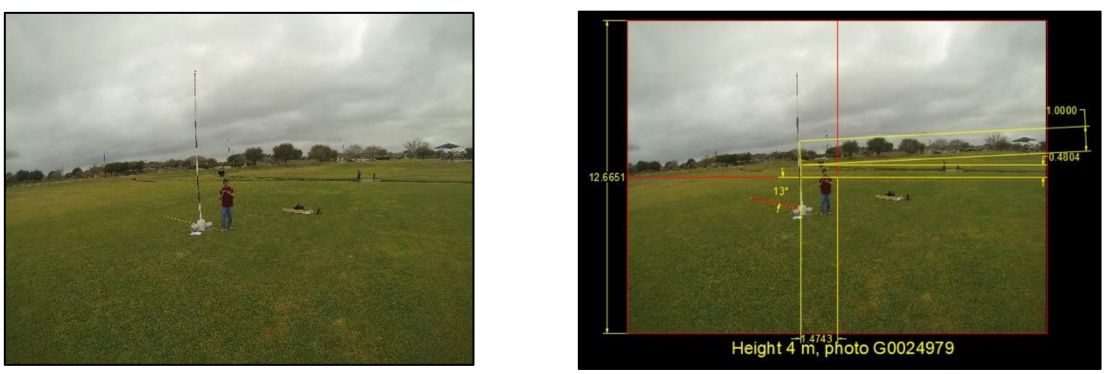



**Figure 163 Photo G0024979 at a height of 4 m with measurements**

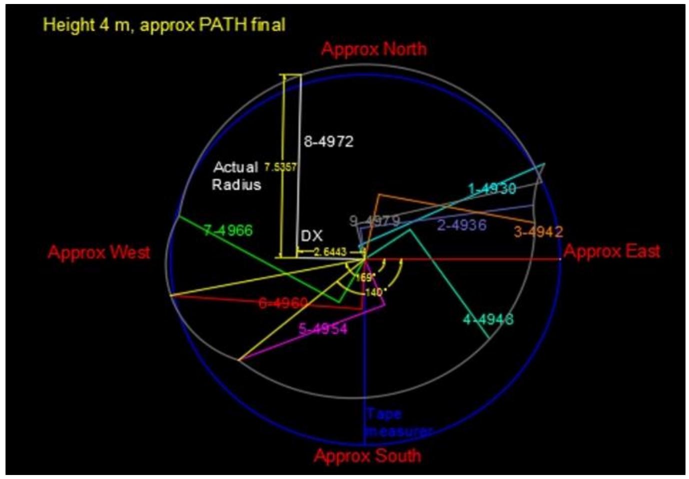



Figure 164 Planned and actual path at a height of 4 m in Test 1 - app1, evaluation 3

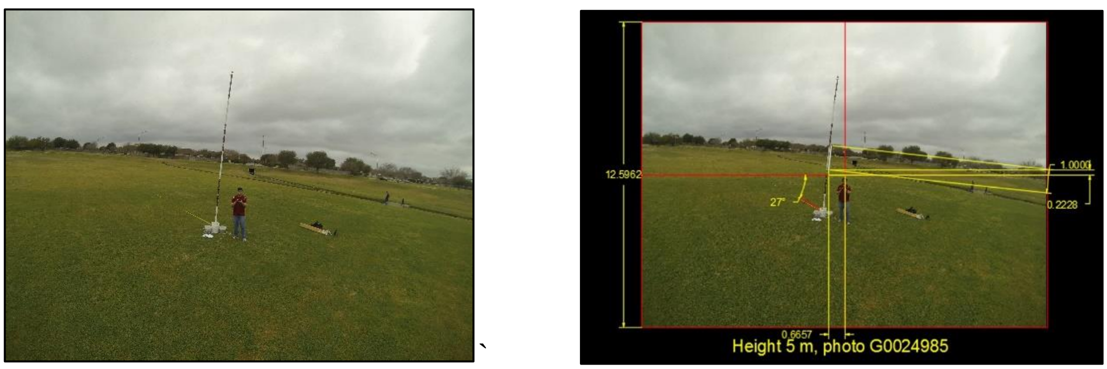



Figure 165 Photo G0024985 at a height of 5 m with measurements

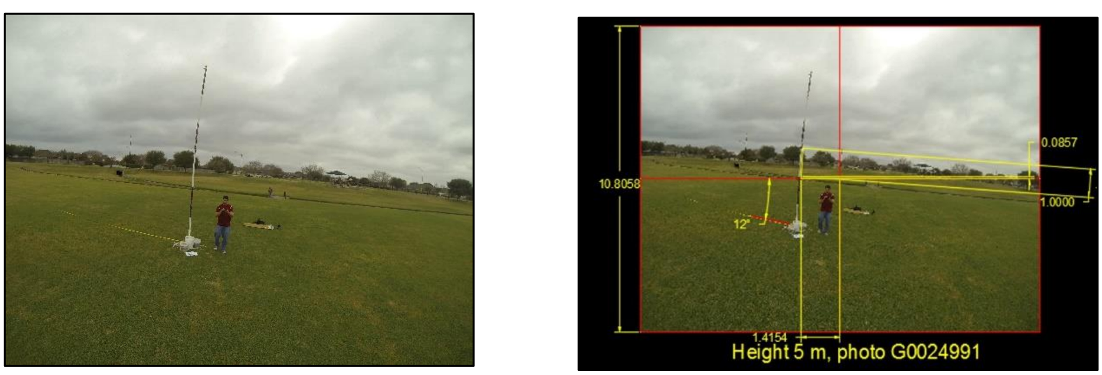



Figure 166 Photo G0024991 at a height of 5 m with measurements

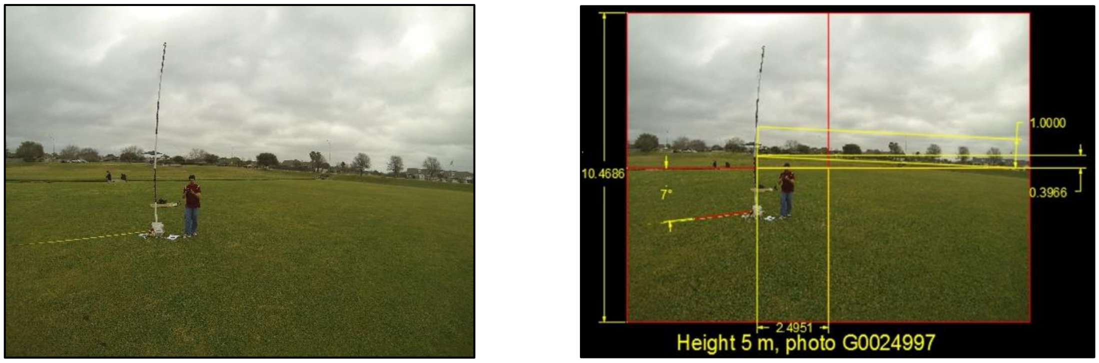



**Figure 167 Photo G0024997 at a height of 5 m with measurements**

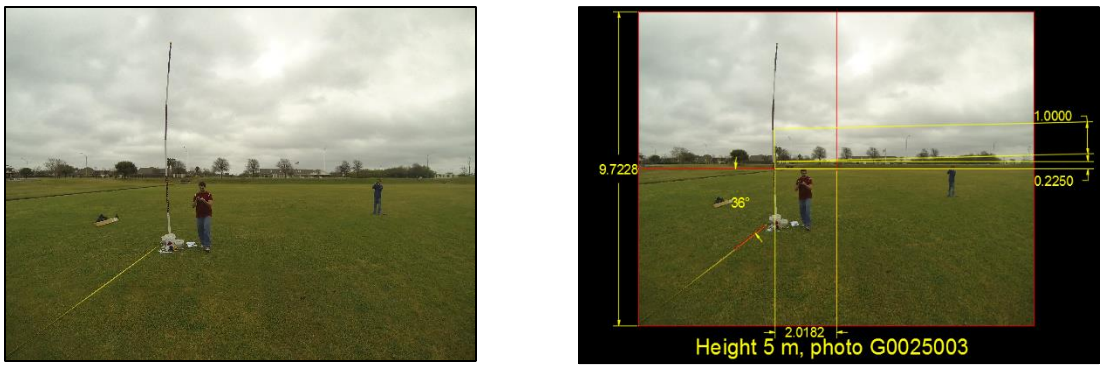



**Figure 168 Photo G0025003 at a height of 5 m with measurements**

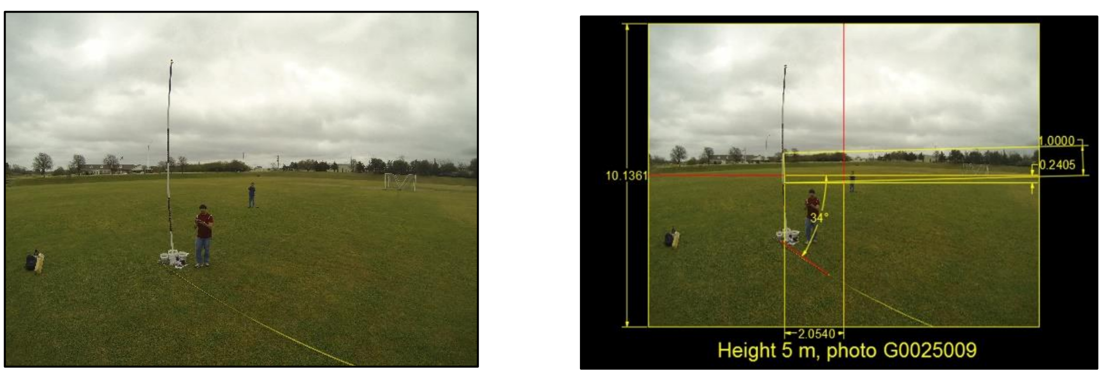



**Figure 169 Photo G0025009 at a height of 5 m with measurements**

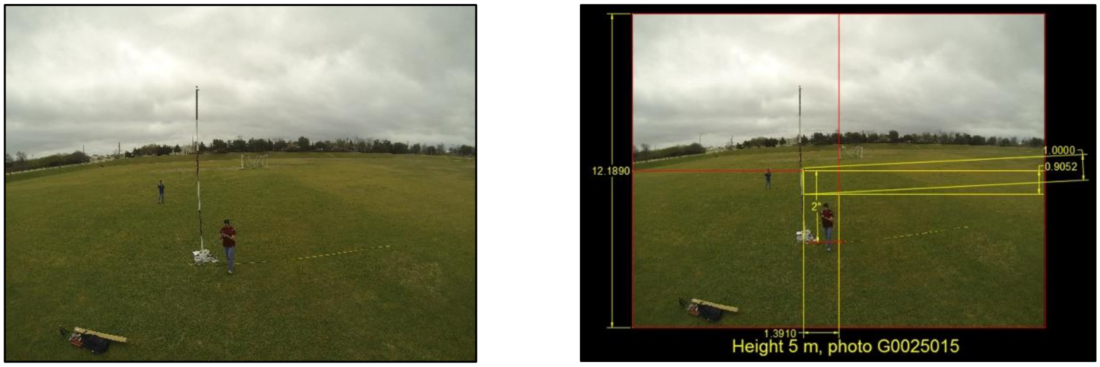



**Figure 170 Photo G0025015 at a height of 5 m with measurements**

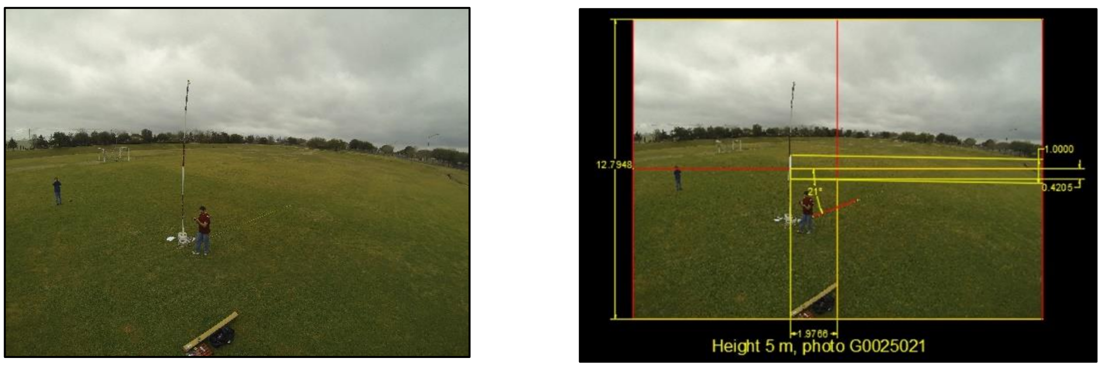



**Figure 171 Photo G0025021 at a height of 5 m with measurements**

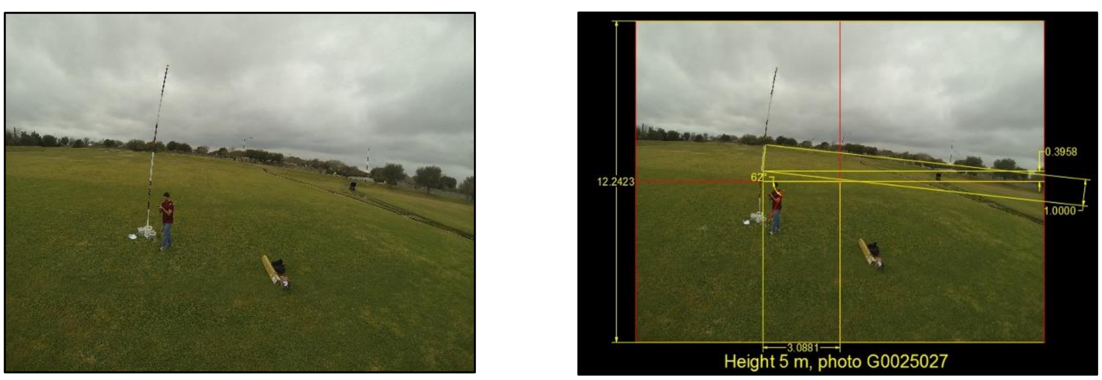



**Figure 172 Photo G0025027 at a height of 5 m with measurements**

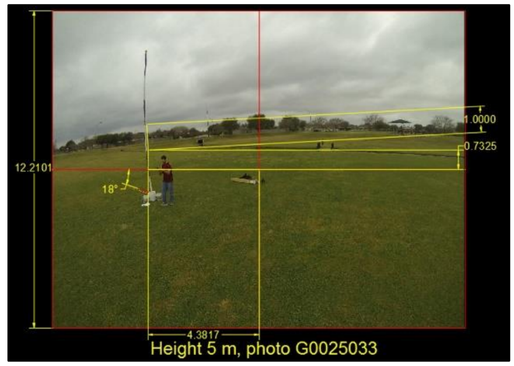



**Figure 173 Photo G0025033 at a height of 5 m with measurements**

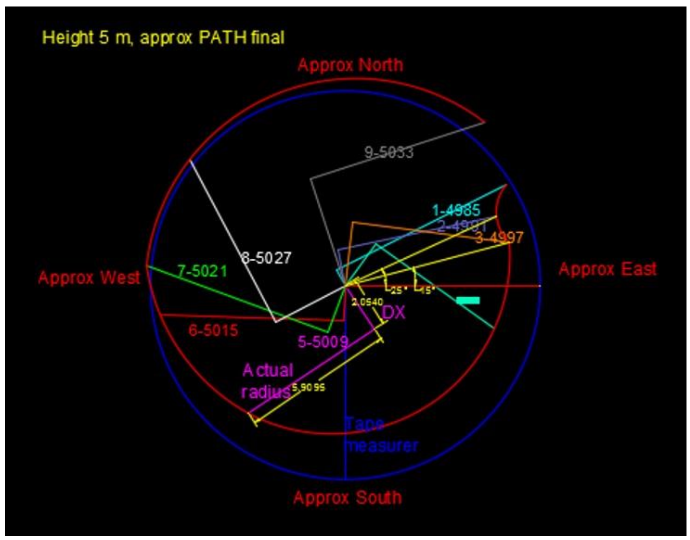
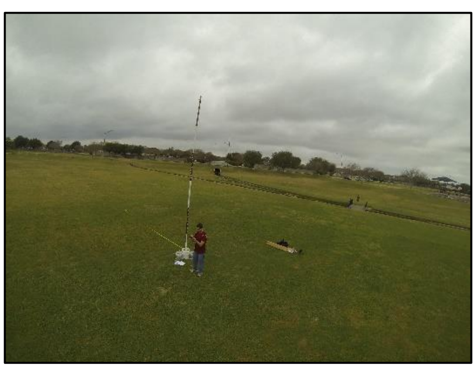



**Figure 174 Planned and actual path at a height of 5 m in Test 1 - app1, evaluation 3**



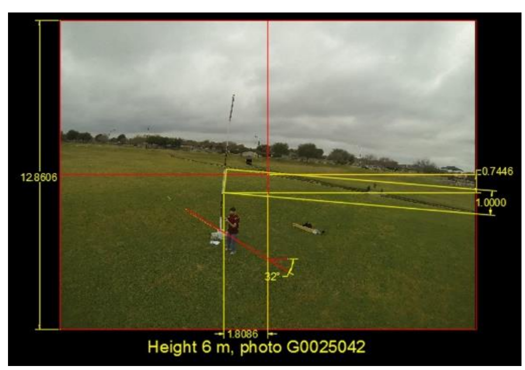



**Figure 175 Photo G0025042 at a height of 6 m with measurements**


**Figure 176 Photo G0025048 at a height of 6 m with measurements**

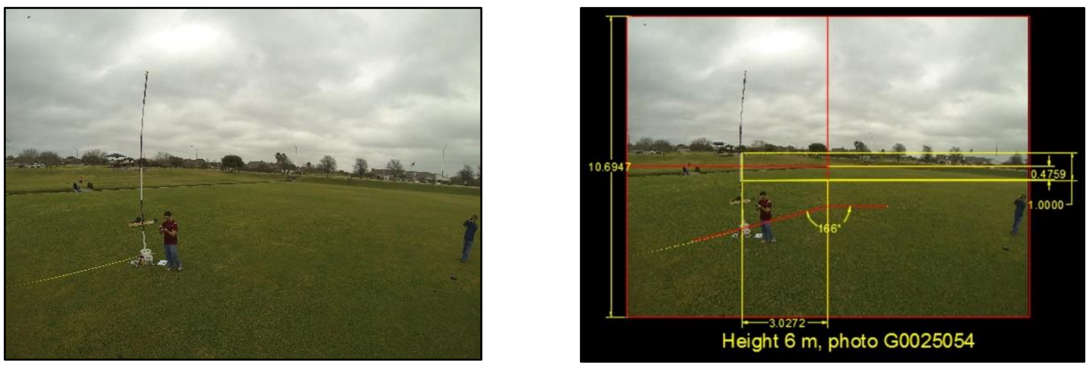



**Figure 177 Photo G0025054 at a height of 6 m with measurements**

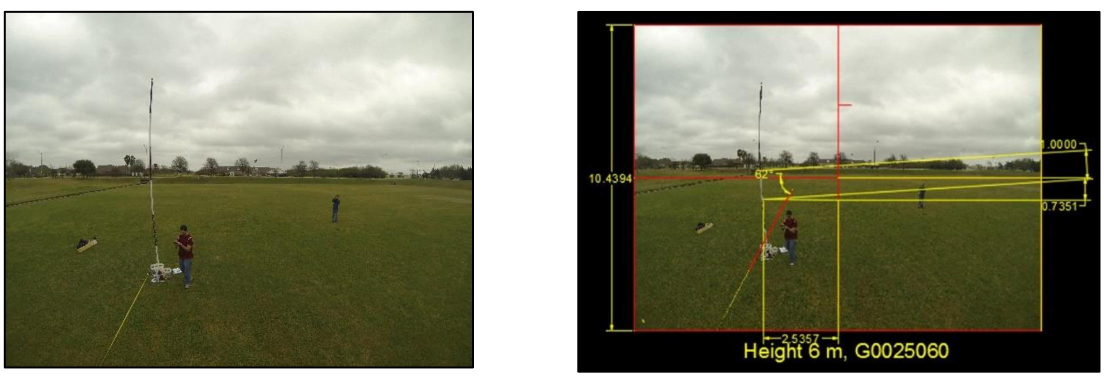



**Figure 178 Photo G0025060 at a height of 6 m with measurements**

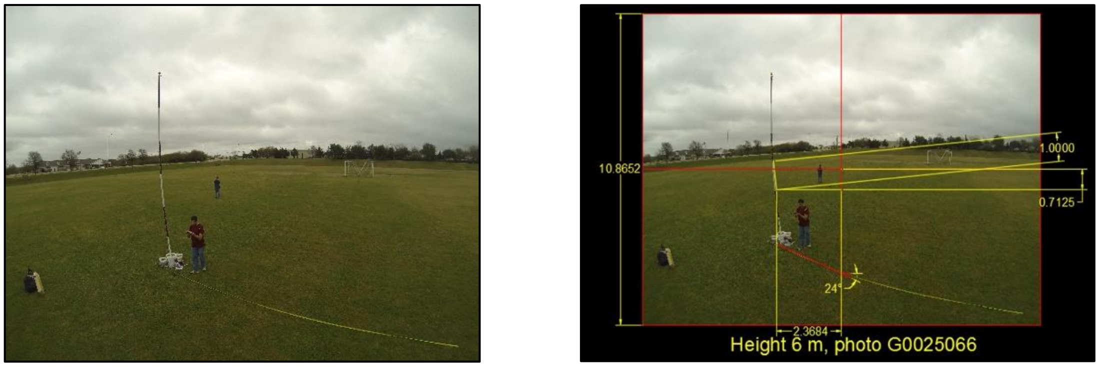



**Figure 179 Photo G0025066 at a height of 6 m with measurements**

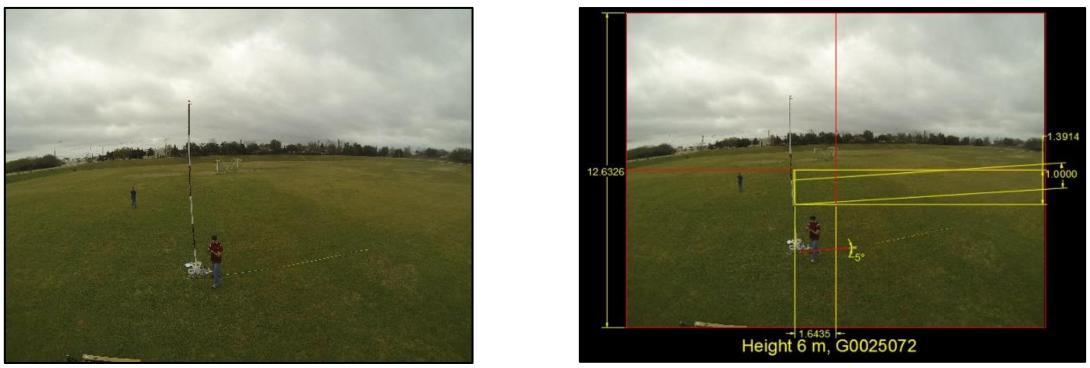



**Figure 180 Photo G0025072 at a height of 6 m with measurements**

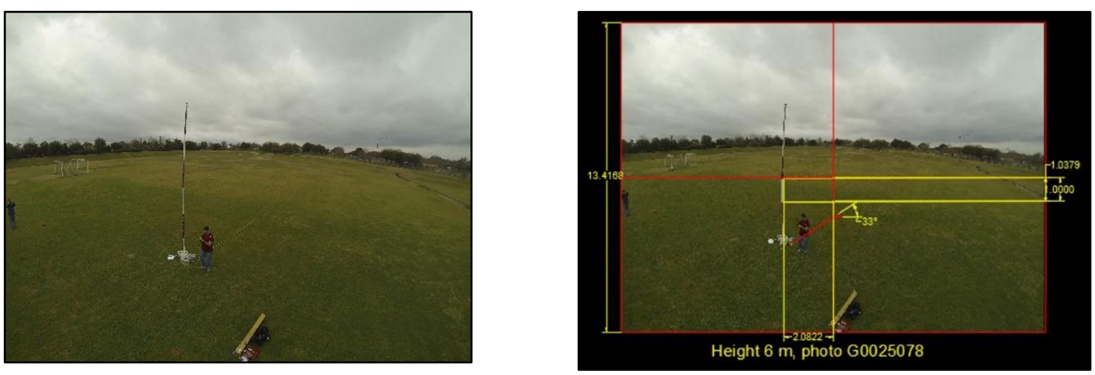



**Figure 181 Photo G0025078 at a height of 6 m with measurements**

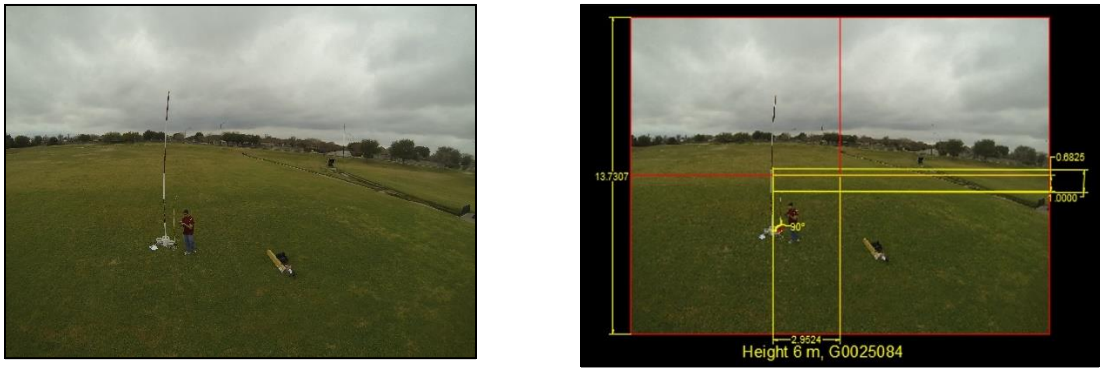



**Figure 182 Photo G0025084 at a height of 6 m with measurements**

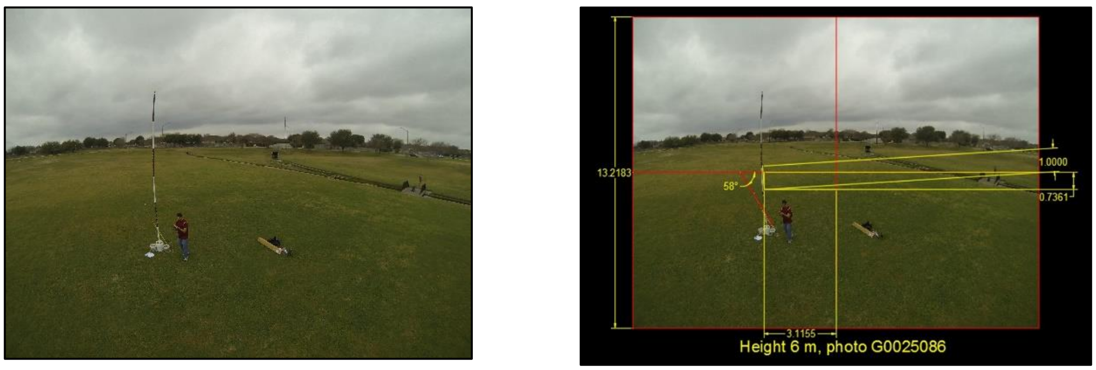



**Figure 183 Photo G0025086 at a height of 6 m with measurements**

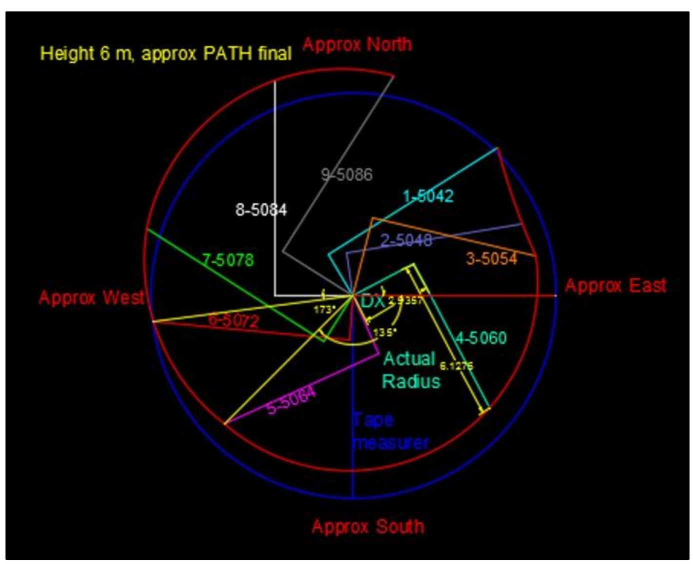



**Figure 184 Planned and actual path at a height of 6 m in Test 1 - app1, evaluation 3**

## A.3. Photos modified in Adobe Photoshop CC 2015

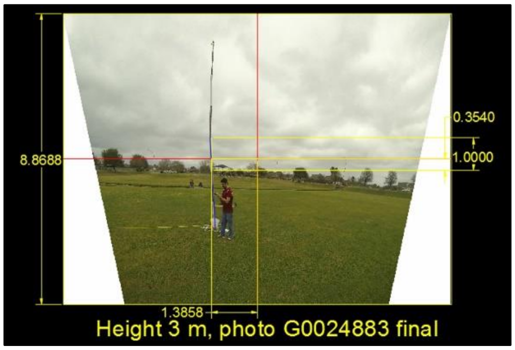



**Figure 185 Photo G0024883 modified with Adobe Photoshop CC 2015 at a height of 3 m with measurements**

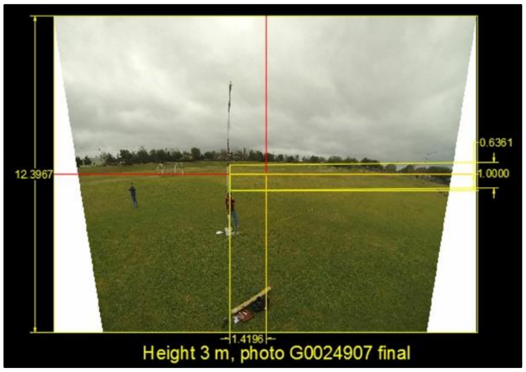



**Figure 186 Photo G0024907 modified with Adobe Photoshop CC 2015 at a height of 3 m with measurements**

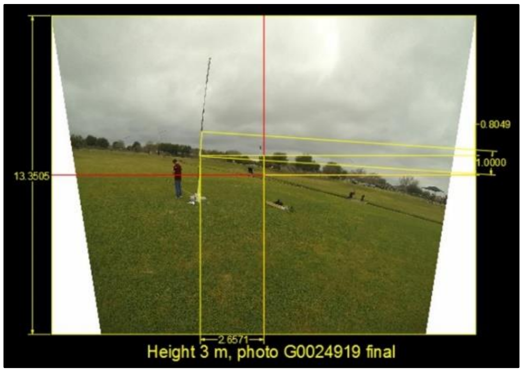



**Figure 187 Photo G0024919 modified with Adobe Photoshop CC 2015 at a height of 3 m with measurements**

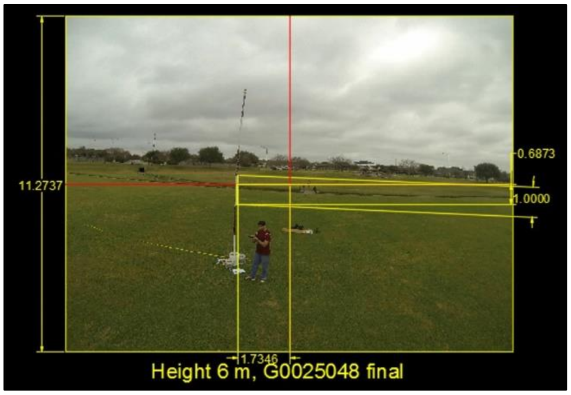



**Figure 188 Photo G0025048 modified with Adobe Photoshop CC 2015 at a height of 6 m with measurements**

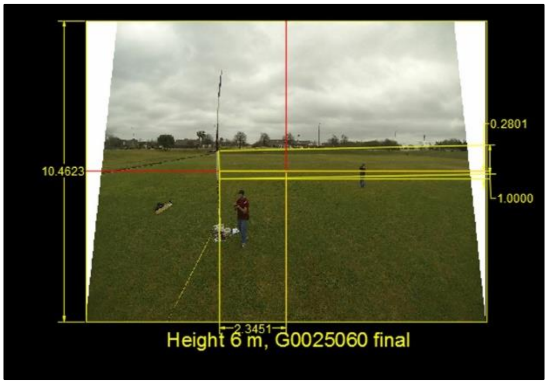



**Figure 189 Photo G0025060 modified with Adobe Photoshop CC 2015 at a height of 6 m with measurements**

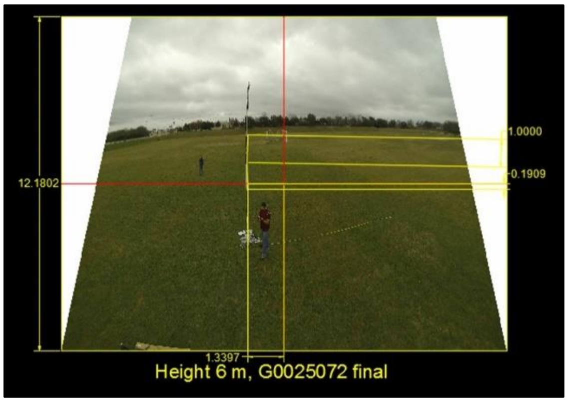



**Figure 190 Photo G0025072 modified with Adobe Photoshop CC 2015 at a height of 6 m with measurements**

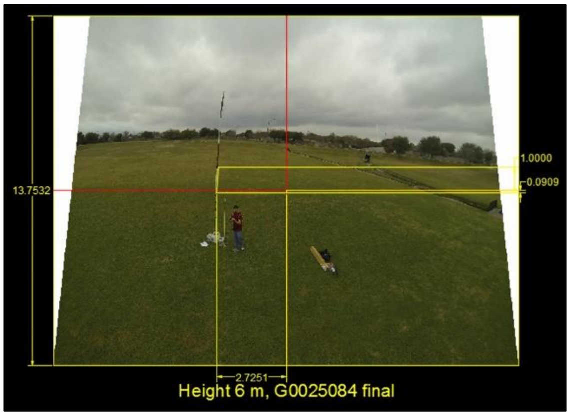



**Figure 191 Photo G0025084 modified with Adobe Photoshop CC 2015 at a height of 6 m with measurements**

**Table 38 Measurements for the original photos which were taken from a height of 6 m in Test 1 - app 1**

| Number | Photo not modified G002 - | DX(m) | DY(m) | Photo frame height (m) | Actual Radius(m) | X-Y axe | Planned radius (m) |
|---|---|---|---|---|---|---|---|
| 1 | 5048 | -1.628 | -1.075 | 11.366 | 6.671 | 0.000 | 7.600 |
| 2 | 5060 | -2.536 | -0.735 | 10.439 | 6.127 | 0.000 | 7.600 |
| 3 | 5072 | -1.644 | -1.391 | 12.633 | 7.415 | 0.000 | 7.600 |
| 4 | 5084 | -2.952 | -0.683 | 13.731 | 8.059 | 0.000 | 7.600 |

**Table 39 Measurements for the modified photos which were taken from a height of 6 m in Test 1 - app 1**

| Number | Photo modified G002 - | DX(m) | DY(m) | Photo frame height (m) | Actual Radius(m) | X-Y axe | Planned radius (m) |
|---|---|---|---|---|---|---|---|
| 1 | 5048 | -1.735 | -0.687 | 11.274 | 6.603 | 0.000 | 7.600 |
| 2 | 5060 | -2.345 | -0.280 | 10.462 | 6.128 | 0.000 | 7.600 |
| 3 | 5072 | -1.340 | -0.191 | 12.180 | 7.134 | 0.000 | 7.600 |
| 4 | 5084 | -2.725 | -0.091 | 13.753 | 8.055 | 0.000 | 7.600 |

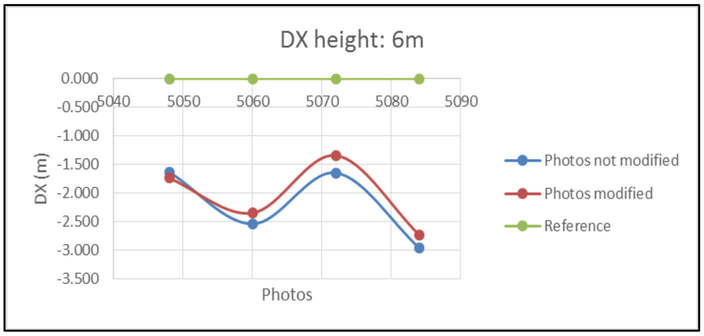



**Figure 192 Horizontal distance (DX) between the center of the photo and the pole at a height of 6 m in Test 1 - app 1**

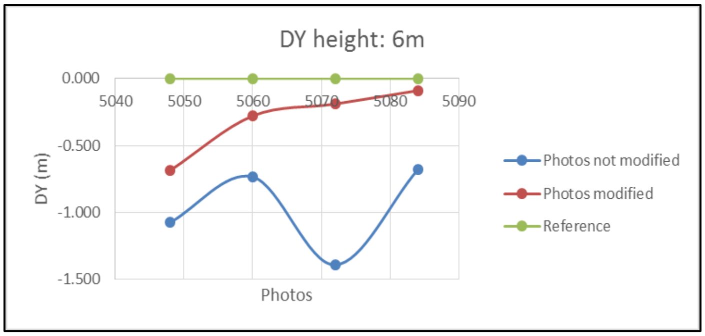



**Figure 193 Vertical distance (DY) between the center of the photo and initial height of the mission (2m) at a height of 6 m in test 1 - app 1**

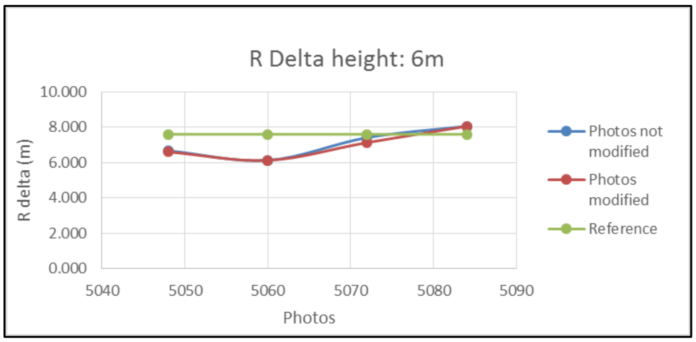



**Figure 194 Planned and actual radius estimation in different points at a height of 6 m in Test 1 - app 1**

**Table 40 Percentage of difference for the calculation of radius between original and modified photos**

| Photo G002 - | Actual Radius difference (m) | % Actual R. Diff |
|---|---|---|
| 5048 | 0.068 | 1.03% |
| 5060 | 0.000 | -0.01% |
| 5072 | 0.281 | 3.94% |
| 5084 | 0.004 | 0.05% |
| Average | 0.088 | 1.25% |

APPENDIX B

*Data collected and other analysis Test 2 - app 1, date 04-16-2016*

## *B.1. Data evaluation 2*

**Table 41 Photos and coordinates were taken from a height of 4 m in Test 2 - app 1**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 283 | 15:01:51 | 15:01:15 | 81 | -96.438744 | 30.633061 | 3.890 | 125.5 | -7.7 | -18.4 | Apr 16, 2016 3:01:15 PM |
| 2 | 284 | 15:01:53 | 15:01:17 | 82 | -96.438736 | 30.633063 | 3.950 | 131.3 | -2.9 | -14.3 | Apr 16, 2016 3:01:17 PM |
| 3 | | | | 83 | -96.438698 | 30.633086 | 4.090 | 146.3 | -6.4 | -9.8 | Apr 16, 2016 3:01:18 PM |
| 4 | | | | 84 | -96.438678 | 30.633094 | 4.320 | 165.0 | -6.4 | -9.3 | Apr 16, 2016 3:01:19 PM |
| 5 | 285 | 15:01:56 | 15:01:20 | 85 | -96.438636 | 30.633105 | 4.260 | -175.6 | -3.9 | -10.4 | Apr 16, 2016 3:01:20 PM |
| 6 | | | | 86 | -96.438595 | 30.633106 | 4.180 | -158.0 | -3.2 | -10.8 | Apr 16, 2016 3:01:21 PM |
| 7 | 286 | 15:01:58 | 15:01:22 | 87 | -96.438548 | 30.633098 | 4.230 | -143.2 | -3.5 | -10.0 | Apr 16, 2016 3:01:22 PM |
| 8 | | | | 88 | -96.438509 | 30.633080 | 4.170 | -129.4 | -2.6 | -10.0 | Apr 16, 2016 3:01:23 PM |
| 9 | 287 | 15:02:00 | 15:01:24 | 89 | -96.438475 | 30.633051 | 3.930 | -112.4 | -0.7 | -9.1 | Apr 16, 2016 3:01:24 PM |

**Table 41 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | | | | 90 | -96.438453 | 30.633014 | 3.760 | -94.9 | -0.5 | -6.2 | Apr 16, 2016 3:01:25 PM |
| 11 | 288 | 15:02:02 | 15:01:26 | 91 | -96.438443 | 30.632973 | 3.740 | -85.1 | -1.3 | -5.8 | Apr 16, 2016 3:01:26 PM |
| 12 | | | | 92 | -96.438446 | 30.632937 | 3.770 | -57.9 | -1.8 | -6.0 | Apr 16, 2016 3:01:27 PM |
| 13 | | | | 93 | -96.438465 | 30.632899 | 3.870 | -49.4 | -0.9 | -4.5 | Apr 16, 2016 3:01:28 PM |
| 14 | 289 | 15:02:05 | 15:01:29 | 94 | -96.438478 | 30.632884 | 3.980 | -32.3 | -1.8 | -3.9 | Apr 16, 2016 3:01:29 PM |
| 15 | | | | 95 | -96.438530 | 30.632851 | 4.100 | -13.3 | -0.1 | -4.1 | Apr 16, 2016 3:01:30 PM |
| 16 | 290 | 15:02:07 | 15:01:31 | 96 | -96.438554 | 30.632843 | 3.960 | 3.9 | -0.5 | -3.4 | Apr 16, 2016 3:01:31 PM |
| 17 | | | | 97 | -96.438596 | 30.632837 | 3.960 | 20.2 | -3.9 | -3.6 | Apr 16, 2016 3:01:32 PM |
| 18 | 291 | 15:02:09 | 15:01:33 | 98 | -96.438641 | 30.632841 | 3.820 | 37.4 | -2.1 | -4.4 | Apr 16, 2016 3:01:33 PM |
| 19 | | | | 99 | -96.438684 | 30.632858 | 3.620 | 51.8 | -2.5 | -3.9 | Apr 16, 2016 3:01:34 PM |
| 20 | | | | 100 | -96.438716 | 30.632883 | 3.830 | 70.6 | -2.1 | -4.0 | Apr 16, 2016 3:01:35 PM |
| 21 | 292 | 15:02:12 | 15:01:36 | 101 | -96.438744 | 30.632920 | 3.870 | 83.8 | -5.6 | -2.0 | Apr 16, 2016 3:01:36 PM |

**Table 41 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 | | | | 102 | -96.438759 | 30.632960 | 3.870 | 104.7 | -7.8 | -2.8 | Apr 16, 2016 3:01:37 PM |

**Table 42 Photos and coordinates were taken from a height of 6 m in Test 2 - app 1**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 307 | 15:02:46 | 15:02:10 | 134 | -96.438765 | 30.633001 | 5.280 | 98.0 | -3.4 | 10.5 | Apr 16, 2016 3:02:10 PM |
| 2 | | | | 135 | -96.438766 | 30.632977 | 5.750 | 88.9 | -5.4 | -27.8 | Apr 16, 2016 3:02:11 PM |
| 3 | 308 | 15:02:48 | 15:02:12 | 136 | -96.438765 | 30.632976 | 5.850 | 90.9 | 1.6 | -15.0 | Apr 16, 2016 3:02:12 PM |
| 4 | | | | 137 | -96.438765 | 30.632995 | 5.720 | 103.6 | -5.0 | -10.1 | Apr 16, 2016 3:02:13 PM |
| 5 | | | | 138 | -96.438759 | 30.633026 | 5.900 | 123.2 | -7.3 | -5.7 | Apr 16, 2016 3:02:14 PM |
| 6 | 309 | 15:02:51 | 15:02:15 | 139 | -96.438742 | 30.633056 | 6.140 | 139.3 | -7.4 | -8.1 | Apr 16, 2016 3:02:15 PM |
| 7 | | | | 140 | -96.438716 | 30.633080 | 6.420 | 155.3 | -7.6 | -8.7 | Apr 16, 2016 3:02:16 PM |
| 8 | 310 | 15:02:53 | 15:02:17 | 141 | -96.438675 | 30.633100 | 6.430 | 174.3 | -9.6 | -7.3 | Apr 16, 2016 3:02:17 PM |

**Table 42 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | | | | 142 | -96.438628 | 30.633109 | 6.430 | -167.2 | -5.0 | -11.0 | Apr 16, 2016 3:02:18 PM |
| 10 | 311 | 15:02:55 | 15:02:19 | 143 | -96.438579 | 30.633107 | 6.400 | -151.6 | -4.8 | -11.4 | Apr 16, 2016 3:02:19 PM |
| 11 | | | | 144 | -96.438531 | 30.633092 | 6.270 | -136.9 | -3.2 | -10.4 | Apr 16, 2016 3:02:20 PM |
| 12 | | | | 145 | -96.438490 | 30.633066 | 5.970 | -128.6 | -2.4 | -9.1 | Apr 16, 2016 3:02:21 PM |
| 13 | 312 | 15:02:58 | 15:02:22 | 146 | -96.438474 | 30.633052 | 5.890 | -111.4 | -2.1 | -7.9 | Apr 16, 2016 3:02:22 PM |
| 14 | | | | 147 | -96.438451 | 30.633018 | 5.710 | -94.3 | -3.8 | -6.7 | Apr 16, 2016 3:02:23 PM |
| 15 | 313 | 15:03:00 | 15:02:24 | 148 | -96.438441 | 30.632977 | 5.590 | -77.0 | -4.0 | -6.7 | Apr 16, 2016 3:02:24 PM |
| 16 | | | | 149 | -96.438446 | 30.632938 | 5.670 | -58.3 | -0.9 | -6.2 | Apr 16, 2016 3:02:25 PM |
| 17 | 314 | 15:03:02 | 15:02:26 | 150 | -96.438462 | 30.632906 | 5.810 | -40.7 | -1.0 | -5.8 | Apr 16, 2016 3:02:26 PM |
| 18 | | | | 151 | -96.438491 | 30.632876 | 5.980 | -21.5 | -2.1 | -5.2 | Apr 16, 2016 3:02:27 PM |
| 19 | 315 | 15:03:04 | 15:02:28 | 152 | -96.438529 | 30.632855 | 6.100 | -3.8 | -0.8 | -4.8 | Apr 16, 2016 3:02:28 PM |
| 20 | | | | 153 | -96.438572 | 30.632844 | 6.030 | 13.4 | -0.2 | -3.7 | Apr 16, 2016 3:02:29 PM |

**Table 42 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 21 | | | | 154 | -96.438613 | 30.632845 | 5.670 | 27.7 | 2.1 | -3.6 | Apr 16, 2016 3:02:30 PM |
| 22 | 316 | 15:03:07 | 15:02:31 | 155 | -96.438659 | 30.632854 | 5.790 | 35.6 | -1.2 | -2.0 | Apr 16, 2016 3:02:31 PM |
| 23 | | | | 156 | -96.438679 | 30.632862 | 5.810 | 52.1 | -1.2 | -1.1 | Apr 16, 2016 3:02:32 PM |
| 24 | 317 | 15:03:09 | 15:02:33 | 157 | -96.438733 | 30.632898 | 5.650 | 72.1 | -4.9 | -1.0 | Apr 16, 2016 3:02:33 PM |
| 25 | | | | 158 | -96.438755 | 30.632933 | 5.770 | 87.1 | -6.4 | -2.0 | Apr 16, 2016 3:02:34 PM |

**Table 43 Photos and coordinates were taken from a height of 8 m in Test 2 - app 1**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 333 | 15:03:44 | 15:03:08 | 191 | -96.438752 | 30.632920 | 7.910 | 64.1 | -0.7 | -4.8 | Apr 16, 2016 3:03:08 PM |
| 2 | | | | 192 | -96.438759 | 30.632933 | 7.790 | 83.2 | -8.5 | -3.5 | Apr 16, 2016 3:03:09 PM |
| 3 | | | | 193 | -96.438768 | 30.632965 | 7.810 | 100.4 | -9.0 | -5.2 | Apr 16, 2016 3:03:10 PM |
| 4 | 334 | 15:03:47 | 15:03:11 | 194 | -96.438766 | 30.632997 | 8.020 | 118.5 | -8.4 | -8.4 | Apr 16, 2016 3:03:11 PM |

**Table 43 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | | | | 195 | -96.438752 | 30.633033 | 8.230 | 135.1 | -9.0 | -9.3 | Apr 16, 2016 3:03:12 PM |
| 6 | 335 | 15:03:49 | 15:03:13 | 196 | -96.438724 | 30.633065 | 8.340 | 154.8 | -9.1 | -9.3 | Apr 16, 2016 3:03:13 PM |
| 7 | | | | 197 | -96.438685 | 30.633089 | 8.230 | 170.9 | -4.7 | -11.7 | Apr 16, 2016 3:03:14 PM |
| 8 | 336 | 15:03:51 | 15:03:15 | 198 | -96.438643 | 30.633101 | 8.100 | -173.0 | -3.7 | -10.1 | Apr 16, 2016 3:03:15 PM |
| 9 | | | | 199 | -96.438593 | 30.633106 | 8.140 | -157.9 | -4.4 | -10.6 | Apr 16, 2016 3:03:16 PM |
| 10 | 337 | 15:03:53 | 15:03:17 | 200 | -96.438544 | 30.633099 | 8.150 | -148.7 | -5.9 | -12.1 | Apr 16, 2016 3:03:17 PM |
| 11 | | | | 201 | -96.438501 | 30.633081 | 7.990 | -132.4 | -5.0 | -11.1 | Apr 16, 2016 3:03:18 PM |
| 12 | | | | 202 | -96.438484 | 30.633068 | 7.910 | -115.8 | -4.9 | -10.8 | Apr 16, 2016 3:03:19 PM |
| 13 | 338 | 15:03:56 | 15:03:20 | 203 | -96.438456 | 30.633034 | 7.750 | -98.7 | -4.5 | -9.2 | Apr 16, 2016 3:03:20 PM |
| 14 | | | | 204 | -96.438444 | 30.632997 | 7.610 | -80.5 | -1.6 | -6.7 | Apr 16, 2016 3:03:21 PM |
| 15 | | | | 205 | -96.438444 | 30.632955 | 7.600 | -62.2 | -1.6 | -5.8 | Apr 16, 2016 3:03:23 PM |
| 16 | 340 | 15:04:00 | 15:03:24 | 206 | -96.438455 | 30.632920 | 7.790 | -44.8 | -0.9 | -6.4 | Apr 16, 2016 3:03:24 PM |

**Table 43 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | | | | 207 | -96.438478 | 30.632887 | 8.070 | -27.1 | -0.9 | -5.0 | Apr 16, 2016 3:03:25 PM |
| 18 | 341 | 15:04:02 | 15:03:26 | 208 | -96.438512 | 30.632862 | 8.020 | -9.9 | 1.1 | -4.4 | Apr 16, 2016 3:03:26 PM |
| 19 | | | | 209 | -96.438553 | 30.632846 | 7.780 | 7.9 | -0.4 | -5.2 | Apr 16, 2016 3:03:27 PM |
| 20 | | | | 210 | -96.438601 | 30.632840 | 7.670 | 23.4 | -4.1 | -3.3 | Apr 16, 2016 3:03:28 PM |
| 21 | 342 | 15:04:05 | 15:03:29 | 211 | -96.438649 | 30.632846 | 7.880 | 32.2 | -4.4 | -2.9 | Apr 16, 2016 3:03:29 PM |
| 22 | | | | 212 | -96.438689 | 30.632862 | 8.010 | 49.4 | -4.3 | -3.2 | Apr 16, 2016 3:03:30 PM |

**Table 44 Photos and coordinates were taken from a height of 10 m in Test 2 - app 1**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 357 | 15:04:39 | 15:04:03 | 245 | -96.438689 | 30.632857 | 9.900 | 39.9 | 0.4 | -7.2 | Apr 16, 2016 3:04:03 PM |
| 2 | | | | 246 | -96.438717 | 30.632879 | 9.890 | 58.3 | -4.1 | -1.2 | Apr 16, 2016 3:04:04 PM |
| 3 | 358 | 15:04:42 | 15:04:06 | 247 | -96.438744 | 30.632908 | 9.960 | 74.3 | -8.5 | -0.9 | Apr 16, 2016 3:04:06 PM |
| 4 | | | | 248 | -96.438764 | 30.632958 | 10.010 | 90.3 | -8.2 | -2.9 | Apr 16, 2016 3:04:07 PM |

**Table 44 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 359 | 15:04:44 | 15:04:08 | 249 | -96.438765 | 30.632976 | 10.050 | 108.9 | -7.9 | -4.4 | Apr 16, 2016 3:04:08 PM |
| 6 | | | | 250 | -96.438757 | 30.633014 | 10.140 | 128.4 | -8.3 | -6.7 | Apr 16, 2016 3:04:09 PM |
| 7 | 360 | 15:04:46 | 15:04:10 | 251 | -96.438736 | 30.633049 | 10.220 | 145.0 | -9.4 | -8.0 | Apr 16, 2016 3:04:10 PM |
| 8 | | | | 252 | -96.438704 | 30.633080 | 10.260 | 153.6 | -10.0 | -8.7 | Apr 16, 2016 3:04:11 PM |
| 9 | 361 | 15:04:48 | 15:04:12 | 253 | -96.438664 | 30.633101 | 10.310 | 170.2 | -10.8 | -8.5 | Apr 16, 2016 3:04:12 PM |
| 10 | | | | 254 | -96.438615 | 30.633111 | 10.300 | -171.2 | -10.7 | -9.6 | Apr 16, 2016 3:04:13 PM |
| 11 | | | | 255 | -96.438570 | 30.633107 | 10.140 | -154.9 | -7.4 | -10.5 | Apr 16, 2016 3:04:14 PM |
| 12 | 362 | 15:04:51 | 15:04:15 | 256 | -96.438524 | 30.633091 | 9.950 | -140.7 | -4.5 | -9.3 | Apr 16, 2016 3:04:15 PM |
| 13 | | | | 257 | -96.438505 | 30.633080 | 9.740 | -126.5 | -3.4 | -8.3 | Apr 16, 2016 3:04:16 PM |
| 14 | 363 | 15:04:53 | 15:04:17 | 258 | -96.438459 | 30.633033 | 9.610 | -108.4 | -2.0 | -6.9 | Apr 16, 2016 3:04:17 PM |
| 15 | | | | 259 | -96.438451 | 30.633017 | 9.600 | -88.8 | -1.9 | -7.8 | Apr 16, 2016 3:04:18 PM |

**Table 44 Continued**

| N. | Photo index FHD0- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | 364 | 15:04:55 | 15:04:19 | 260 | -96.438444 | 30.632979 | 9.640 | -70.9 | 0.2 | -6.8 | Apr 16, 2016 3:04:19 PM |
| 17 | | | | 261 | -96.438451 | 30.632942 | 9.760 | -52.3 | 2.5 | -5.8 | Apr 16, 2016 3:04:20 PM |
| 18 | | | | 262 | -96.438466 | 30.632910 | 9.880 | -35.1 | 2.0 | -5.3 | Apr 16, 2016 3:04:21 PM |
| 19 | 365 | 15:04:58 | 15:04:22 | 263 | -96.438492 | 30.632881 | 9.870 | -18.5 | 2.0 | -5.4 | Apr 16, 2016 3:04:22 PM |
| 20 | | | | 264 | -96.438528 | 30.632858 | 9.980 | -3.0 | 0.7 | -4.5 | Apr 16, 2016 3:04:23 PM |
| 21 | 366 | 15:05:00 | 15:04:24 | 265 | -96.438567 | 30.632846 | 10.040 | 13.5 | -1.9 | -1.9 | Apr 16, 2016 3:04:24 PM |
| 22 | | | | 266 | -96.438614 | 30.632843 | 10.110 | 21.3 | -1.3 | -2.9 | Apr 16, 2016 3:04:25 PM |

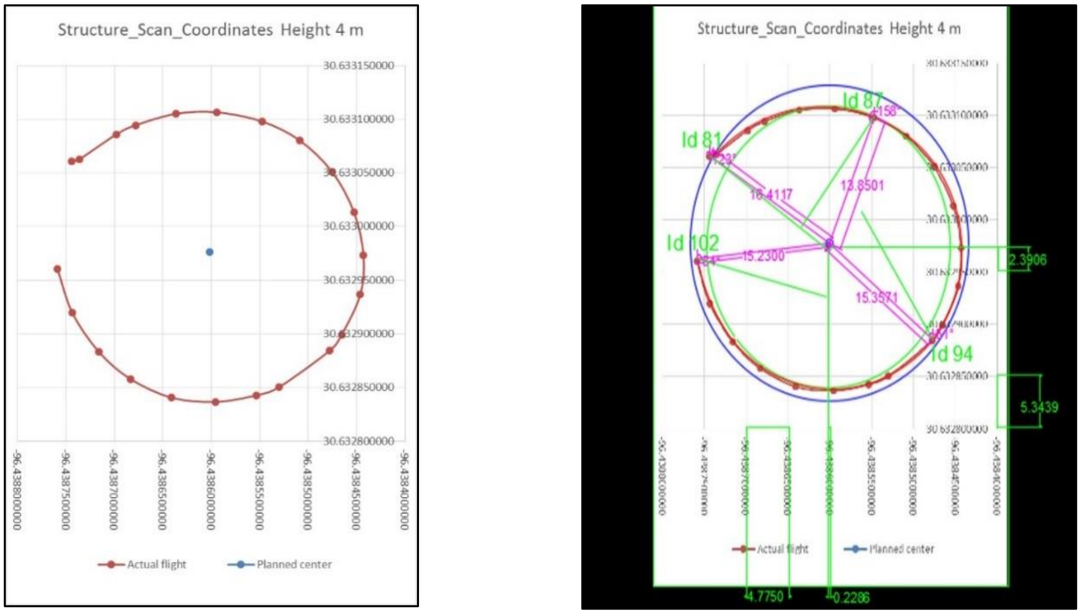



**Figure 195 Planned and actual path at a height of 4 m in Test 2 - app 1, evaluation 2**

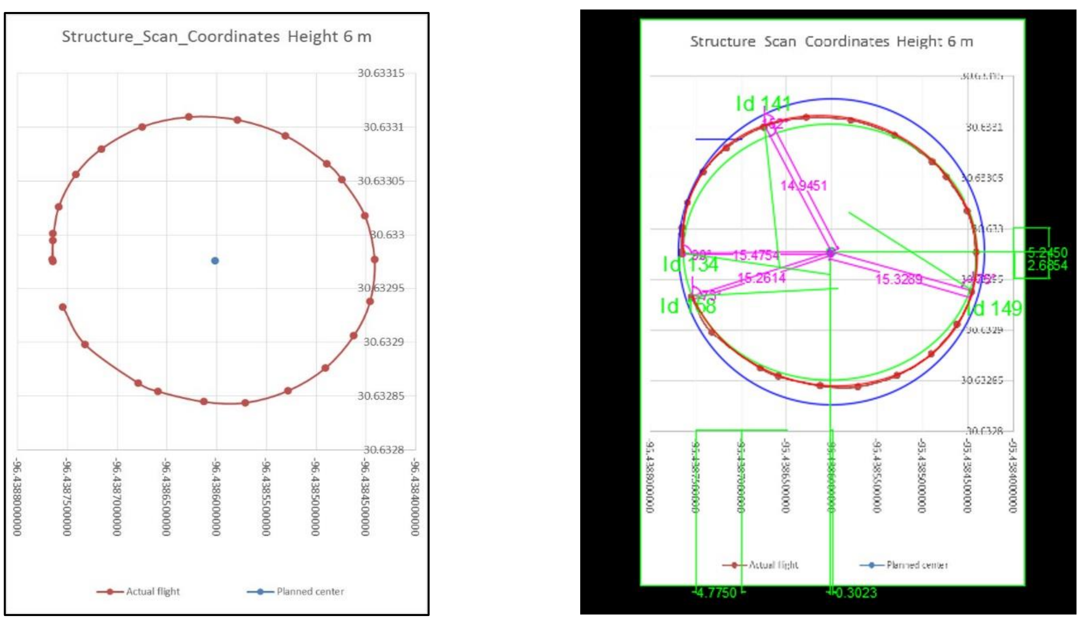



**Figure 196 Planned and actual path at a height of 6 m in Test 2 - app 1, evaluation 2**

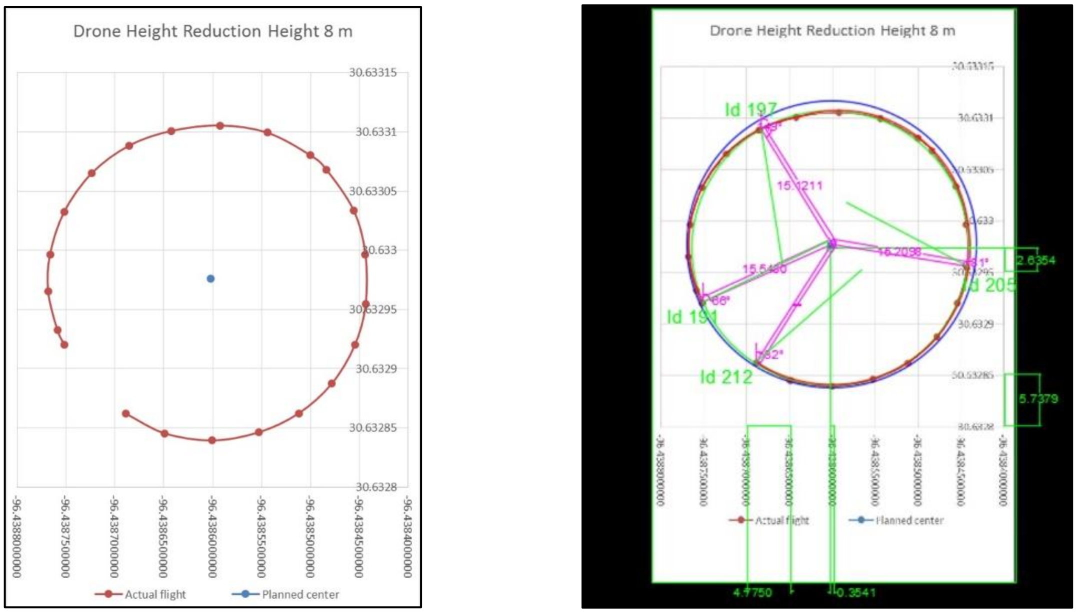



**Figure 197 Planned and actual path at a height of 8 m in Test 2 - app 1, evaluation 2**

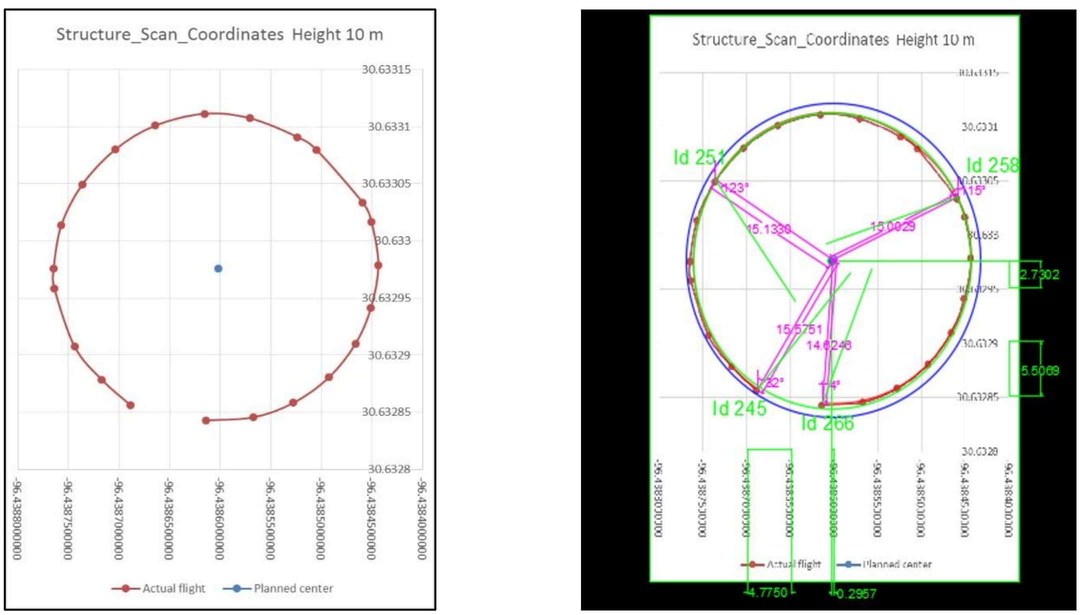



**Figure 198 Planned and actual path at a height of 10 m in Test 2 - app 1, evaluation 2**

## *B.2. Data evaluation 3*

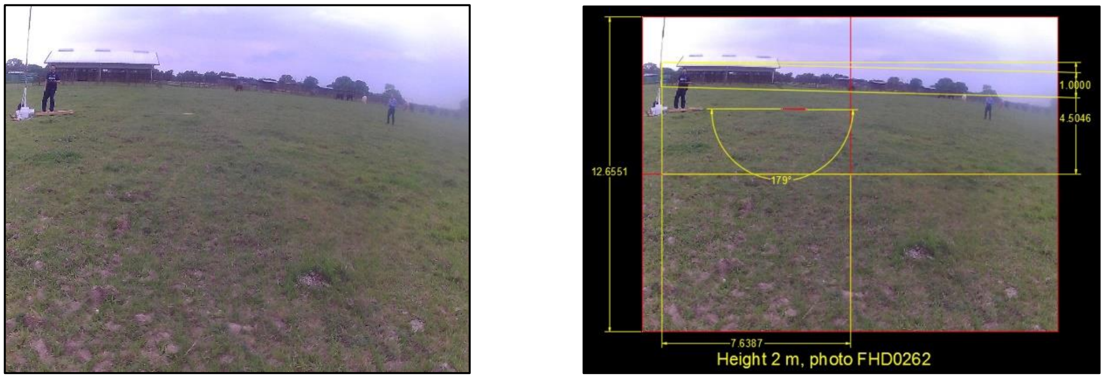



**Figure 199 Photo FHD0262 at a height of 2 m with measurements**


**Figure 200 Photo FHD0264 at a height of 2 m with measurements**

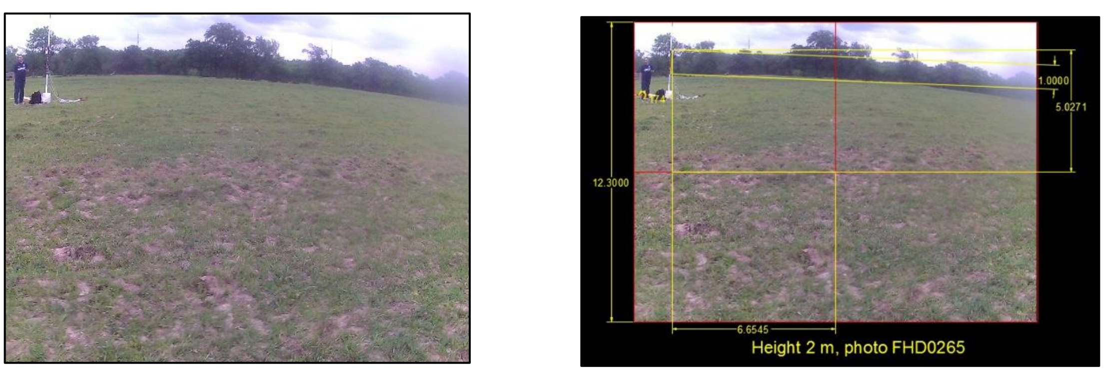



**Figure 201 Photo FHD0265 at a height of 2 m with measurements**

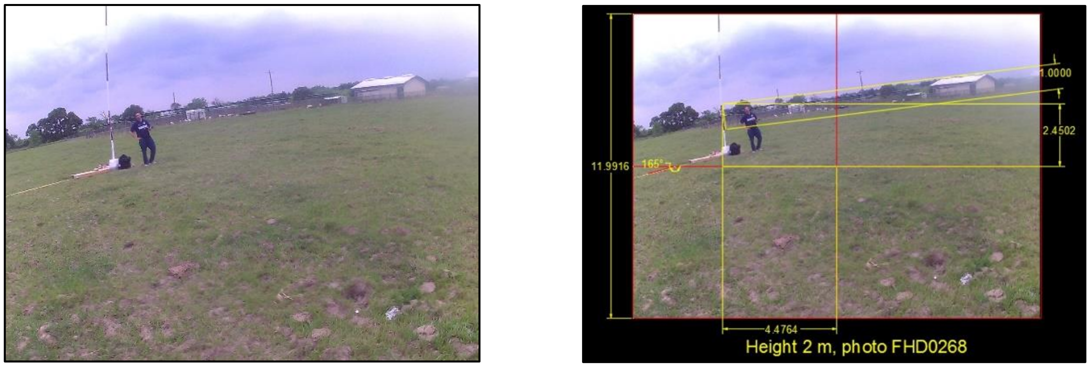



**Figure 202 Photo FHD0268 at a height of 2 m with measurements**


**Figure 203 Photo FHD0283 at a height of 4 m with measurements**

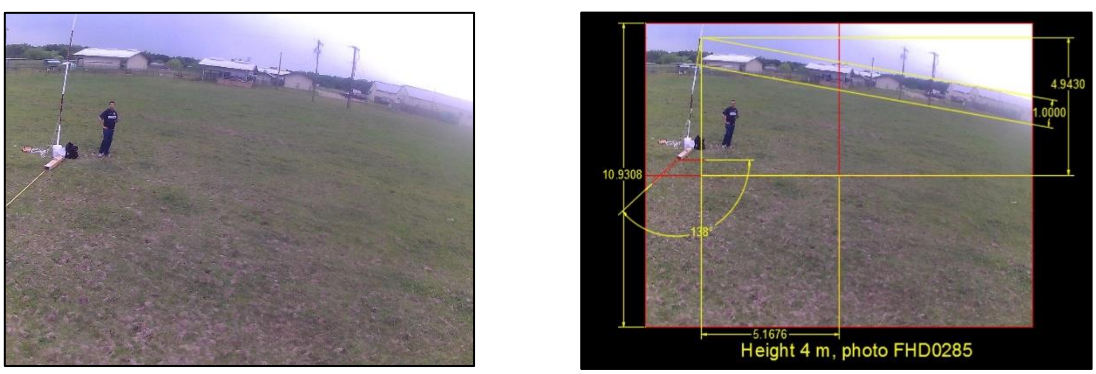



**Figure 204 Photo FHD0285 at a height of 4 m with measurements**

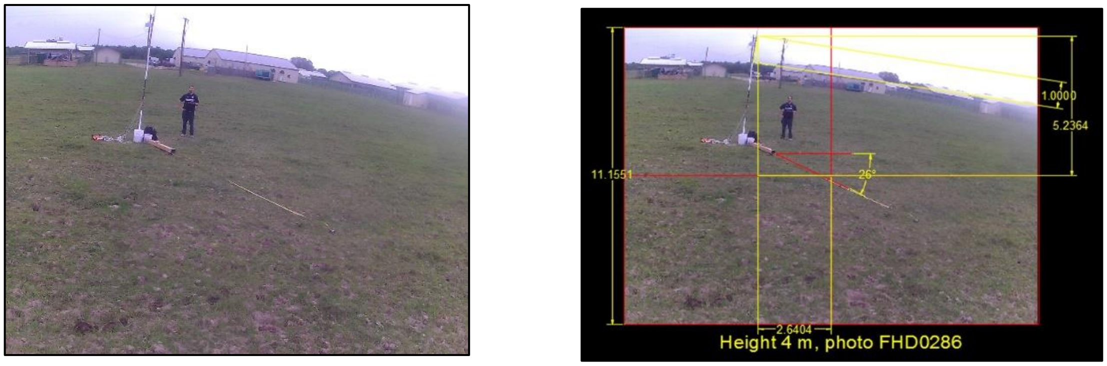



**Figure 205 Photo FHD0286 at a height of 4 m with measurements**


**Figure 206 Photo FHD0289 at a height of 4 m with measurements**

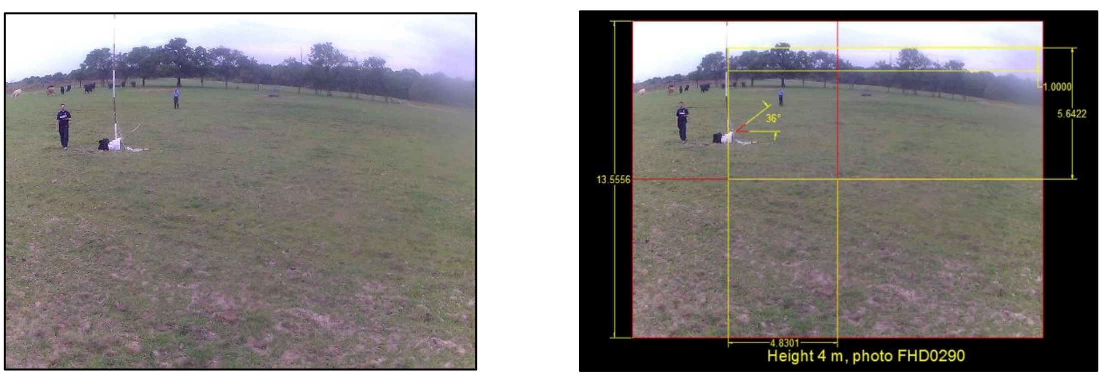



**Figure 207 Photo FHD0290 at a height of 4 m with measurements**

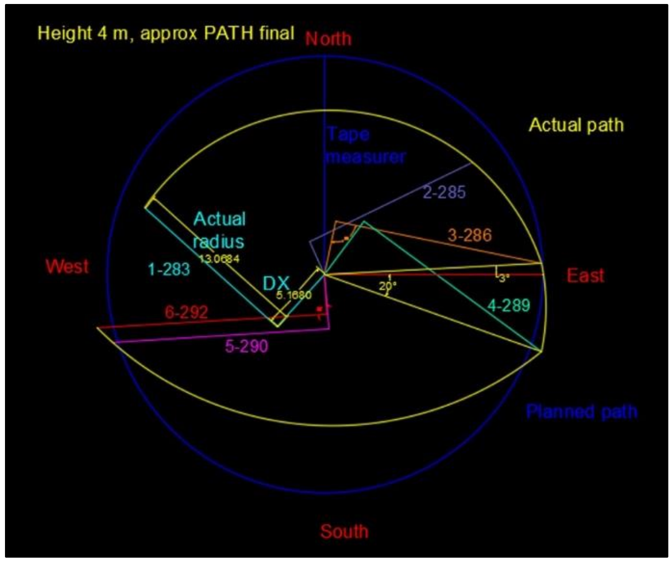



**Figure 208 Planned and actual path at a height of 4 m in Test 2 - app1, evaluation 3**


**Figure 209 Photo FHD0307 at a height of 6 m with measurements**

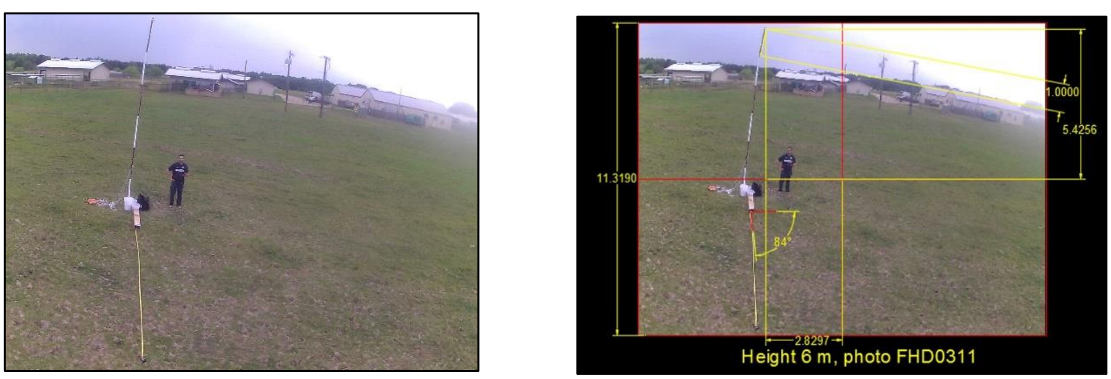



**Figure 210 Photo FHD0311 at a height of 6 m with measurements**

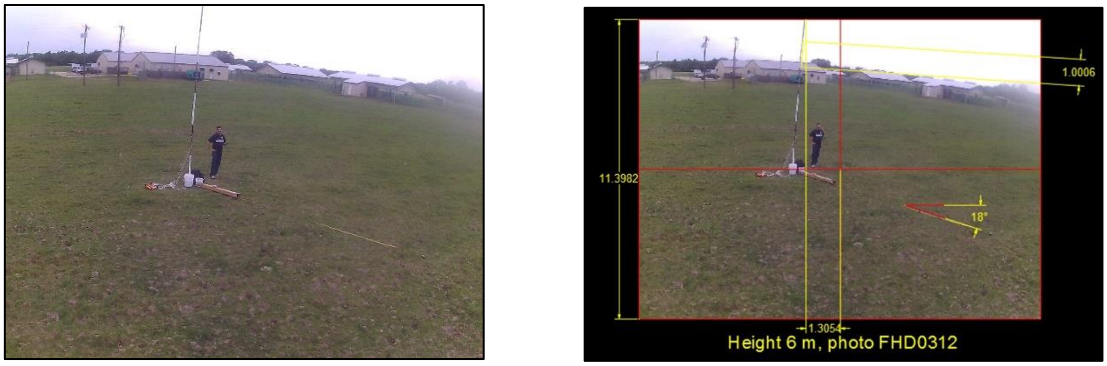



**Figure 211 Photo FHD0312 at a height of 6 m with measurements**


**Figure 212 Photo FHD0315 at a height of 6 m with measurements**

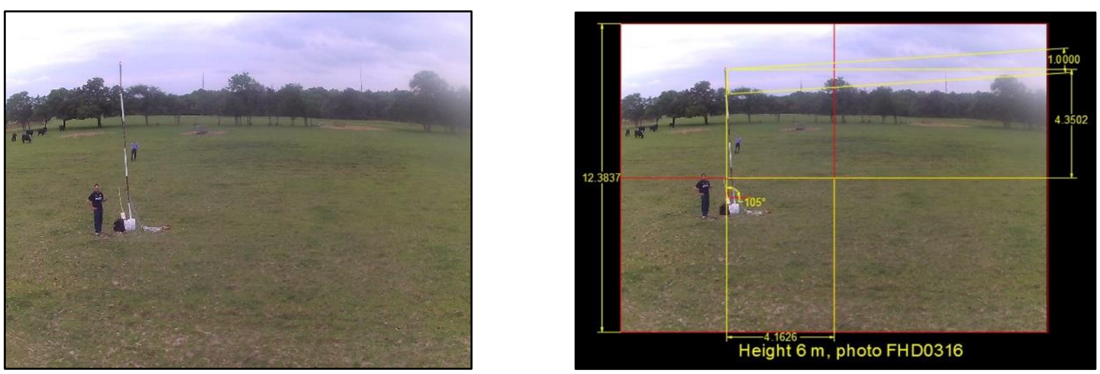



**Figure 213 Photo FHD0316 at a height of 6 m with measurements**

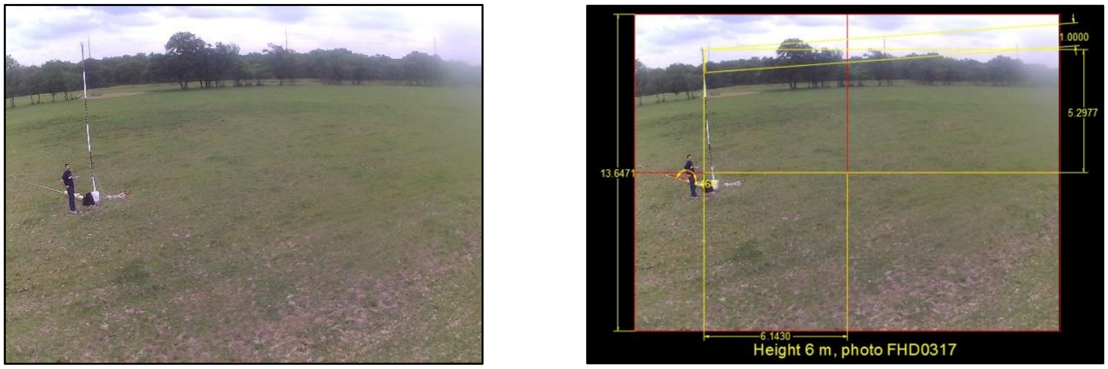



**Figure 214 Photo FHD0317 at a height of 6 m with measurements**

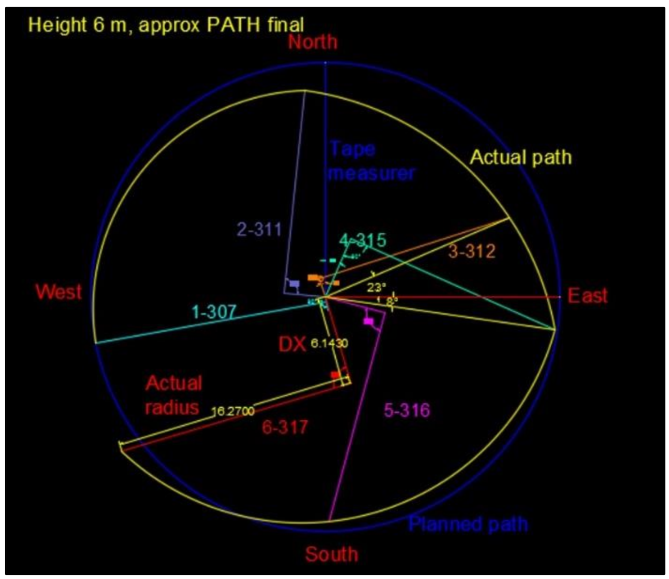



**Figure 215 Planned and actual path at a height of 6 m in Test 2 - app1, evaluation 3**

APPENDIX C

## *Data collected and other analysis Test 1 - app 2, date 04-16-2016*

## *C.1. Data evaluation 2*

**Table 45 Photos and coordinates were taken from a height of 4 m in Test 1 - app 2**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9103 | 14:20:56 | 14:20:25 | 37 | -96.438524 | 30.632988 | 2.640 | -85.6 | 1.7 | 5.0 | Apr 16, 2016 2:20:25 PM |
| 2 | 9104 | 14:20:57 | 14:20:26 | 38 | -96.438524 | 30.632997 | 3.350 | -93.9 | 3.9 | -19.4 | Apr 16, 2016 2:20:26 PM |
| 3 | 9105 | 14:20:58 | 14:20:27 | 39 | -96.438529 | 30.632985 | 3.600 | -89.0 | 6.7 | -7.8 | Apr 16, 2016 2:20:27 PM |
| 4 | 9106 | 14:20:59 | 14:20:28 | 40 | -96.438535 | 30.632964 | 4.290 | -67.6 | 2.0 | -0.1 | Apr 16, 2016 2:20:28 PM |
| 5 | 9107 | 14:21:00 | 14:20:29 | 41 | -96.438546 | 30.632945 | 4.240 | -46.8 | 5.5 | 1.2 | Apr 16, 2016 2:20:29 PM |
| 6 | 9108 | 14:21:01 | 14:20:30 | 42 | -96.438558 | 30.632932 | 3.990 | -25.7 | 5.9 | -0.2 | Apr 16, 2016 2:20:30 PM |
| 7 | 9109 | 14:21:02 | 14:20:31 | 43 | -96.438575 | 30.632921 | 4.060 | -5.2 | 2.4 | 2.6 | Apr 16, 2016 2:20:31 PM |
| 8 | 9111 | 14:21:04 | 14:20:33 | 44 | -96.438597 | 30.632915 | 3.910 | 19.0 | -0.2 | 1.9 | Apr 16, 2016 2:20:33 PM |
| 9 | 9112 | 14:21:05 | 14:20:34 | 45 | -96.438619 | 30.632916 | 3.860 | 38.8 | -1.3 | 1.4 | Apr 16, 2016 2:20:34 PM |

Table 45 Continued

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 9113 | 14:21:06 | 14:20:35 | 46 | -96.438643 | 30.632925 | 3.940 | 57.9 | -4.1 | -0.1 | Apr 16, 2016 2:20:35 PM |
| 11 | 9114 | 14:21:07 | 14:20:36 | 47 | -96.438664 | 30.632942 | 3.970 | 79.8 | -6.5 | -2.1 | Apr 16, 2016 2:20:36 PM |
| 12 | 9115 | 14:21:08 | 14:20:37 | 48 | -96.438675 | 30.632962 | 4.040 | 103.0 | -7.2 | -3.8 | Apr 16, 2016 2:20:37 PM |
| 13 | 9116 | 14:21:09 | 14:20:38 | 49 | -96.438677 | 30.632975 | 4.100 | 114.9 | -6.6 | -5.8 | Apr 16, 2016 2:20:38 PM |
| 14 | 9117 | 14:21:10 | 14:20:39 | 50 | -96.438673 | 30.632998 | 4.370 | 135.7 | -6.0 | -7.2 | Apr 16, 2016 2:20:39 PM |
| 15 | 9118 | 14:21:11 | 14:20:40 | 51 | -96.438658 | 30.633021 | 4.230 | 159.6 | -8.1 | -8.6 | Apr 16, 2016 2:20:40 PM |
| 16 | 9119 | 14:21:12 | 14:20:41 | 52 | -96.438633 | 30.633033 | 4.150 | 179.2 | -2.0 | -7.7 | Apr 16, 2016 2:20:41 PM |
| 17 | 9120 | 14:21:13 | 14:20:42 | 53 | -96.438621 | 30.633037 | 4.060 | -171.9 | -3.5 | -9.5 | Apr 16, 2016 2:20:42 PM |
| 18 | 9121 | 14:21:14 | 14:20:43 | 54 | -96.438581 | 30.633034 | 3.860 | -143.2 | 0.3 | -8.5 | Apr 16, 2016 2:20:43 PM |
| 19 | 9122 | 14:21:15 | 14:20:44 | 55 | -96.438559 | 30.633022 | 3.670 | -119.1 | 2.5 | -7.2 | Apr 16, 2016 2:20:44 PM |
| 20 | 9123 | 14:21:16 | 14:20:45 | 56 | -96.438551 | 30.633015 | 3.790 | -84.3 | 0.6 | 13.7 | Apr 16, 2016 2:20:45 PM |

**Table 46 Photos and coordinates were taken from a height of 6 m in Test 1 - app 2**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9124 | 14:21:17 | 14:20:46 | 57 | -96.438542 | 30.633007 | 4.120 | -64.4 | -3.1 | 7.3 | Apr 16, 2016 2:20:46 PM |
| 2 | 9125 | 14:21:18 | 14:20:47 | 58 | -96.438544 | 30.633017 | 4.560 | -57.0 | 5.9 | -1.9 | Apr 16, 2016 2:20:47 PM |
| 3 | 9126 | 14:21:19 | 14:20:48 | 59 | -96.438547 | 30.633021 | 5.330 | -82.0 | 12.7 | -13.0 | Apr 16, 2016 2:20:48 PM |
| 4 | 9127 | 14:21:20 | 14:20:49 | 60 | -96.438546 | 30.633004 | 5.930 | -114.3 | 2.6 | -9.4 | Apr 16, 2016 2:20:49 PM |
| 5 | 9128 | 14:21:21 | 14:20:50 | 61 | -96.438545 | 30.632981 | 6.060 | -88.0 | 3.4 | -2.8 | Apr 16, 2016 2:20:50 PM |
| 6 | 9129 | 14:21:22 | 14:20:51 | 62 | -96.438546 | 30.632963 | 6.040 | -64.7 | 0.8 | -1.5 | Apr 16, 2016 2:20:51 PM |
| 7 | 9130 | 14:21:23 | 14:20:52 | 63 | -96.438553 | 30.632949 | 6.280 | -40.6 | 1.8 | -1.1 | Apr 16, 2016 2:20:52 PM |
| 8 | 9131 | 14:21:24 | 14:20:53 | 64 | -96.438559 | 30.632943 | 6.280 | -20.2 | 5.0 | -0.4 | Apr 16, 2016 2:20:53 PM |
| 9 | 9132 | 14:21:25 | 14:20:54 | 65 | -96.438573 | 30.632936 | 6.000 | -11.1 | 3.3 | 0.2 | Apr 16, 2016 2:20:54 PM |
| 10 | 9133 | 14:21:26 | 14:20:55 | 66 | -96.438591 | 30.632929 | 5.890 | 10.5 | 0.1 | -1.2 | Apr 16, 2016 2:20:55 PM |
| 11 | 9134 | 14:21:27 | 14:20:56 | 67 | -96.438610 | 30.632929 | 5.840 | 36.1 | -0.2 | 0.9 | Apr 16, 2016 2:20:56 PM |
| 12 | 9135 | 14:21:28 | 14:20:57 | 68 | -96.438630 | 30.632936 | 5.810 | 55.4 | -1.5 | 2.0 | Apr 16, 2016 2:20:57 PM |

**Table 46 Continued**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 9136 | 14:21:29 | 14:20:58 | 69 | -96.438648 | 30.632948 | 5.860 | 75.4 | -4.9 | 0.3 | Apr 16, 2016 2:20:58 PM |
| 14 | 9137 | 14:21:30 | 14:20:59 | 70 | -96.438659 | 30.632962 | 6.020 | 97.2 | -6.1 | -0.5 | Apr 16, 2016 2:20:59 PM |
| 15 | 9138 | 14:21:31 | 14:21:00 | 71 | -96.438663 | 30.632982 | 6.290 | 119.0 | -8.3 | -1.8 | Apr 16, 2016 2:21:00 PM |
| 16 | 9139 | 14:21:32 | 14:21:01 | 72 | -96.438657 | 30.632999 | 6.280 | 140.6 | -6.2 | -5.2 | Apr 16, 2016 2:21:01 PM |
| 17 | 9140 | 14:21:33 | 14:21:02 | 73 | -96.438640 | 30.633016 | 6.190 | 160.7 | -9.0 | -4.6 | Apr 16, 2016 2:21:02 PM |
| 18 | 9141 | 14:21:34 | 14:21:03 | 74 | -96.438619 | 30.633025 | 6.260 | -176.7 | -7.3 | -7.5 | Apr 16, 2016 2:21:03 PM |
| 19 | 9142 | 14:21:35 | 14:21:04 | 75 | -96.438598 | 30.633026 | 6.280 | -154.0 | -5.2 | -7.7 | Apr 16, 2016 2:21:04 PM |
| 20 | 9143 | 14:21:36 | 14:21:05 | 76 | -96.438587 | 30.633023 | 6.140 | -144.6 | -1.7 | -8.1 | Apr 16, 2016 2:21:05 PM |
| 21 | 9144 | 14:21:37 | 14:21:06 | 77 | -96.438568 | 30.633014 | 5.960 | -93.8 | -7.1 | -0.2 | Apr 16, 2016 2:21:06 PM |
| 22 | 9145 | 14:21:38 | 14:21:07 | 78 | -96.438572 | 30.633014 | 6.430 | -93.4 | -1.7 | -3.2 | Apr 16, 2016 2:21:07 PM |

**Table 47 Photos and coordinates were taken from a height of 8 m in Test 1 - app 2**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9146 | 14:21:39 | 14:21:08 | 79 | -96.438582 | 30.633014 | 7.310 | -108.2 | 10.3 | -13.7 | Apr 16, 2016 2:21:08 PM |
| 2 | 9147 | 14:21:40 | 14:21:09 | 80 | -96.438580 | 30.633010 | 8.030 | -140.2 | 0.1 | -14.5 | Apr 16, 2016 2:21:09 PM |
| 3 | 9148 | 14:21:41 | 14:21:10 | 81 | -96.438572 | 30.632995 | 7.980 | -112.1 | 6.4 | -2.5 | Apr 16, 2016 2:21:10 PM |
| 4 | 9149 | 14:21:42 | 14:21:11 | 82 | -96.438570 | 30.632981 | 7.910 | -93.1 | 7.2 | -0.7 | Apr 16, 2016 2:21:11 PM |
| 5 | 9150 | 14:21:43 | 14:21:12 | 83 | -96.438571 | 30.632973 | 7.660 | -71.0 | 8.9 | 0.7 | Apr 16, 2016 2:21:12 PM |
| 6 | 9151 | 14:21:44 | 14:21:13 | 84 | -96.438574 | 30.632966 | 7.840 | -51.8 | 8.1 | 2.2 | Apr 16, 2016 2:21:13 PM |
| 7 | 9152 | 14:21:45 | 14:21:14 | 85 | -96.438577 | 30.632959 | 8.100 | -30.8 | 4.3 | 4.0 | Apr 16, 2016 2:21:14 PM |
| 8 | 9153 | 14:21:46 | 14:21:15 | 86 | -96.438580 | 30.632956 | 8.280 | -20.9 | 3.3 | 4.0 | Apr 16, 2016 2:21:15 PM |
| 9 | 9154 | 14:21:47 | 14:21:16 | 87 | -96.438587 | 30.632951 | 8.220 | 1.3 | 1.2 | 4.3 | Apr 16, 2016 2:21:16 PM |
| 10 | 9155 | 14:21:48 | 14:21:17 | 88 | -96.438597 | 30.632950 | 8.180 | 25.4 | 2.4 | 5.8 | Apr 16, 2016 2:21:17 PM |
| 11 | 9156 | 14:21:49 | 14:21:18 | 89 | -96.438610 | 30.632951 | 8.060 | 46.5 | -0.1 | 7.1 | Apr 16, 2016 2:21:18 PM |
| 12 | 9157 | 14:21:50 | 14:21:19 | 90 | -96.438623 | 30.632954 | 7.900 | 63.9 | -3.7 | 4.7 | Apr 16, 2016 2:21:19 PM |

**Table 47 Continued**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 9158 | 14:21:51 | 14:21:20 | 91 | -96.438633 | 30.632960 | 7.860 | 87.0 | -6.0 | 0.7 | Apr 16, 2016 2:21:20 PM |
| 14 | 9159 | 14:21:52 | 14:21:21 | 92 | -96.438639 | 30.632971 | 7.800 | 111.3 | -6.4 | -0.6 | Apr 16, 2016 2:21:21 PM |
| 15 | 9160 | 14:21:53 | 14:21:22 | 93 | -96.438637 | 30.632985 | 7.940 | 132.3 | -7.5 | -2.1 | Apr 16, 2016 2:21:22 PM |
| 16 | 9161 | 14:21:54 | 14:21:23 | 94 | -96.438630 | 30.632998 | 8.100 | 152.7 | -7.2 | -4.3 | Apr 16, 2016 2:21:23 PM |
| 17 | 9162 | 14:21:55 | 14:21:24 | 95 | -96.438618 | 30.633006 | 8.170 | 174.3 | -6.2 | -5.4 | Apr 16, 2016 2:21:24 PM |
| 18 | 9163 | 14:21:56 | 14:21:25 | 96 | -96.438603 | 30.633010 | 8.370 | -160.0 | -6.6 | -6.7 | Apr 16, 2016 2:21:25 PM |
| 19 | 9164 | 14:21:57 | 14:21:26 | 97 | -96.438595 | 30.633009 | 8.250 | -148.5 | -5.4 | 1.9 | Apr 16, 2016 2:21:26 PM |

**Table 48 Photos and coordinates were taken from a height of 10 m in Test 1 - app 2**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9167 | 14:21:59 | 14:21:28 | 98 | -96.438591 | 30.633004 | 8.210 | -147.4 | -4.8 | -2.9 | Apr 16, 2016 2:21:28 PM |
| 2 | 9168 | 14:22:00 | 14:21:29 | 99 | -96.438596 | 30.632998 | 9.240 | -153.8 | 2.0 | -5.9 | Apr 16, 2016 2:21:29 PM |
| 3 | 9169 | 14:22:01 | 14:21:30 | 100 | -96.438596 | 30.632994 | 9.470 | -153.3 | 1.6 | -7.7 | Apr 16, 2016 2:21:30 PM |

**Table 48 Continued**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 9170 | 14:22:02 | 14:21:31 | 101 | -96.438593 | 30.632991 | 9.770 | -130.9 | 1.4 | -4.7 | Apr 16, 2016 2:21:31 PM |
| 5 | 9171 | 14:22:03 | 14:21:32 | 102 | -96.438591 | 30.632987 | 9.910 | -110.7 | 3.4 | -5.1 | Apr 16, 2016 2:21:32 PM |
| 6 | 9172 | 14:22:04 | 14:21:33 | 103 | -96.438591 | 30.632982 | 10.020 | -87.0 | 6.9 | -1.0 | Apr 16, 2016 2:21:33 PM |
| 7 | 9173 | 14:22:05 | 14:21:34 | 104 | -96.438593 | 30.632978 | 9.970 | -65.8 | 7.9 | 0.0 | Apr 16, 2016 2:21:34 PM |
| 8 | 9174 | 14:22:06 | 14:21:35 | 105 | -96.438593 | 30.632977 | 10.180 | -56.1 | 3.9 | 1.1 | Apr 16, 2016 2:21:35 PM |
| 9 | 9175 | 14:22:07 | 14:21:36 | 106 | -96.438594 | 30.632976 | 10.010 | -35.0 | 9.0 | 2.0 | Apr 16, 2016 2:21:36 PM |
| 10 | 9176 | 14:22:08 | 14:21:37 | 107 | -96.438594 | 30.632973 | 10.120 | -13.3 | 8.5 | 4.1 | Apr 16, 2016 2:21:37 PM |
| 11 | 9177 | 14:22:09 | 14:21:38 | 108 | -96.438594 | 30.632970 | 10.030 | 11.1 | 5.4 | 5.9 | Apr 16, 2016 2:21:38 PM |
| 12 | 9178 | 14:22:10 | 14:21:39 | 109 | -96.438597 | 30.632964 | 10.100 | 32.6 | 1.0 | 4.8 | Apr 16, 2016 2:21:39 PM |
| 13 | 9179 | 14:22:11 | 14:21:40 | 110 | -96.438602 | 30.632961 | 10.190 | 52.7 | 0.8 | 3.4 | Apr 16, 2016 2:21:40 PM |
| 14 | 9180 | 14:22:12 | 14:21:41 | 111 | -96.438610 | 30.632960 | 10.090 | 74.0 | -5.7 | 0.3 | Apr 16, 2016 2:21:41 PM |
| 15 | 9181 | 14:22:13 | 14:21:42 | 112 | -96.438616 | 30.632963 | 10.050 | 95.6 | -3.9 | -0.1 | Apr 16, 2016 2:21:42 PM |

**Table 48 Continued**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | 9182 | 14:22:14 | 14:21:43 | 113 | -96.438618 | 30.632971 | 10.060 | 116.8 | -5.1 | -0.4 | Apr 16, 2016 2:21:43 PM |
| 17 | 9183 | 14:22:15 | 14:21:44 | 114 | -96.438617 | 30.632978 | 10.010 | 138.8 | -3.2 | -2.3 | Apr 16, 2016 2:21:44 PM |
| 18 | 9184 | 14:22:16 | 14:21:45 | 115 | -96.438612 | 30.632985 | 10.120 | 160.2 | -2.2 | -3.3 | Apr 16, 2016 2:21:45 PM |
| 19 | 9185 | 14:22:17 | 14:21:46 | 116 | -96.438609 | 30.632987 | 10.090 | 174.1 | -5.0 | -3.9 | Apr 16, 2016 2:21:46 PM |

**Table 49 Photos and coordinates were taken from a height of 12 m in Test 1 - app 2**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9186 | 14:22:18 | 14:21:47 | 117 | -96.438603 | 30.632987 | 10.000 | -168.5 | 2.6 | -0.3 | Apr 16, 2016 2:21:47 PM |
| 2 | 9187 | 14:22:19 | 14:21:48 | 118 | -96.438606 | 30.632989 | 10.580 | -169.4 | -0.3 | -1.4 | Apr 16, 2016 2:21:48 PM |
| 3 | 9188 | 14:22:20 | 14:21:49 | 119 | -96.438608 | 30.632992 | 11.310 | -176.8 | -1.1 | -13.8 | Apr 16, 2016 2:21:49 PM |
| 4 | 9189 | 14:22:21 | 14:21:50 | 120 | -96.438605 | 30.632993 | 11.880 | 168.5 | -2.9 | -5.8 | Apr 16, 2016 2:21:50 PM |
| 5 | 9190 | 14:22:22 | 14:21:51 | 121 | -96.438600 | 30.632993 | 12.090 | -164.3 | -1.7 | -5.5 | Apr 16, 2016 2:21:51 PM |
| 6 | 9191 | 14:22:23 | 14:21:52 | 122 | -96.438596 | 30.632991 | 11.930 | -140.0 | 0.8 | -7.3 | Apr 16, 2016 2:21:52 PM |

**Table 49 Continued**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 9192 | 14:22:24 | 14:21:53 | 123 | -96.438594 | 30.632986 | 11.820 | -122.5 | 3.7 | -4.4 | Apr 16, 2016 2:21:53 PM |
| 8 | 9193 | 14:22:25 | 14:21:54 | 124 | -96.438593 | 30.632979 | 11.750 | -102.4 | 5.3 | -1.3 | Apr 16, 2016 2:21:54 PM |
| 9 | 9194 | 14:22:26 | 14:21:55 | 125 | -96.438592 | 30.632974 | 12.060 | -78.3 | 5.8 | 0.4 | Apr 16, 2016 2:21:55 PM |
| 10 | 9195 | 14:22:27 | 14:21:56 | 126 | -96.438593 | 30.632974 | 12.150 | -66.2 | 4.1 | 1.1 | Apr 16, 2016 2:21:56 PM |
| 11 | 9196 | 14:22:28 | 14:21:57 | 127 | -96.438592 | 30.632975 | 12.120 | -45.9 | 6.5 | -3.2 | Apr 16, 2016 2:21:57 PM |
| 12 | 9197 | 14:22:29 | 14:21:58 | 128 | -96.438590 | 30.632975 | 12.130 | -25.8 | 5.0 | -0.9 | Apr 16, 2016 2:21:58 PM |
| 13 | 9198 | 14:22:30 | 14:21:59 | 129 | -96.438592 | 30.632975 | 12.010 | -7.1 | 13.8 | 2.1 | Apr 16, 2016 2:21:59 PM |
| 14 | 9199 | 14:22:31 | 14:22:00 | 130 | -96.438594 | 30.632969 | 11.920 | 16.2 | 1.7 | 3.2 | Apr 16, 2016 2:22:00 PM |
| 15 | 9200 | 14:22:32 | 14:22:01 | 131 | -96.438595 | 30.632962 | 11.790 | 40.7 | 4.0 | 1.3 | Apr 16, 2016 2:22:01 PM |
| 16 | 9201 | 14:22:33 | 14:22:02 | 132 | -96.438600 | 30.632959 | 11.800 | 61.1 | 2.2 | 2.0 | Apr 16, 2016 2:22:02 PM |
| 17 | 9202 | 14:22:34 | 14:22:03 | 133 | -96.438609 | 30.632958 | 11.940 | 78.6 | -3.6 | 0.1 | Apr 16, 2016 2:22:03 PM |

**Table 49 Continued**

| N. | Photo index G015- | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | 9203 | 14:22:35 | 14:22:04 | 134 | -96.438616 | 30.632962 | 12.000 | 91.8 | -0.9 | 0.8 | Apr 16, 2016 2:22:04 PM |
| 19 | 9204 | 14:22:36 | 14:22:05 | 135 | -96.438621 | 30.632970 | 12.200 | 124.9 | -5.5 | -3.9 | Apr 16, 2016 2:22:05 PM |
| 20 | 9205 | 14:22:37 | 14:22:06 | 136 | -96.438619 | 30.632978 | 12.140 | 146.1 | -2.8 | -3.7 | Apr 16, 2016 2:22:06 PM |
| 21 | 9206 | 14:22:38 | 14:22:07 | 137 | -96.438617 | 30.632982 | 12.100 | 150.5 | -4.8 | 1.7 | Apr 16, 2016 2:22:07 PM |

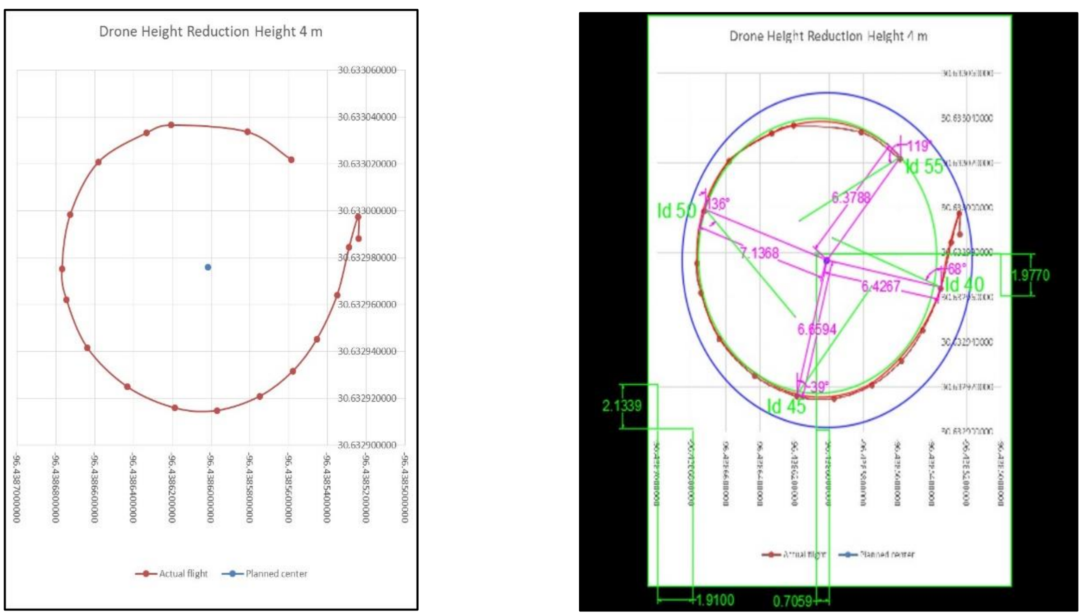



**Figure 216 Planned and actual path at a height of 4 m in Test 1 - app 2, evaluation 2**

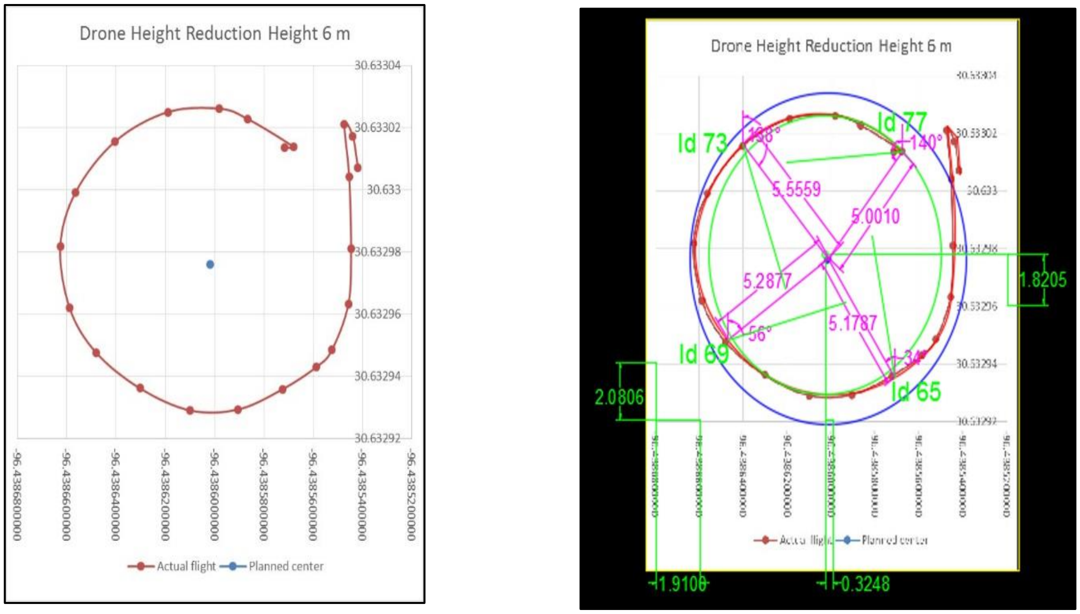



**Figure 217 Planned and actual path at a height of 6 m in Test 1 - app 2, evaluation 2**

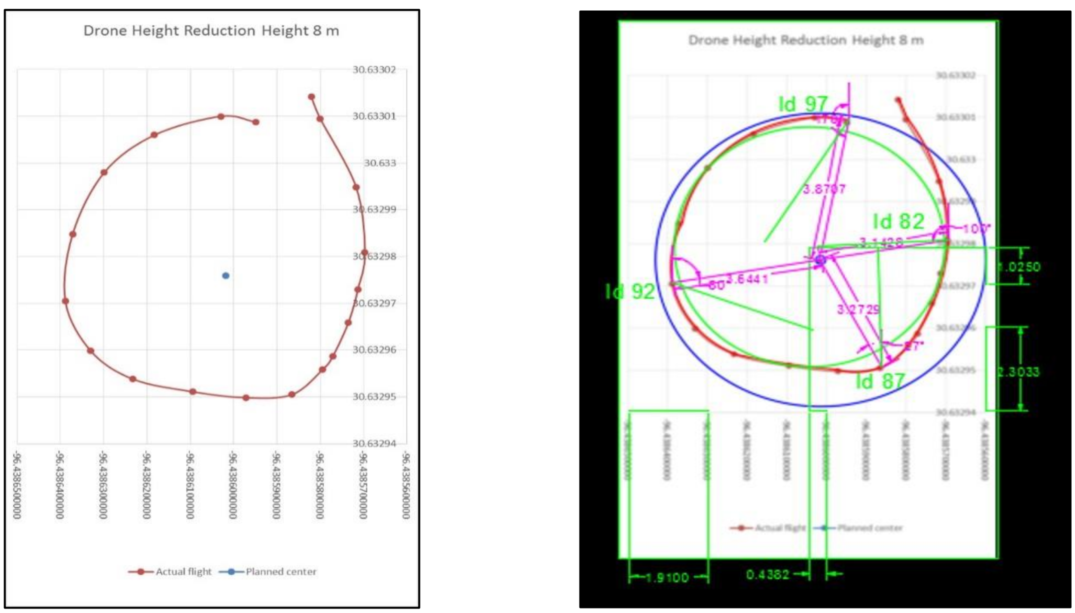



**Figure 218 Planned and actual path at a height of 8 m in Test 1 - app 2, evaluation 2**

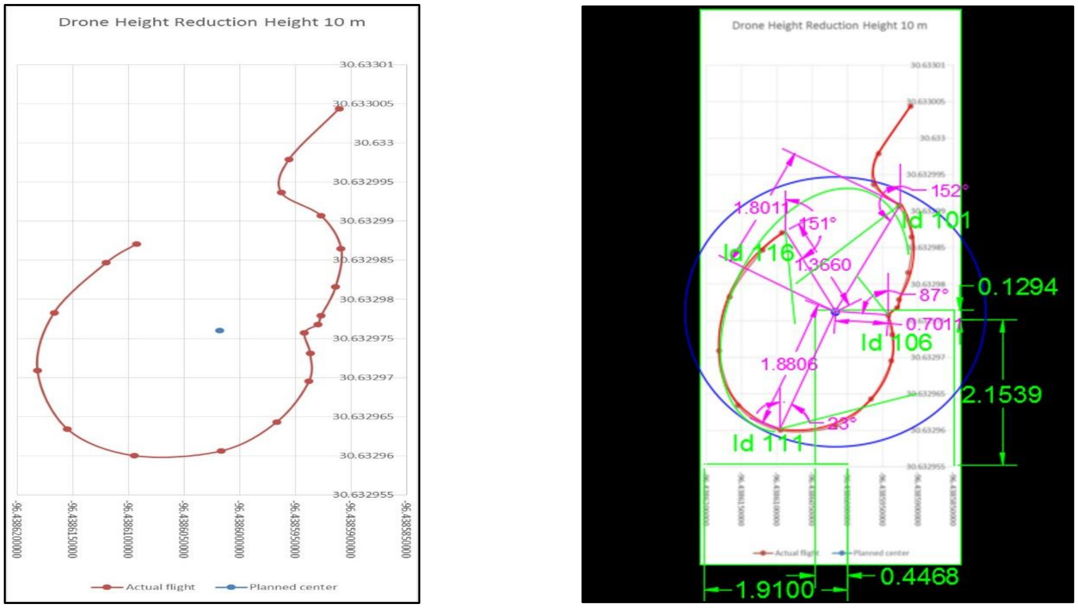



**Figure 219 Planned and actual path at a height of 10 m in Test 1 - app 2, evaluation 2**

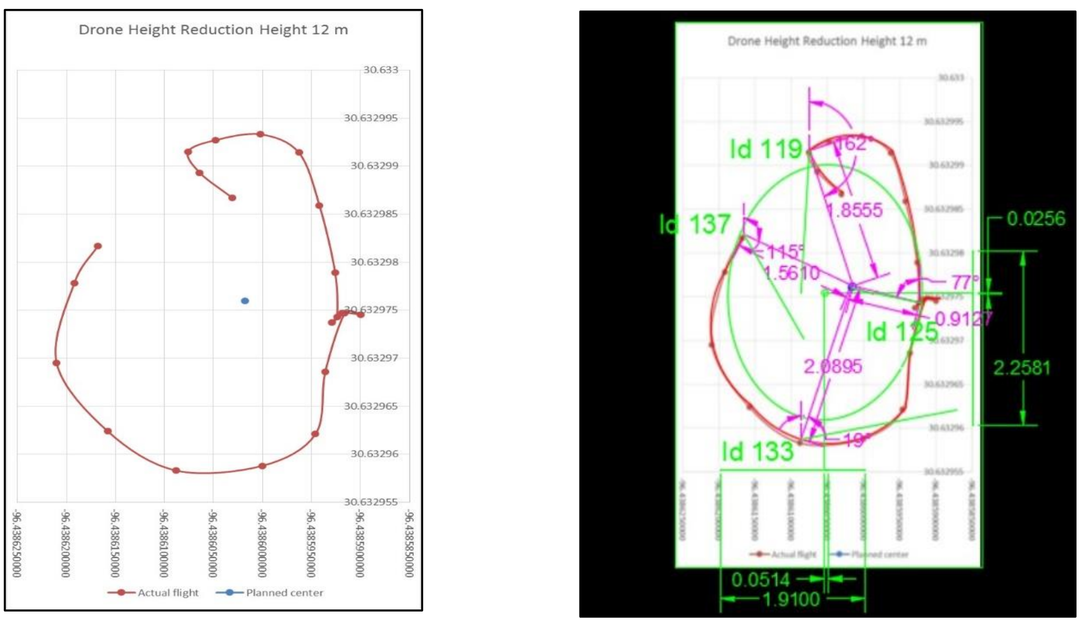



**Figure 220 Planned and actual path at a height of 12 m in Test 1 - app 2, evaluation 2**

## *C.2. Data evaluation 3*


**Figure 221 Photo G0159081 at a height of 2 m with measurements**


**Figure 222 Photo G0159088 at a height of 2 m with measurements**

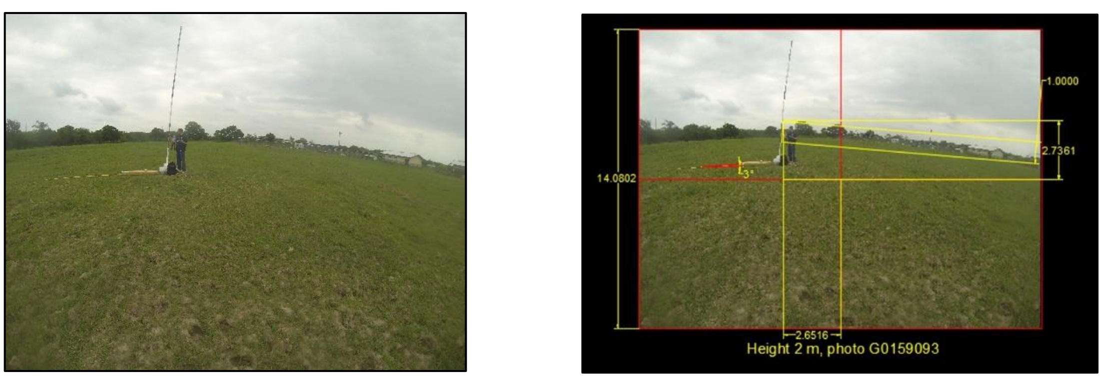



**Figure 223 Photo G0159093 at a height of 2 m with measurements**

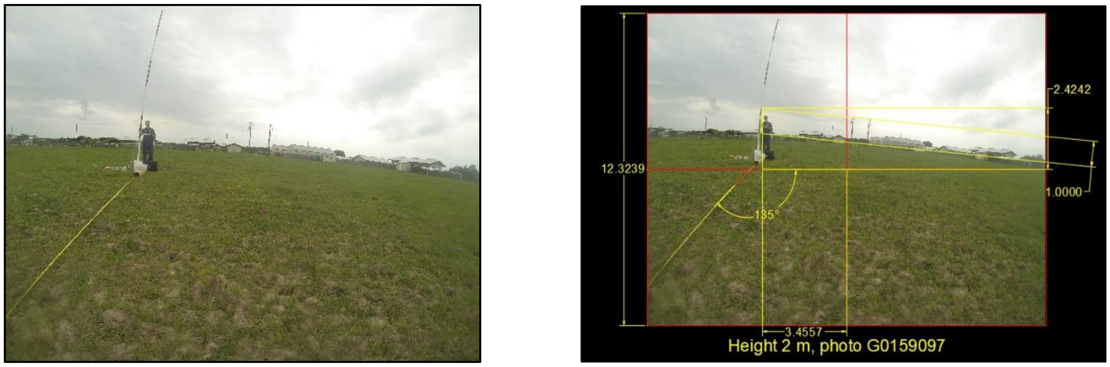



**Figure 224 Photo G0159097 at a height of 2 m with measurements**

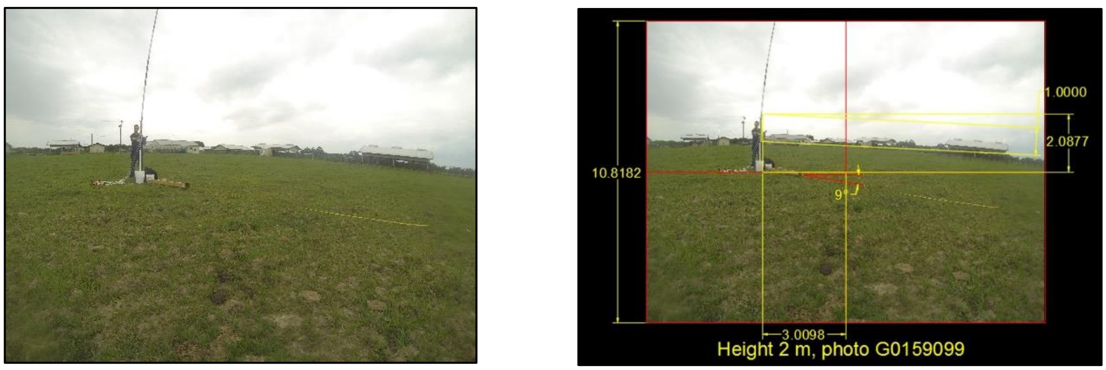



**Figure 225 Photo G0159099 at a height of 2 m with measurements**


**Figure 226 Photo G0159102 at a height of 2 m with measurements**


**Figure 227 Photo G0159103 at a height of 4 m with measurements**


**Figure 228 Photo G0159110 at a height of 4 m with measurements**


**Figure 229 Photo G0159117 at a height of 4 m with measurements**

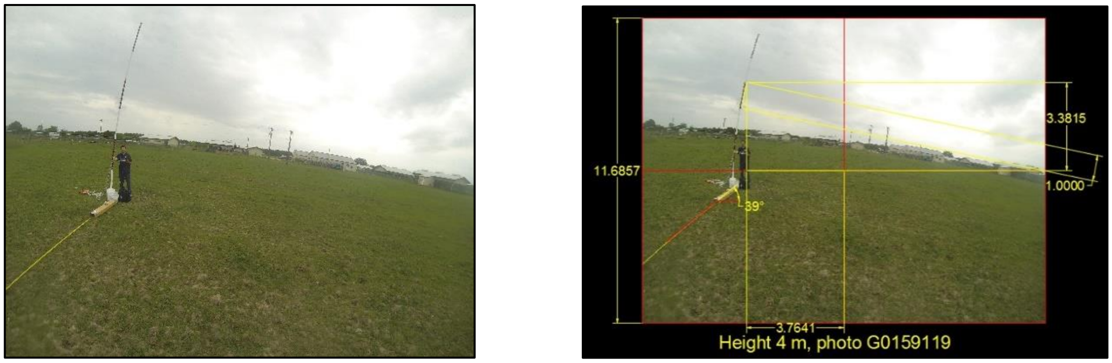



**Figure 230 Photo G0159119 at a height of 4 m with measurements**

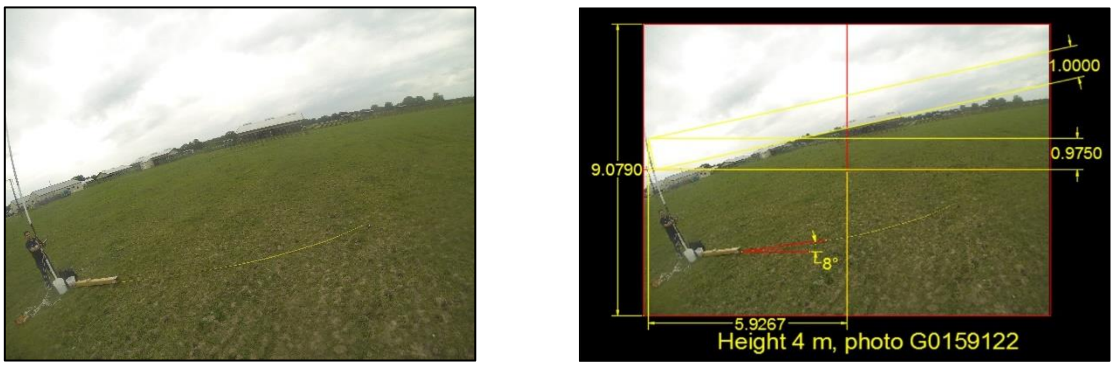



**Figure 231 Photo G0159122 at a height of 4 m with measurements**

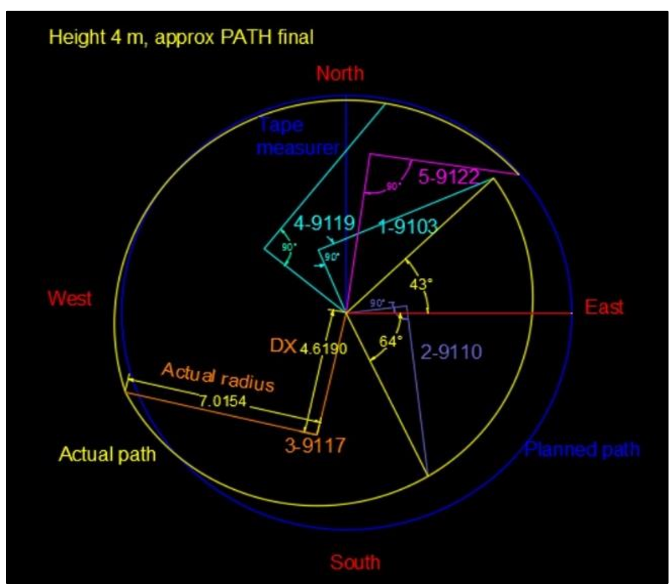



**Figure 232 Planned and actual path at a height of 4 m in Test 1 - app 2, evaluation 3**


**Figure 233 Photo G0159125 at a height of 6 m with measurements**

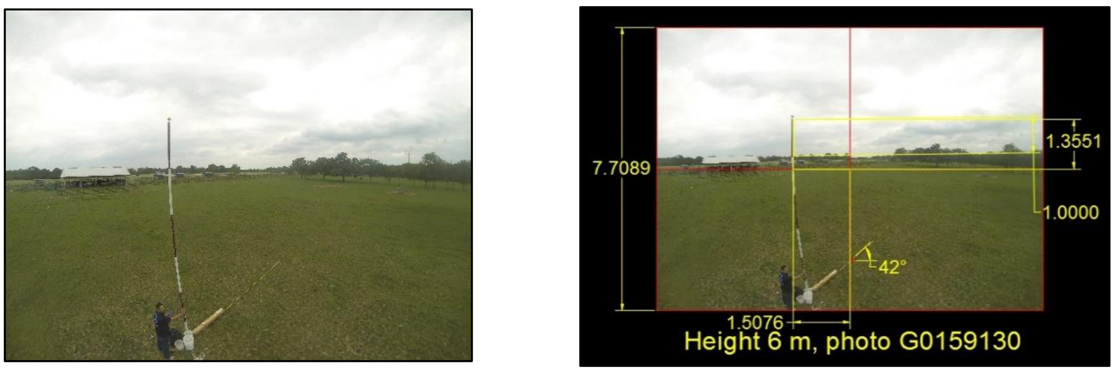



**Figure 234 Photo G0159130 at a height of 6 m with measurements**

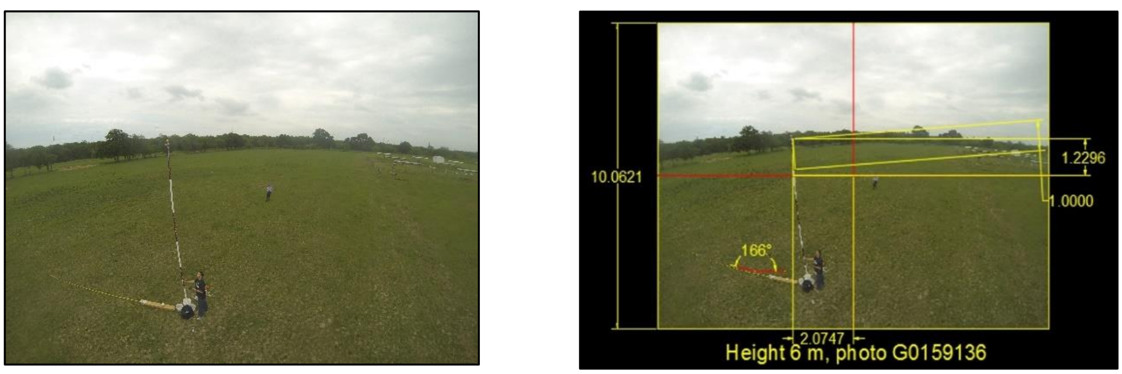



**Figure 235 Photo G0159136 at a height of 6 m with measurements**

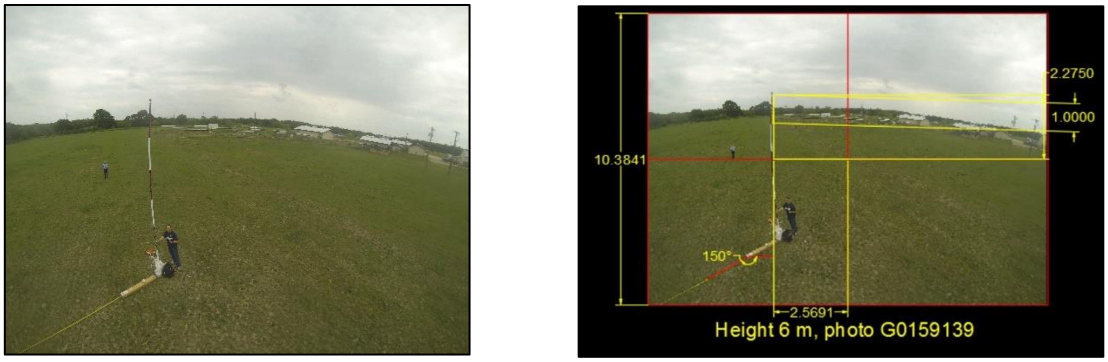



**Figure 236 Photo G0159139 at a height of 6 m with measurements**

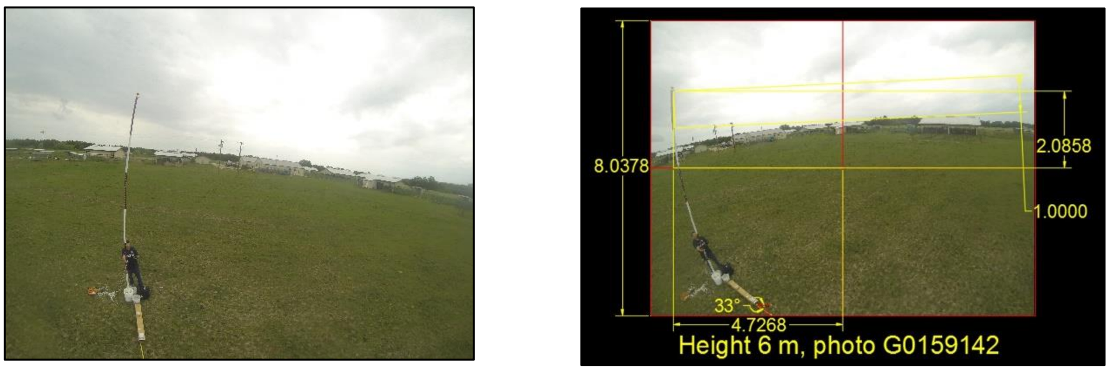



**Figure 237 Photo G0159142 at a height of 6 m with measurements**

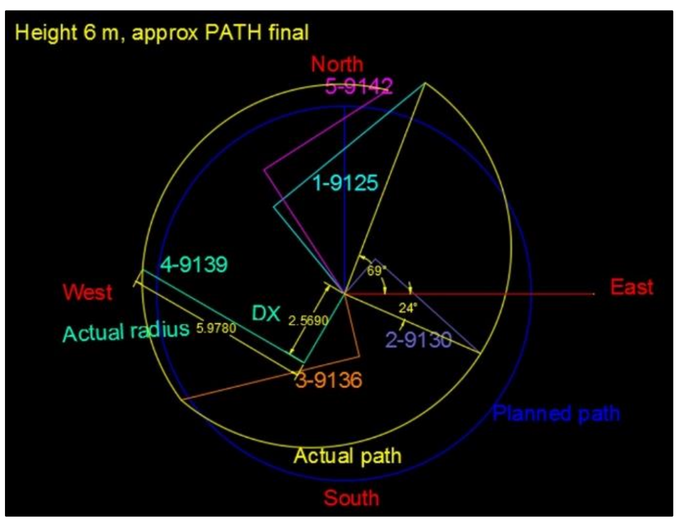



**Figure 238 Planned and actual path at a height of 6 m in Test 1 - app2, evaluation 3**

APPENDIX D

## *Data collected and other analysis Test 2 - app 2, date 04-16-2016*

### *D.1. Data evaluation 2*

**Table 50 Photos and coordinates were taken from a height of 4 m in Test 2 - app 2**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 140 | 14:52:02 | 14:51:26 | 63 | -96.438596 | 30.633126 | 3.730 | -172.8 | 2.1 | -23.6 | Apr 16, 2016 2:51:26 PM |
| 2 | | | | 64 | -96.438574 | 30.633119 | 4.160 | -166.2 | 1.7 | -14.4 | Apr 16, 2016 2:51:27 PM |
| 3 | 141 | 14:52:04 | 14:51:28 | 65 | -96.438539 | 30.633103 | 4.220 | -148.8 | 0.8 | -6.7 | Apr 16, 2016 2:51:28 PM |
| 4 | | | | 66 | -96.438508 | 30.633082 | 4.190 | -134.0 | -0.8 | -6.2 | Apr 16, 2016 2:51:29 PM |
| 5 | | | | 67 | -96.438492 | 30.633067 | 4.110 | -118.7 | 0.5 | -5.7 | Apr 16, 2016 2:51:30 PM |
| 6 | 142 | 14:52:07 | 14:51:31 | 68 | -96.438469 | 30.633040 | 4.060 | -99.7 | 0.1 | -7.3 | Apr 16, 2016 2:51:31 PM |
| 7 | | | | 69 | -96.438451 | 30.632990 | 4.190 | -80.3 | 2.4 | -4.5 | Apr 16, 2016 2:51:32 PM |
| 8 | 143 | 14:52:09 | 14:51:33 | 70 | -96.438451 | 30.632970 | 4.080 | -62.6 | 3.8 | -4.0 | Apr 16, 2016 2:51:33 PM |

**Table 50 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | | | | 71 | -96.438460 | 30.632936 | 3.930 | -44.5 | 3.5 | -4.7 | Apr 16, 2016 2:51:34 PM |
| 10 | 144 | 14:52:11 | 14:51:35 | 72 | -96.438478 | 30.632903 | 3.860 | -36.3 | 3.3 | -4.4 | Apr 16, 2016 2:51:35 PM |
| 11 | | | | 73 | -96.438505 | 30.632876 | 3.810 | -20.1 | 1.7 | -3.5 | Apr 16, 2016 2:51:36 PM |
| 12 | 145 | 14:52:13 | 14:51:37 | 74 | -96.438542 | 30.632853 | 4.040 | -2.6 | -3.4 | -3.5 | Apr 16, 2016 2:51:37 PM |
| 13 | | | | 75 | -96.438586 | 30.632842 | 4.010 | 15.1 | -2.2 | -4.1 | Apr 16, 2016 2:51:38 PM |
| 14 | 146 | 14:52:16 | 14:51:40 | 76 | -96.438632 | 30.632843 | 3.840 | 31.9 | -3.2 | -3.0 | Apr 16, 2016 2:51:39 PM |
| 15 | | | | 77 | -96.438653 | 30.632847 | 3.770 | 50.8 | -2.5 | -2.4 | Apr 16, 2016 2:51:40 PM |
| 16 | 147 | 14:52:18 | 14:51:42 | 78 | -96.438695 | 30.632867 | 3.730 | 60.5 | -3.6 | -2.6 | Apr 16, 2016 2:51:41 PM |
| 17 | | | | 79 | -96.438730 | 30.632895 | 3.650 | 77.7 | -6.8 | -3.9 | Apr 16, 2016 2:51:42 PM |
| 18 | 148 | 14:52:20 | 14:51:44 | 80 | -96.438750 | 30.632927 | 3.810 | 101.4 | -6.7 | -6.3 | Apr 16, 2016 2:51:44 PM |
| 19 | | | | 81 | -96.438760 | 30.632968 | 4.020 | 110.1 | -7.9 | -7.7 | Apr 16, 2016 2:51:45 PM |

**Table 50 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 149 | 14:52:22 | 14:51:46 | 82 | -96.438755 | 30.633008 | 4.110 | 127.6 | -6.8 | -10.0 | Apr 16, 2016 2:51:46 PM |
| 21 | | | | 83 | -96.438738 | 30.633043 | 4.170 | 145.0 | -6.9 | -11.3 | Apr 16, 2016 2:51:47 PM |
| 22 | 150 | 14:52:24 | 14:51:48 | 84 | -96.438707 | 30.633076 | 4.180 | 162.7 | -6.3 | -12.2 | Apr 16, 2016 2:51:48 PM |
| 23 | | | | 85 | -96.438664 | 30.633098 | 4.160 | 177.5 | -5.0 | -12.4 | Apr 16, 2016 2:51:49 PM |

**Table 51 Photos and coordinates were taken from a height of 6 m in Test 2 - app 2**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 153 | 14:52:31 | 14:51:55 | 91 | -96.438638 | 30.633085 | 5.900 | -178.2 | 5.7 | -22.3 | Apr 16, 2016 2:51:55 PM |
| 2 | | | | 92 | -96.438606 | 30.633083 | 6.250 | -174.1 | -3.0 | -13.6 | Apr 16, 2016 2:51:56 PM |
| 3 | 154 | 14:52:33 | 14:51:57 | 93 | -96.438567 | 30.633076 | 6.310 | -155.8 | -2.1 | -10.1 | Apr 16, 2016 2:51:57 PM |
| 4 | | | | 94 | -96.438536 | 30.633062 | 6.070 | -138.6 | -0.2 | -9.5 | Apr 16, 2016 2:51:58 PM |
| 5 | | | | 95 | -96.438523 | 30.633053 | 5.960 | -117.8 | 0.7 | -8.8 | Apr 16, 2016 2:51:59 PM |
| 6 | 155 | 14:52:36 | 14:52:00 | 96 | -96.438494 | 30.633013 | 5.890 | -95.7 | 4.1 | -4.5 | Apr 16, 2016 2:52:00 PM |

**Table 51 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | | | | 97 | -96.438489 | 30.632983 | 5.800 | -76.1 | 1.1 | -7.0 | Apr 16, 2016 2:52:01 PM |
| 8 | 156 | 14:52:38 | 14:52:02 | 98 | -96.438491 | 30.632952 | 5.830 | -53.9 | 2.0 | -4.8 | Apr 16, 2016 2:52:02 PM |
| 9 | | | | 99 | -96.438498 | 30.632939 | 5.990 | -35.3 | 3.0 | -3.0 | Apr 16, 2016 2:52:03 PM |
| 10 | 157 | 14:52:40 | 14:52:04 | 100 | -96.438518 | 30.632914 | 5.870 | -16.1 | 3.1 | -2.7 | Apr 16, 2016 2:52:04 PM |
| 11 | | | | 101 | -96.438548 | 30.632892 | 5.920 | -7.1 | 1.1 | -2.2 | Apr 16, 2016 2:52:05 PM |
| 12 | 158 | 14:52:42 | 14:52:06 | 102 | -96.438584 | 30.632878 | 6.180 | 12.6 | -1.7 | -1.6 | Apr 16, 2016 2:52:06 PM |
| 13 | | | | 103 | -96.438620 | 30.632877 | 6.090 | 31.1 | -2.1 | -0.5 | Apr 16, 2016 2:52:07 PM |
| 14 | 159 | 14:52:44 | 14:52:08 | 104 | -96.438657 | 30.632887 | 5.850 | 50.6 | -4.2 | -2.7 | Apr 16, 2016 2:52:08 PM |
| 15 | | | | 105 | -96.438688 | 30.632907 | 5.670 | 69.5 | -4.5 | -4.8 | Apr 16, 2016 2:52:09 PM |
| 16 | | | | 106 | -96.438707 | 30.632933 | 5.820 | 90.7 | -5.4 | -5.6 | Apr 16, 2016 2:52:10 PM |
| 17 | 160 | 14:52:47 | 14:52:11 | 107 | -96.438718 | 30.632970 | 6.050 | 114.0 | -7.8 | -7.2 | Apr 16, 2016 2:52:11 PM |

**Table 51 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | | | | 108 | -96.438718 | 30.632987 | 6.170 | 123.5 | -7.6 | -7.9 | Apr 16, 2016 2:52:12 PM |
| 19 | 161 | 14:52:49 | 14:52:13 | 109 | -96.438707 | 30.633024 | 6.280 | 142.3 | -10.0 | -8.4 | Apr 16, 2016 2:52:13 PM |
| 20 | | | | 110 | -96.438681 | 30.633054 | 6.150 | 163.4 | -11.5 | -8.9 | Apr 16, 2016 2:52:14 PM |
| 21 | 162 | 14:52:51 | 14:52:15 | 111 | -96.438658 | 30.633070 | 5.970 | -153.4 | -14.7 | -3.9 | Apr 16, 2016 2:52:15 PM |
| 22 | | | | 112 | -96.438651 | 30.633059 | 6.350 | -157.6 | -7.0 | -3.8 | Apr 16, 2016 2:52:16 PM |

**Table 52 Photos and coordinates were taken from a height of 8 m in Test 2 - app 2**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 163 | 14:52:53 | 14:52:17 | 114 | -96.438652 | 30.633041 | 7.740 | -179.7 | 10.8 | -11.4 | Apr 16, 2016 2:52:18 PM |
| 2 | | | | 115 | -96.438636 | 30.633050 | 7.870 | 161.9 | -11.1 | -6.9 | Apr 16, 2016 2:52:19 PM |
| 3 | 164 | 14:52:56 | 14:52:20 | 116 | -96.438608 | 30.633054 | 8.050 | -170.8 | -7.4 | -8.6 | Apr 16, 2016 2:52:20 PM |
| 4 | | | | 117 | -96.438583 | 30.633050 | 8.090 | -148.5 | -4.9 | -10.7 | Apr 16, 2016 2:52:21 PM |

**Table 52 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 165 | 14:52:58 | 14:52:22 | 118 | -96.438558 | 30.633037 | 8.160 | -129.0 | -3.5 | -11.4 | Apr 16, 2016 2:52:22 PM |
| 6 | | | | 119 | -96.438541 | 30.633019 | 8.160 | -110.9 | -1.6 | -10.0 | Apr 16, 2016 2:52:23 PM |
| 7 | 166 | 14:53:00 | 14:52:24 | 120 | -96.438530 | 30.632993 | 7.980 | -90.4 | 1.1 | -8.4 | Apr 16, 2016 2:52:24 PM |
| 8 | | | | 121 | -96.438530 | 30.632966 | 7.720 | -66.3 | 2.8 | -4.7 | Apr 16, 2016 2:52:25 PM |
| 9 | 167 | 14:53:02 | 14:52:26 | 122 | -96.438537 | 30.632945 | 7.830 | -43.3 | 3.3 | -2.0 | Apr 16, 2016 2:52:26 PM |
| 10 | | | | 123 | -96.438554 | 30.632928 | 7.730 | -22.4 | 4.4 | -1.7 | Apr 16, 2016 2:52:27 PM |
| 11 | | | | 124 | -96.438563 | 30.632922 | 7.690 | -3.0 | 2.7 | -0.5 | Apr 16, 2016 2:52:28 PM |
| 12 | 168 | 14:53:05 | 14:52:29 | 125 | -96.438604 | 30.632913 | 7.840 | 17.6 | 1.0 | 1.9 | Apr 16, 2016 2:52:29 PM |
| 13 | | | | 126 | -96.438616 | 30.632913 | 7.910 | 29.5 | 0.4 | 1.7 | Apr 16, 2016 2:52:31 PM |
| 14 | | | | 127 | -96.438652 | 30.632927 | 7.910 | 62.8 | -3.7 | 1.0 | Apr 16, 2016 2:52:32 PM |
| 15 | 170 | 14:53:09 | 14:52:33 | 128 | -96.438661 | 30.632935 | 8.030 | 73.2 | -3.9 | 1.3 | Apr 16, 2016 2:52:33 PM |

**Table 52 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | | | | 129 | -96.438676 | 30.632956 | 8.080 | 92.3 | -7.6 | 0.1 | Apr 16, 2016 2:52:34 PM |
| 17 | | | | 130 | -96.438680 | 30.632981 | 8.100 | 117.0 | -6.4 | -4.1 | Apr 16, 2016 2:52:35 PM |
| 18 | 171 | 14:53:12 | 14:52:36 | 131 | -96.438672 | 30.633004 | 8.200 | 139.9 | -9.0 | -4.3 | Apr 16, 2016 2:52:36 PM |
| 19 | | | | 132 | -96.438656 | 30.633020 | 8.250 | 174.6 | -15.2 | 0.4 | Apr 16, 2016 2:52:37 PM |

**Table 53 Photos and coordinates were taken from a height of 10 m in Test 2 - app 2**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 173 | 14:53:16 | 14:52:40 | 135 | -96.438638 | 30.633007 | 9.740 | 139.6 | -6.6 | -9.0 | Apr 16, 2016 2:52:40 PM |
| 2 | | | | 136 | -96.438622 | 30.633014 | 10.120 | 175.5 | -3.8 | -7.3 | Apr 16, 2016 2:52:41 PM |
| 3 | 174 | 14:53:18 | 14:52:42 | 137 | -96.438614 | 30.633015 | 10.080 | -162.9 | -3.0 | -7.3 | Apr 16, 2016 2:52:42 PM |
| 4 | | | | 138 | -96.438600 | 30.633013 | 9.970 | -141.4 | 0.2 | -8.2 | Apr 16, 2016 2:52:43 PM |
| 5 | | | | 139 | -96.438587 | 30.633007 | 9.890 | -132.4 | 1.2 | -8.0 | Apr 16, 2016 2:52:44 PM |

**Table 53 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 175 | 14:53:21 | 14:52:45 | 140 | -96.438576 | 30.632997 | 9.940 | -113.2 | 1.1 | -7.1 | Apr 16, 2016 2:52:45 PM |
| 7 | | | | 141 | -96.438569 | 30.632987 | 10.100 | -92.8 | 1.7 | -5.0 | Apr 16, 2016 2:52:46 PM |
| 8 | 176 | 14:53:23 | 14:52:47 | 142 | -96.438570 | 30.632974 | 10.170 | -68.2 | 7.1 | 0.2 | Apr 16, 2016 2:52:47 PM |
| 9 | | | | 143 | -96.438572 | 30.632964 | 9.810 | -48.0 | 5.0 | -1.2 | Apr 16, 2016 2:52:48 PM |
| 10 | 177 | 14:53:25 | 14:52:49 | 144 | -96.438576 | 30.632955 | 9.930 | -28.0 | 3.6 | 0.2 | Apr 16, 2016 2:52:49 PM |
| 11 | | | | 145 | -96.438585 | 30.632948 | 9.940 | -7.2 | 1.5 | 2.1 | Apr 16, 2016 2:52:50 PM |
| 12 | | | | 146 | -96.438595 | 30.632944 | 9.900 | 16.5 | 1.3 | 1.4 | Apr 16, 2016 2:52:51 PM |
| 13 | 178 | 14:53:28 | 14:52:52 | 147 | -96.438608 | 30.632943 | 9.960 | 35.2 | -1.8 | 2.1 | Apr 16, 2016 2:52:52 PM |
| 14 | | | | 148 | -96.438621 | 30.632947 | 10.040 | 56.0 | -1.8 | 2.0 | Apr 16, 2016 2:52:53 PM |
| 15 | 179 | 14:53:30 | 14:52:54 | 149 | -96.438631 | 30.632955 | 10.110 | 78.1 | -5.2 | -1.6 | Apr 16, 2016 2:52:54 PM |
| 16 | | | | 150 | -96.438638 | 30.632967 | 10.170 | 99.3 | -4.5 | -1.8 | Apr 16, 2016 2:52:55 PM |

**Table 53 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 17 | 180 | 14:53:32 | 14:52:56 | 151 | -96.438639 | 30.632973 | 10.210 | 120.0 | -4.3 | -3.6 | Apr 16, 2016 2:52:56 PM |
| 18 | | | | 152 | -96.438635 | 30.632990 | 10.150 | 130.8 | -3.2 | 3.6 | Apr 16, 2016 2:52:57 PM |

**Table 54 Photos and coordinates were taken from a height of 12 m in Test 2 - app 2**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | 155 | -96.438640 | 30.632990 | 11.710 | 114.7 | -8.4 | -4.9 | Apr 16, 2016 2:53:00 PM |
| 2 | 182 | 14:53:37 | 14:53:01 | 156 | -96.438635 | 30.632999 | 12.000 | 140.7 | -6.5 | -5.5 | Apr 16, 2016 2:53:01 PM |
| 3 | | | | 157 | -96.438627 | 30.633006 | 12.120 | 164.1 | -5.0 | -8.4 | Apr 16, 2016 2:53:02 PM |
| 4 | 183 | 14:53:39 | 14:53:03 | 158 | -96.438614 | 30.633009 | 12.200 | -175.0 | -0.8 | -7.7 | Apr 16, 2016 2:53:03 PM |
| 5 | | | | 159 | -96.438600 | 30.633009 | 12.170 | -154.0 | -1.6 | -8.3 | Apr 16, 2016 2:53:04 PM |
| 6 | | | | 160 | -96.438587 | 30.633003 | 12.050 | -136.2 | 1.2 | -6.6 | Apr 16, 2016 2:53:05 PM |
| 7 | 184 | 14:53:42 | 14:53:06 | 161 | -96.438582 | 30.632999 | 11.900 | -126.8 | 2.3 | -4.6 | Apr 16, 2016 2:53:06 PM |

**Table 54 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | | | | 162 | -96.438573 | 30.632988 | 11.920 | -104.1 | 3.2 | -2.6 | Apr 16, 2016 2:53:07 PM |
| 9 | 185 | 14:53:44 | 14:53:08 | 163 | -96.438568 | 30.632974 | 12.110 | -69.8 | 2.6 | -2.9 | Apr 16, 2016 2:53:08 PM |
| 10 | 186 | 14:53:46 | 14:53:10 | 164 | -96.438569 | 30.632967 | 12.040 | -48.2 | 6.3 | -2.4 | Apr 16, 2016 2:53:10 PM |
| 11 | 187 | 14:53:48 | 14:53:12 | 166 | -96.438574 | 30.632956 | 12.110 | -17.8 | 4.0 | -2.8 | Apr 16, 2016 2:53:12 PM |
| 12 | | | | 167 | -96.438585 | 30.632950 | 12.070 | 0.9 | 3.4 | 0.9 | Apr 16, 2016 2:53:13 PM |
| 13 | | | | 168 | -96.438597 | 30.632947 | 11.860 | 23.6 | 2.4 | 1.7 | Apr 16, 2016 2:53:14 PM |
| 14 | 188 | 14:53:51 | 14:53:15 | 169 | -96.438610 | 30.632946 | 11.700 | 47.1 | 1.3 | 0.7 | Apr 16, 2016 2:53:15 PM |
| 15 | | | | 170 | -96.438624 | 30.632949 | 11.800 | 65.8 | -3.9 | 0.1 | Apr 16, 2016 2:53:16 PM |
| 16 | 189 | 14:53:53 | 14:53:17 | 171 | -96.438634 | 30.632956 | 11.920 | 87.8 | -4.1 | -1.3 | Apr 16, 2016 2:53:17 PM |
| 17 | | | | 172 | -96.438639 | 30.632969 | 11.990 | 110.2 | -6.8 | 1.1 | Apr 16, 2016 2:53:18 PM |
| 18 | 190 | 14:53:55 | 14:53:19 | 173 | -96.438638 | 30.632978 | 12.190 | 111.1 | -2.8 | 1.8 | Apr 16, 2016 2:53:19 PM |

**Table 54 Continued**

| N. | Photo index FHD0 | Camera hour | Mobile hour | Ind. | Long. (DD) | Lat. (DD) | Alt. (m) | Yaw angle (Deg) | Pitch angle (Deg) | Roll angle (Deg) | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 | | | | 174 | -96.438638 | 30.632981 | 12.480 | 110.5 | -0.8 | -0.6 | Apr 16, 2016 2:53:20 PM |

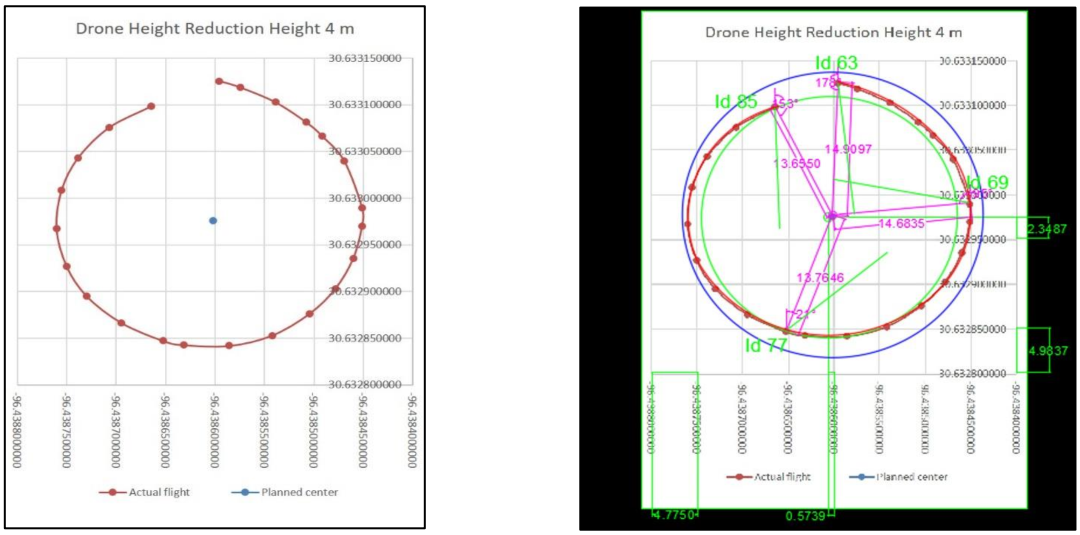



**Figure 239 Planned and actual path at a height of 4 m in Test 2 - app 2, evaluation 2**

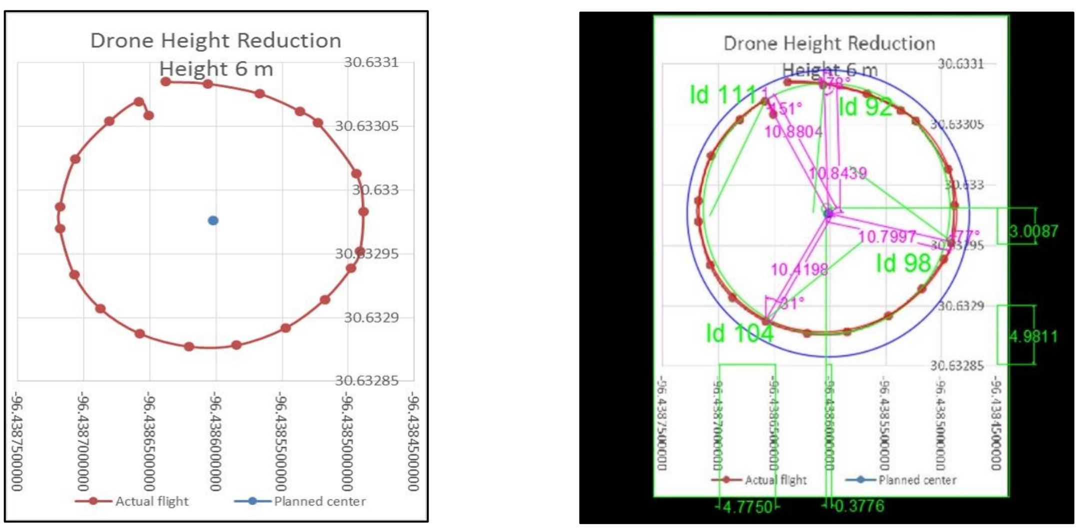



**Figure 240 Planned and actual path at a height of 6 m in Test 2 - app 2, evaluation 2**

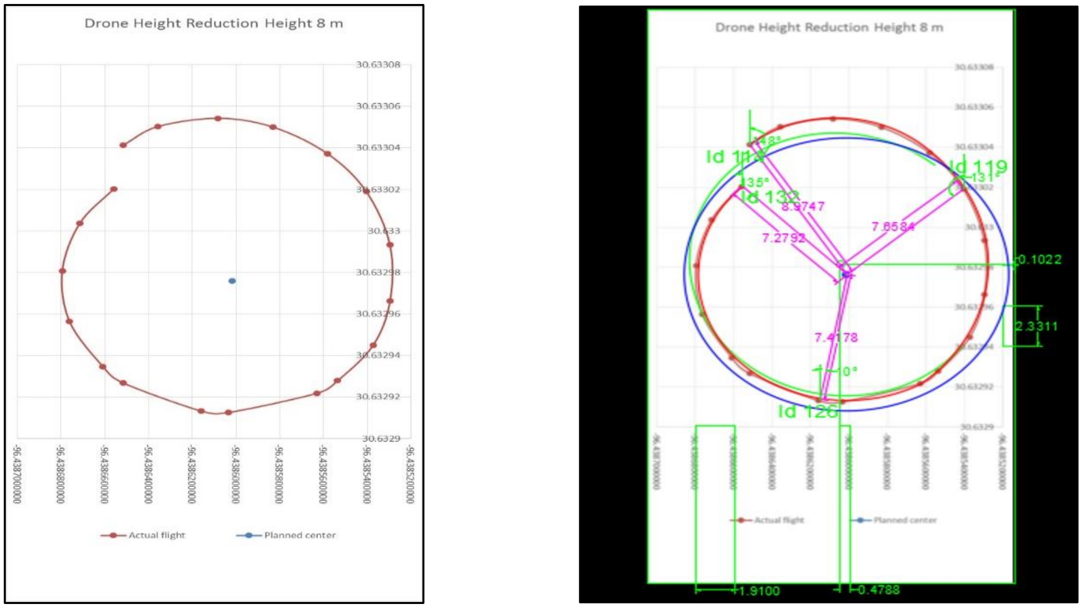



**Figure 241 Planned and actual path at a height of 8 m in Test 2 - app 2, evaluation 2**

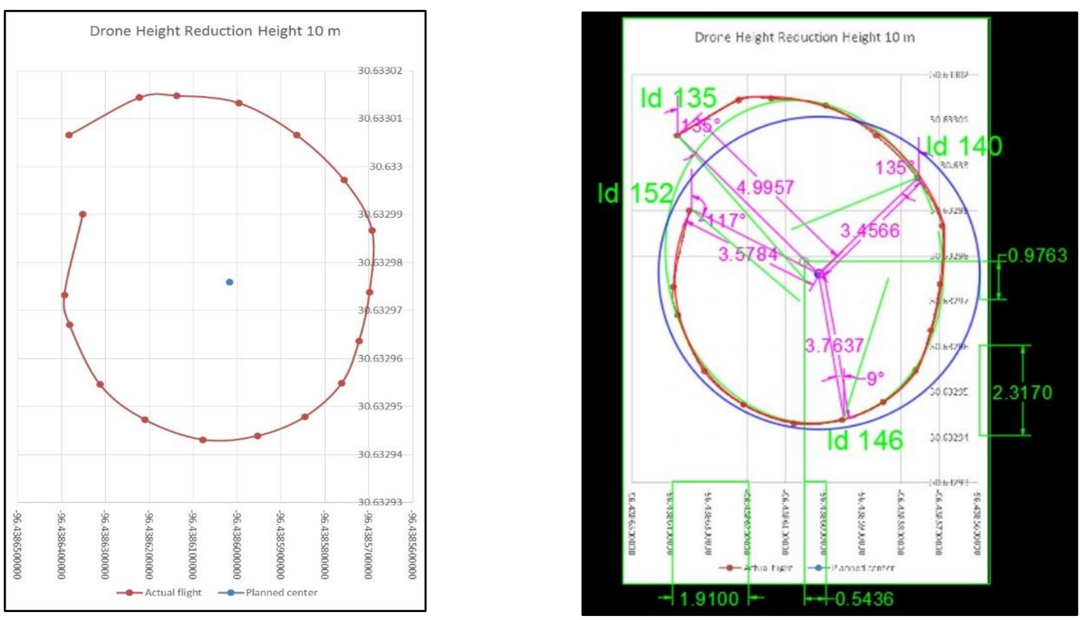



**Figure 242 Planned and actual path at a height of 10 m in Test 2 - app 2, evaluation 2**

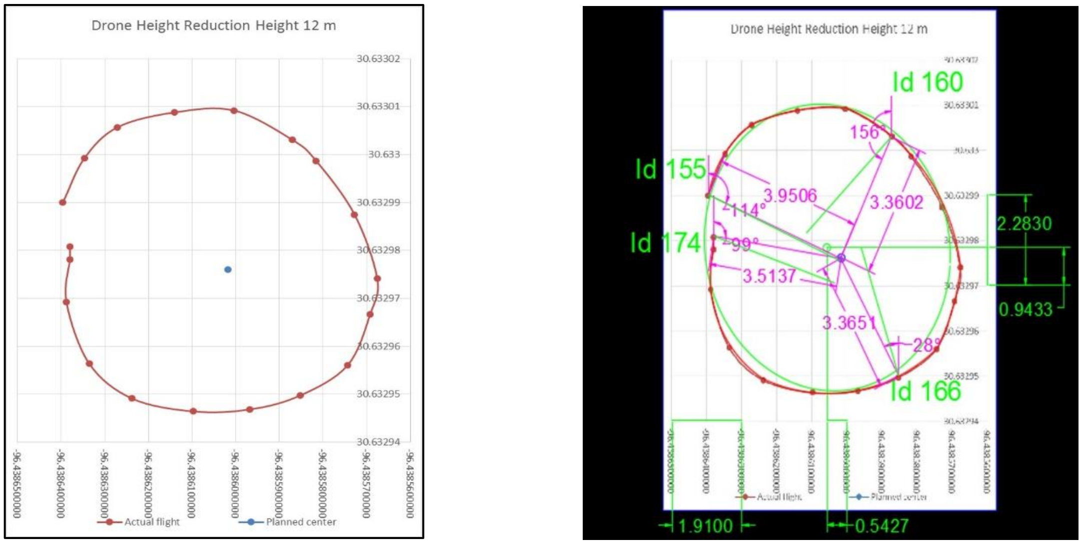



Figure 243 Planned and actual path at a height of 12 m in Test 2 - app 2, evaluation 2

## *D.2. Data evaluation 3*


**Figure 244 Photo FHD0128 at a height of 2 m with measurements**

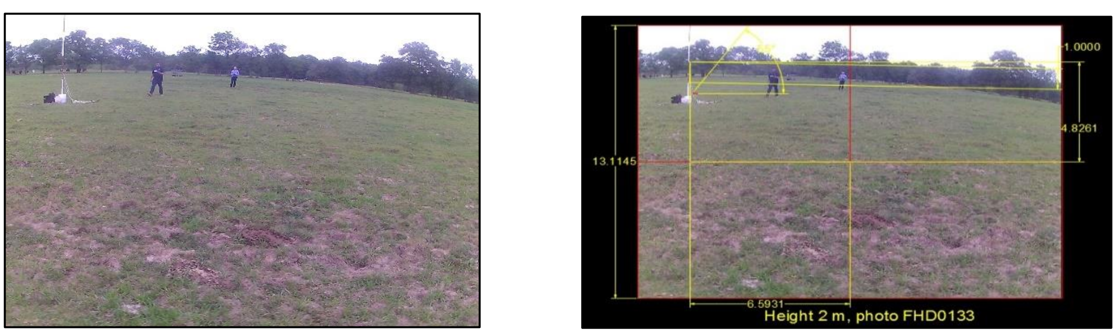



**Figure 245 Photo FHD0133 at a height of 2 m with measurements**

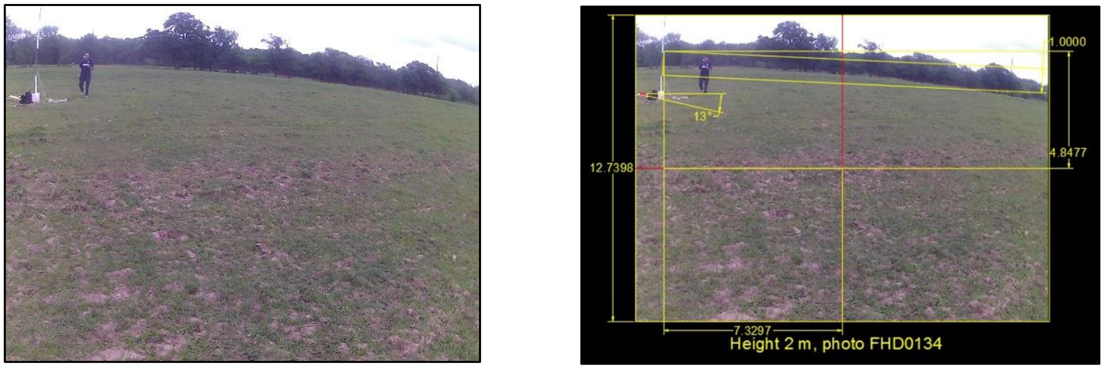



**Figure 246 Photo FHD0134 at a height of 2 m with measurements**

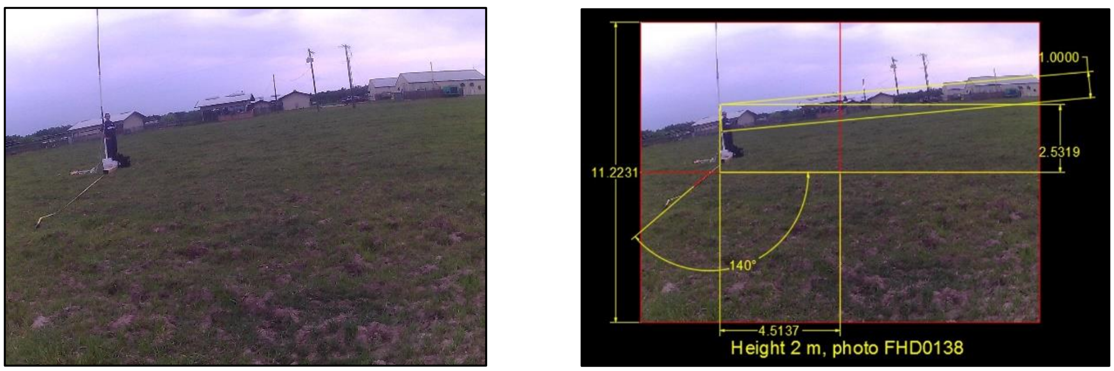



**Figure 247 Photo FHD0138 at a height of 2 m with measurements**


**Figure 248 Photo FHD0140 at a height of 4 m with measurements**


**Figure 249 Photo FHD0142 at a height of 4 m with measurements**

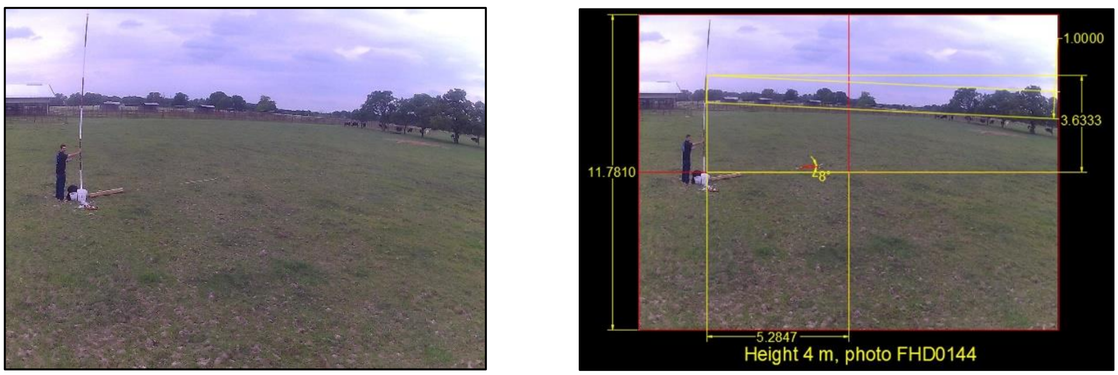



**Figure 250 Photo FHD0144 at a height of 4 m with measurements**

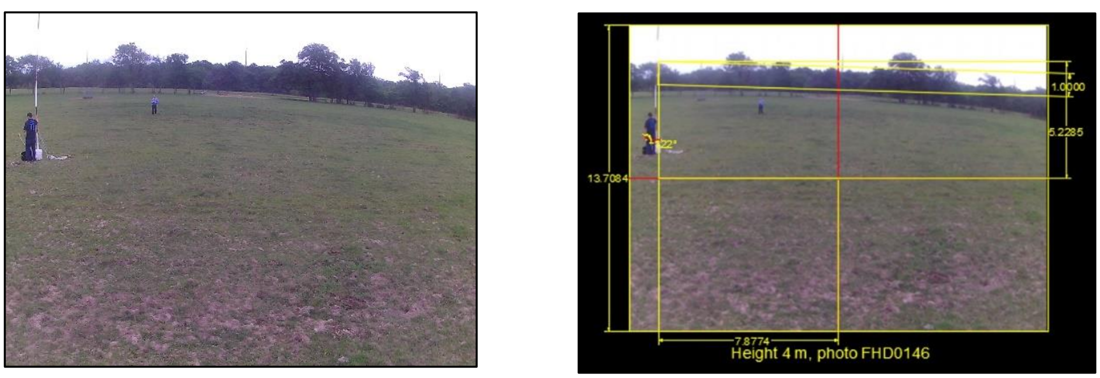



**Figure 251 Photo FHD0146 at a height of 4 m with measurements**

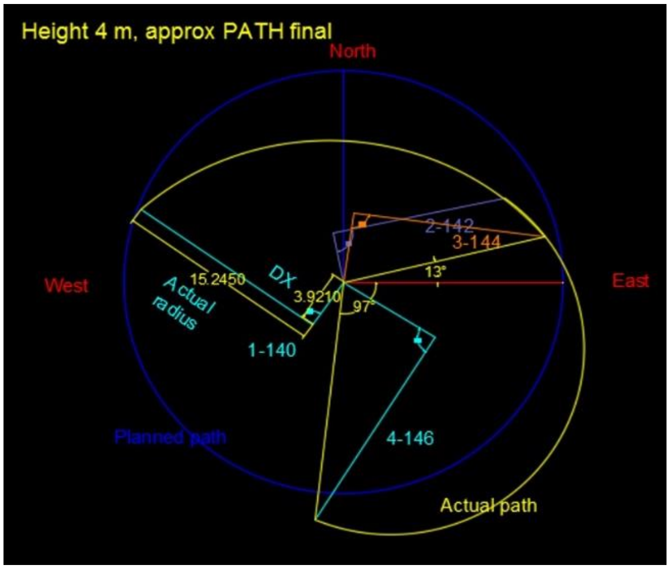



**Figure 252 Planned and actual path at a height of 4 m in Test 2 - app 2, evaluation 3**

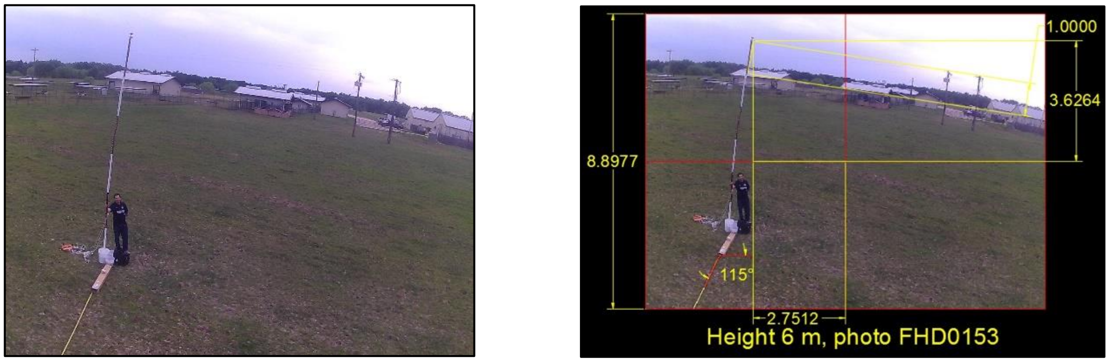



**Figure 253 Photo FHD0153 at a height of 6 m with measurements**


**Figure 254 Photo FHD0155 at a height of 6 m with measurements**

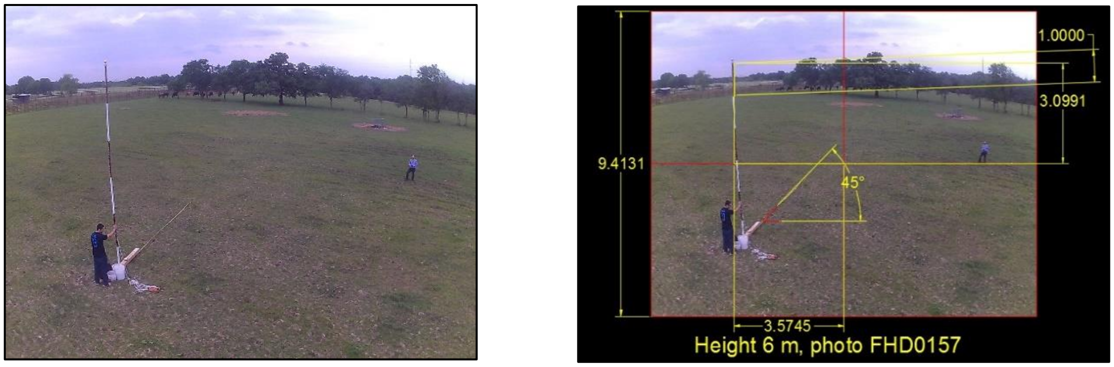



**Figure 255 Photo FHD0157 at a height of 6 m with measurements**


**Figure 256 Photo FHD0159 at a height of 6 m with measurements**

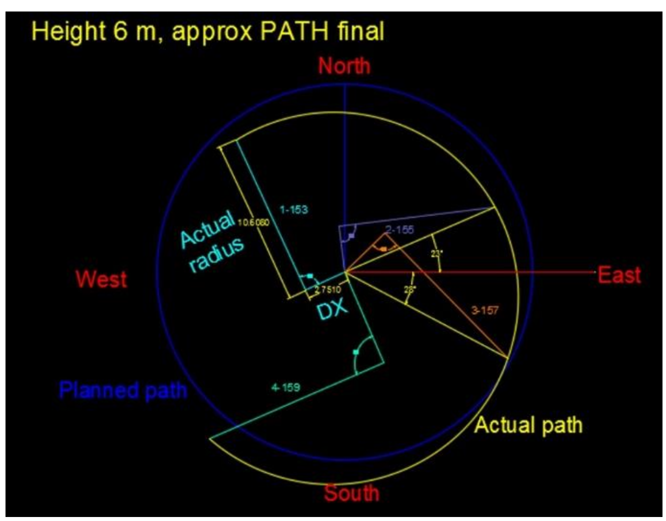



**Figure 257 Planned and actual path at a height of 6 m in Test 2 - app2, evaluation 3**

APPENDIX E

*VITA*

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