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**UAWOS - Unmanned
Airborne Water
Observing System**

Deliverable 3.1:
WSE Surveying Protocol

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3. Overview and Summary

This document summarizes the contactless airborne water surface elevation (WSE) surveying workflow developed in UAWOS. The document constitutes deliverable D3.1 of the Horizon Europe project “UAWOS – Unmanned Airborne Water Observing System”, contract number 101081783.

As demonstrated in [1], drone-borne radar altimetry is the most effective technique to measure WSE in rivers and streams at high spatial resolution and coverage and high accuracy. UAWOS D2.1 describes a new radar altimetry drone payload based on the Geolux LX80 instrument. This document presents an overview of the surveying workflow using the UAWOS radar altimetry payload or any similar radar altimeter on board an airborne platform. The purpose of the document is to describe hardware components required for the survey, pre-survey planning procedures, field operations and post-survey data processing steps.

Moreover, the document provides an overview of typical survey productivity, expected accuracy, and spatial coverage that can be achieved in UAS radar altimetry surveys.

4. Purpose of WSE surveying

Measuring water surface elevation is crucial for various environmental and engineering purposes. It plays a vital role in flood management, irrigation planning, hydroelectric power generation, and maintaining aquatic ecosystems. Accurate measurement of water levels helps in predicting flood risks, ensuring efficient water resource management, and safeguarding communities and ecosystems dependent on water bodies. WSE profiles along rivers are powerful calibration-validation datasets for hydraulic river models used in flood risk assessment and operational flood forecasting.

Previous studies have demonstrated the value of UAS radar altimetry datasets to establish hydraulic gradients in remote and poorly monitored areas [2], to map conveyance changes along rivers [3], to estimate river discharge [4] and to constrain spatial variation of river hydraulic properties using hydraulic inverse modeling [5].

Utilizing Unmanned Aerial Vehicles (UAVs) for Water Surface Elevation (WSE) surveys greatly enhances efficiency and cost-effectiveness. UAVs can rapidly cover large areas, significantly reducing the survey time, which is particularly beneficial in environments where water levels frequently change. UAVs provide a more economical alternative to manned aircraft surveys, thanks to reduced operational and logistical expenses and fewer personnel required on site. Their ability to access remote or challenging areas allows for the collection of critical WSE data that might be unobtainable through conventional methods. Additionally, employing UAVs minimizes the risk to survey personnel, especially in hazardous or hard-to-reach zones. Overall, the use of UAV technology in WSE surveys leads to more accurate, time-efficient, and cost-effective results, enhancing resource management and decision-making processes in water-related projects.

Figure 1 provides an overview of the WSE surveying setup and the different hardware components. The centerpiece is the drone carrying both a radar altimeter and a GNSS receiver. In areas with good GNSS coverage, the drone can be directly linked up to an RTK network provider. In areas with non-optimal GNSS coverage, we use a local base station providing RTK corrections to the drone via Starlink.

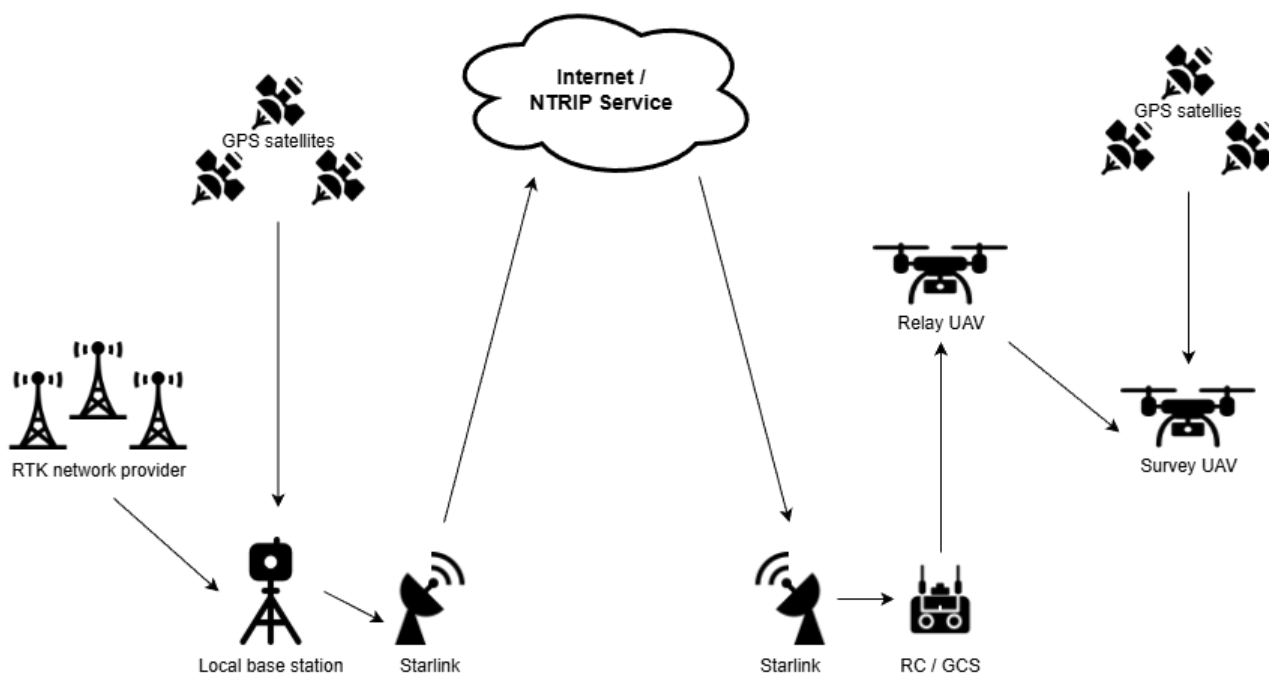


Figure 1 - Overview of WSE surveying setup

5. Surveying specifications

5.1. Radar altimetry – WSE

5.1.1. Accuracy

The WSE surveying workflow provides water surface elevation data at <1m spatial resolution along the river centerline with an accuracy of **3cm or better**. Such performance has been demonstrated in previous surveys and published in the peer-reviewed literature [1]. Elevation data are referenced to the WGS84 ellipsoid a priori and can be re-referenced to any chosen local geoid model.

5.1.2. Productivity & Scale (VLOS)

The productivity which can be expected is highly dependent on the survey area's characteristics and the degree of planning performed prior to the survey. Challenging accessibility to takeoff locations and restrictive visual line of sight to the UAV are the two primary factors that can hamper a high productivity. Based on practical experience from a variety of rivers a productivity of **1.5-4.5 km/hour** can be expected.

5.1.3. Productivity & Scale (BVLOS)

Productivity of BVLOS surveys has not yet been evaluated in the field. This is planned for 2026. We will be able to provide robust estimates by end-2026. We expect a productivity increase of at least factor 2, depending on survey area characteristics.

5.1.4. Flight parameters

The flight parameters are variable depending on the specific equipment. In general, the following flight parameters are recommended:

Altitude: 10-45m, depending on payload

Velocity: Max. 5 m/s

Terrain-follow: True (DEM based)

Coverage: Two passes

6. Requirements

6.1. Legal / legislation

This document aligns with [EASA REGULATION \(EU\) 2019/947](#). For non-EU countries, operators must consult local regulations for UAV operations.

Under EASA REGULATION (EU) 2019/947, the 'open' category allows the use of UAVs with a maximum take-off weight (MTOW) of up to 25kg for operators with an A3 license. This category, while facilitating a range of operations, imposes several safety and compliance constraints, such as:

- Visual Line of Sight (VLOS) Operations: The UAV must be operated within the visual line of sight of either the remote pilot or a designated observer in direct communication with the pilot.
- Restrictions on Flying Over Uninvolved People: To ensure public safety, UAVs in the open category are prohibited from flying over people who are not part of the operation.
- Local Restrictions: Operators must adhere to specific national regulations within EU member states. These can include safety distances from sensitive areas like airports, military installations, and embassies.

Under EASA REGULATION (EU) 2019/947, the 'specific' category is tailored for UAV operations with higher risks, necessitating in-depth risk assessments and stringent safety protocols. This category facilitates complex operations like Beyond Visual Line of Sight (BVLOS) flights.

One regulatory pathway for such operations is the [Pre-Defined Risk Assessment PDRA-G03](#) established by EASA. PDRA-G03 enables BVLOS operations under predefined operational and technical conditions, typically in sparsely populated environments.

The PDRA-G03 framework defines the general operational boundaries and safety requirements for BVLOS missions. These include operation in areas with low ground risk, the use of reliable command and control links between the ground control station and the UAV, clearly defined operational volumes and contingency procedures, and appropriate measures to ensure separation from other airspace users.

Compared to custom operational approvals based on a full SORA assessment, PDRA scenarios provide a standardized regulatory framework that simplifies the authorization process, since the overall risk model and operational assumptions are predefined.

For BVLOS river surveying operations within the UAWOS project, the PDRA-G03 scenario represents a suitable regulatory framework.

This WSE Surveying Protocol describes VLOS UAV operation in the 'open' category and BVLOS UAV operation in the 'specific' category under PDRA-G03.

6.2. Equipment

This WSE Surveying Protocol outlines generic equipment requirements, complemented by specific equipment recommendations. The protocol's descriptions and guidelines are based on these recommendations.

6.2.1. UAV Multirotors

Any RTK-enabled multirotor UAV with sufficient payload capacity for the chosen sensors is appropriate for VLOS operation. The WSE surveying protocol recommends the DJI M300 RTK as a reference for VLOS operation due to its compatibility with UAWOS payload requirements. The M300 RTK provides reasonable flight time and is compatible with UgCS and the Skyhub payload interface, making it a suitable choice for the protocol's applications.

For BVLOS operation it is recommended to utilize two UAV platforms: a Survey UAV responsible for data acquisition and a Relay UAV supporting command and control link extension and situational awareness. As Survey UAV it is recommended to utilize a UAV platform based on an Ardupilot/Pixhawk open architecture, allowing integration of a relay communication system, firmware-level control, configurable failsafe procedures and integration of custom FPV and collision avoidance solutions. For BVLOS operation the WSE surveying protocol recommends the Dronevolt Kobra as Survey UAV and the DJI M300 RTK as Relay UAV. The Kobra survey UAV provides long flight time and operational characteristics comparable to the DJI M300 RTK.

The DJI M300 RTK Relay UAV is recommended to be equipped with a DJI Zenmuse H20 payload. The H20 provides up to 23x hybrid zoom capability and stabilized visual observation of the operational area, which is useful for maintaining situational awareness around the Survey UAV. The payload also supports smart tracking functions, allowing operators to lock onto and continuously follow moving or stationary objects of interest, improving monitoring of the Survey UAV and surrounding airspace.



Figure 2 - DJI M300 RTK without payload



Figure 3 - Dronevolt Kobra

6.2.2. Relay system

The relay system facilitates transmission of command-and-control link, telemetry, payload data, and video feeds between the ground control station and the survey UAV.

This enables operations in areas where direct radio line-of-sight cannot be maintained by relaying the communication link through the Relay UAV thus providing reliable connectivity over longer distances and in terrain where direct communication would otherwise be obstructed.

This Flow Velocimetry Surveying Protocol recommends using the following relay system equipment:

Doodle Labs radios:

- 2 × RM-1700-22M3 mini dual-band radios, installed on the UAV platforms.
- 1 × RM-1700-22W3 dual-band wearable radio, used at the ground control station (GCS).

Different antenna polarizations are used to separate the two communication links. The relay-to-survey link operates with RHCP antennas, while the GCS-to-relay link operates with LHCP antennas. This configuration reduces interference between the two simultaneous radio links and improves overall link stability when the Relay UAV maintains both connections. The following antenna setup is recommended.

GCS:

- 2 × X-Air 2.4 GHz LHCP directional antennas

Relay UAV:

- 1 × Singularity 2.4 GHz LHCP omnidirectional antenna
- 1 × X-Air 2.4 GHz RHCP directional antenna

Survey UAV:

- 2 × Singularity 2.4 GHz RHCP omnidirectional antennas

6.2.3. Gimbal

Stabilizing the WSE sensor on a high-quality brushless 2- or 3-axis gimbal is crucial for precision. Gimbals with encoders and heated or temperature calibrated IMUs are preferred for their accuracy. For instance, a 2-degree deviation on pitch or roll axis at an altitude of 40 meters introduces a ~2.5 cm error in measured water surface elevation. Yaw stabilization is not necessary since the gimbal maintains the payload perpendicular to the water surface. The yaw motor in a 3-axis gimbal adds extra weight without benefiting this specific application. The [Gremsy T3V3](#) is the recommended choice for its overall effectiveness and reliability in various scenarios.

- Key features:
- Mapping mode
- Temperature Sensor
- Gremsy Specialized Gimbal Drive Motors with Encoders
- Gremsy Advanced 32-Bit high performance ARM microprocessor
- S-Bus/Spektrum/PPM Receiver Supported



Figure 4 - Gremsy T3V3

6.2.4.WSE Payload

Any radar altimeter sensor which fulfills the following requirements can be utilized:

- Minimum range 20m
- Full waveform data output, enabling retrieval of water heights below vegetation
- High data acquisition rate (2 Hz or higher), to obtain high spatial resolution along the flight path

This WSE surveying protocol recommends using SkyHub as payload controller in conjunction with Geolux LX-80 (described in UAWOS D2.1) as WSE sensor.

SkyHub

SkyHub is an onboard computer and payload interface, which is compatible with all sensors deployed in the UAWOS project. SkyHub facilitates sensor configuration, control and storage of georeferenced raw data from supported sensors. Configuration can be performed using a GUI or command prompt on both Windows PCs and Macs.



Figure 5 - SkyHub payload interface

Geolux LX-80

- Contactless water level measurement
- The narrowest beam measurement angle on the market (2.5°)
- RS-232, RS-485 Modbus, SDI-12, analog 4-20 mA interfaces in all models
- Remote configuration of all instrument parameters through any digital communication interface

- Robust small size IP68 aluminum or stainless steel enclosure
- Please refer to UAWOS D2.1 for details



Figure 6 - Geolux LX-80

6.2.5. VLOS GCS

Any ground control station software that is designed for planning and executing UAV flights can be utilized. It is highly recommended to use a solution with the following features:

- Terrain follow capability (DEM based)
- Import custom layers / background maps
- Import overlay layers, ex. as kml
- Compatible with PC/MAC for detailed route planning (not practically feasible on tablet / app)

This WSE surveying protocol recommends [UgCS](#) as GCS. UgCS is designed for planning and executing UAV flight missions. It supports a wide range of drones, offering intuitive tools for route planning, including terrain-following flights. UgCS offers functionality for importing custom layers, maps, and KML files, enhancing its utility for detailed mission planning. These features allow users to overlay custom geographical data onto the base map, facilitating precise and informed route planning. UgCS is fully compatible with the recommended payload equipment (SkyHub and Geolux LX-80).

6.2.6. BVLOS GCS

The BVLOS GCS extends the VLOS GCS with additional displays/outputs required during BVLOS operations.

The setup includes four displays:

- UgCS and CPM for route execution, telemetry, TTF output, and payload data
- Survey UAV FPV feed for low-altitude monitoring
- Relay UAV (Zenmuse H20) feed for cross section overview and situational awareness
- Doodle Labs interface for link quality, latency, and bandwidth monitoring

The Doodle Labs GCS radio unit is mounted on a telescopic mast with directional antennas aligned towards the relay UAV.

Supporting Infrastructure

- Two laptops run GCS software, video feeds, and link monitoring, connected to the displays.
- A wired network (RJ45) connects laptops and the Doodle Labs unit via a switch, with Starlink providing internet access and NTRIP corrections for RTK.
- Power is supplied by a portable generator, including battery charging for survey and relay UAVs.

6.2.7. Rover GNSS

Any multi-band, RTK/PPK enabled rover GNSS with an update frequency of at least 5 Hz and RINEX output capability can be utilized.

This WSE surveying protocol recommends the [Emlid Reach M2](#) as rover GNSS. The Emlid Reach M2 is fully compatible with the recommended payload equipment (SkyHub and Geolux LX-80).



Figure 7 - Emlid Reach M2

6.2.8. Local Base Station

Any professional grade, multi-band base station that allows connecting to a local RTK network and with NTRIP casting capabilities can be utilized.

This WSE surveying protocol recommends the [Emlid RS3](#) as local base station.



Figure 8 - Emlid RS3

6.2.9. Mobile Broadband Modem

Any mobile broadband modem and ISP that provides reliable connectivity in the area of interest can be utilized. The recommended setup is RTK based on NTRIP corrections between the base station and rover GNSS, which requires two mobile broadband modems, one at the base station, and one at the GCS.

Often WSE surveys are to be performed in remote locations and/or at locations which do not have reliable mobile broadband connectivity from common ISPs.

Therefore, this WSE surveying protocol recommends utilizing Starlink as mobile broadband ISP. Starlink is the most reliable solution for providing low latency internet connectivity in remote areas across multiple countries with speeds between 25-220 Mbps.

See <https://www.starlink.com/map> for availability.



Figure 9 - Starlink receiver and router

7. Desktop Reconnaissance

The purpose of desktop reconnaissance is:

- Decide if onsite reconnaissance is required
- Decide upon VLOS operation in the Open Category vs. BVLOS operation in the Specific Category using PDRA-G03
- Decide upon equipment setup

BVLOS operations under PDRA-G03 are conducted within controlled conditions to manage ground and air risk and ensure safe separation from people and other airspace users. During desktop reconnaissance the main points that must be fulfilled are:

- Environment: Controlled or sparsely populated areas only, no flights over assemblies of people
- Operational volume: Clearly defined flight area with ground risk buffer and contingency zones
- Airspace: Strategic deconfliction required (segregation, coordination, or NOTAM)

In general, onsite reconnaissance is always recommended prior to survey. It is especially recommended if either:

- Takeoff locations for UAV flight covering the area of interest cannot be reliably identified, or
- Accessibility to the takeoff locations cannot be clearly identified, or
- Elements/obstacles that may constitute a hazard for flights cannot be identified/defined with high confidence

The purpose of a pre-survey is to attain a precise up to date reference of the river path. This can be achieved by creating a GCP georeferenced orthomosaic or LiDAR point cloud of the area. The orthomosaic/point cloud can thereafter be used as a basis for planning the WSE survey flight routes. Performing a pre-survey may be relevant if either:

- The river pathing is dynamic/readily changing, or
- The river to be surveyed is narrow (<5 m), or
- No precise digital reference of the river path available (centerline or satellite imagery)

Often WSE surveys are to be performed in remote locations and/or at locations which do not have an optimal line-of-sight to satellites. Therefore, GNSS and mobile broadband reception can be unreliable. It is recommended to research these conditions as best possible as part of the desktop reconnaissance.

If mobile broadband reception is expected to be unreliable from a specific ISP, examine alternative ISP's. If no ISP's are expected to provide reliable reception it is recommended to employ Starlink as the mobile broadband ISP.

It is important that the GNSS base station is placed in a location with optimal GNSS reception and preferably within 10 km of the survey area.

8. Planning

During the planning phase the flight routes are created. Any appropriate software solution for this purpose can be utilized. Often meticulous planning is required due to site characteristics combined with a relatively low flight altitude.

If no digital centerline of the river is available, then the first task is to create the centerline. The basis for defining the centerline can be existing satellite imagery if the accuracy is higher than half the river width with a comfortable margin. The preferred basis for defining the centerline is the pre-survey product (Orthomosaic, point cloud or a product derived thereof).

Import/add the centerline to the GCS. Plot the desired flight route such that the UAV flies along the river stretch. The river shall as a minimum be covered with two passes. The recommended approach is to plan the outbound pass on one side of the centerline and the inbound pass on the other side of the centerline.

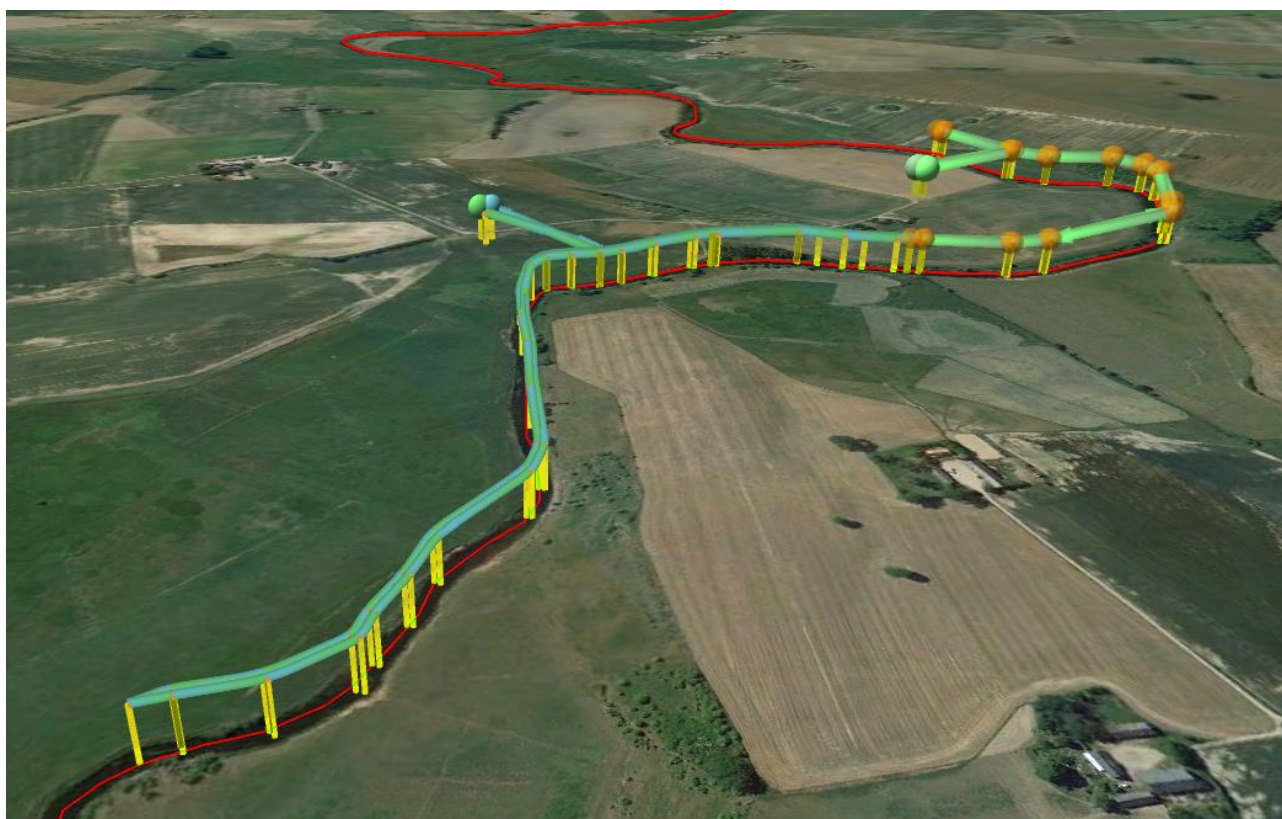


Figure 10 - Flight routes example

8.1.1.Centerline offset

If the river is narrow, it is especially important to pay attention to the distance offset from the centerline to the flightpath. The primary goal is to ensure that the payload continuously is directly above the water surface. As a starting point, this WSE surveying protocol recommends a centerline offset of 2m.

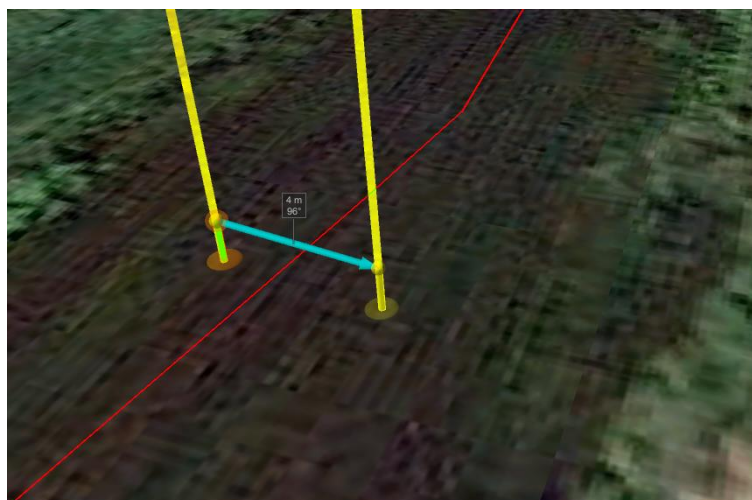


Figure 11 - 2m offset from centerline in a narrow river

8.1.2.Overlap between flight routes

This WSE surveying protocol recommends that the flight routes are planned such that flight routes overlap with at least 10m.



Figure 12 - 15m overlap between flight routes

8.1.3.Sharp river bends

When planning flight routes at sharp river bends, it is important to consider UAV flight characteristics which can cause the actual flight path to deviate slightly from the planned flight path. The amount of deviation depends on several variables, such as the UAV model, GCS type, waypoint type and flight speed.

The impact of this deviation is often negligible at wide rivers but can cause missing coverage at narrow rivers. Therefore, it is especially important to compensate for these deviations by offsetting the planned flight path at sharp bends when surveying narrow rivers.

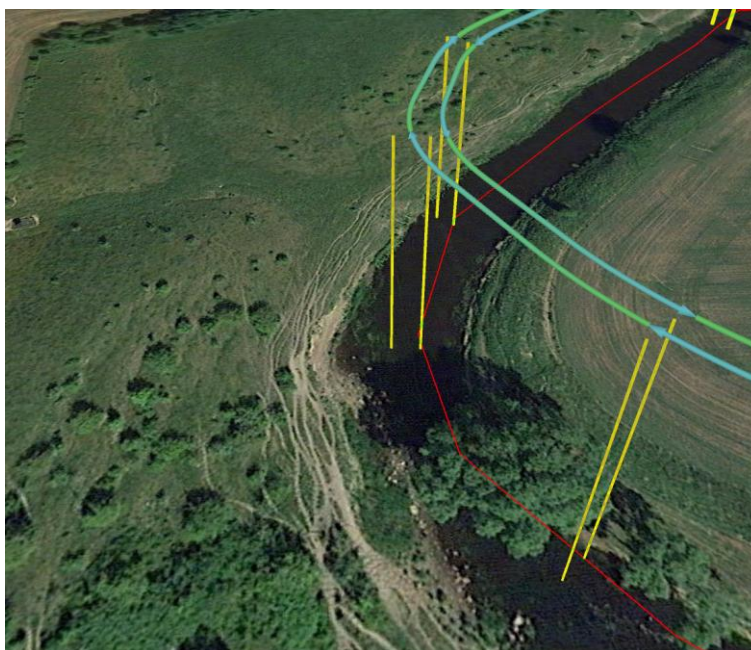


Figure 13 - Offsetting WP in sharp turns

9. VLOS Flight Execution

9.1. VLOS WSE Flights

WSE flights should be conducted according to common best practices. There are no special considerations regarding WSE flights. In mountainous regions it is recommended to pay enhanced attention to VLOS conditions due to steep elevation changes.

Steps for WSE flights:

- Load prepared route in the GCS software
- Decide upon AGL or AMSL flight altitude depending on area characteristics and/or available GCS software reference/capability
- Execute the automated flight

Ensure that the UAV has RTK fix during data collection.

During flight it is recommended to verify that the WSE payload outputs valid/expected values.

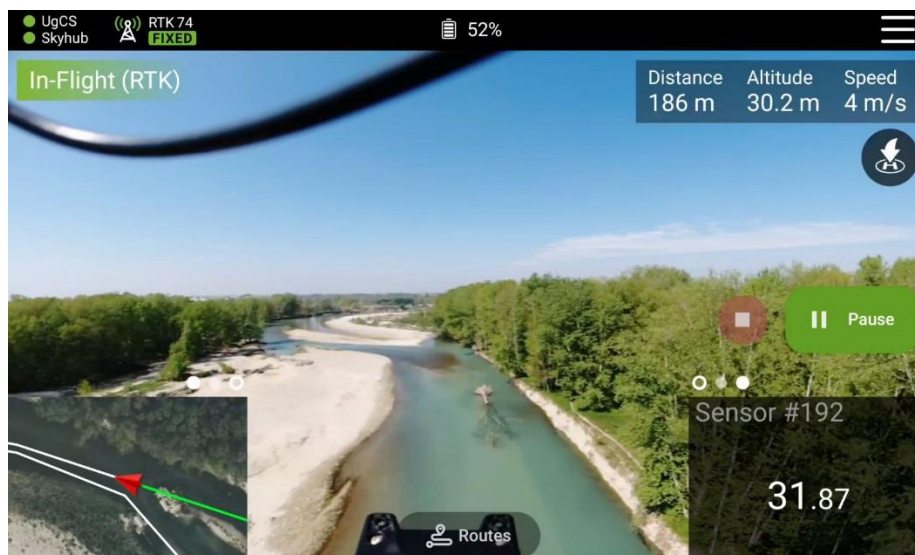


Figure 14 - WSE payload output during flight (lower right corner)

10. BVLOS Flight Execution

10.1. Relay System Setup

Antennas are connected to the Doodle Labs radio units as specified in Section 6.2.2

The following actions must be performed on all Doodle Labs radio units:

- Power on and connect to radio unit using wifi
- Go to simple setup menu
- Choose profile “UAV/UGV/Robot”
- Set “Active frequency band” to 2.4 GHz
- Activate “Optimize for latency”

The following actions must be performed on the mini dual-band radio for the Survey UAV:

- Connect the mini dual-band radio serial port to Survey UAV UART/Telemetry port
- In the setup menu, navigate to: Utilities → GCS Finder
- Enable GCS Finder

The following actions must be performed on the dual-band wearable radio for the GCS:

- Connect to GCS laptop running UgCS via ethernet
- Specify required static IP address on GCS laptop running UgCS

When the Relay System is set up correctly the Survey UAV will be present in UgCS.

10.2. Ground Control Station

As described in Section 6.2.6, the BVLOS GCS includes four monitors showing telemetry and feeds essential for the operation.

- **Display 1:**

This display shows the Survey UAV FPV feed transmitted via the Doodle Labs relay system as a UDP stream. GStreamer or a similar software solution can be utilized. In combination with UgCS, it provides the Survey UAV Operator with the primary visual reference for the Survey UAV during the mission

- **Display 2:**

UgCS is used as the primary GCS software and shows the position and orientation of both the Survey UAV and the Relay UAV. The Custom Payload Monitor (CPM) is also displayed on this screen. CPM supports managing payloads, viewing live payload data and managing the Skyhub payload controller.

- **Display 3:**

This display is used to monitor link stability and link quality for the Doodle Labs relay setup. It also shows RTK Client, which shows the RTK connection quality of the Survey UAV, and facilitates connectivity to NTRIP service and injecting the RTK data into the mavlink stream, enabling RTK fix on the survey drone. RTK Client must be set up according to guidelines from SPH.

- **Display 4:**

This display shows the output from the Relay UAV H20 camera. It is used for overview and situational awareness.

10.3. Crew

For BVLOS operations, a minimum crew of two licensed and PDRA-G03-trained operators are required. In A three-person crew setup is recommended especially if the operators are not significantly experienced and confident regarding workflows, equipment, and BVLOS operator coordination.

- **Operator 1: Survey UAV**

Operator 1 is responsible for operation of the Survey UAV, including payload setup and payload operation. Operator 1 is responsible for keeping the Survey UAV operation within mission parameters. Displays 1 and 2 are the primary sources of information for Operator 1.

- **Operator 2: Relay UAV / GCS Support**

Operator 2 is responsible for operation of the Relay UAV. Operator 2 is responsible for maintaining the Survey UAV in the Relay UAV H20 feed and for maintaining Relay UAV position and orientation relative to the Survey UAV, as this is critical for maintaining relay signal strength and link quality. Displays 3 and 4 are the primary source of information for Operator 2.

Both operators shall communicate vocally during the operation and call out all commands and mission-critical information. The operators shall maintain clear task separation, but both shall maintain sufficient situational awareness to call out an abort of the operation.

10.4. BVLOS WSE Flights

Steps for BVLOS WSE flights, which shall be considered in conjunction with the steps from Section 9.1:

1. Verify that all systems are operational, including Survey UAV, Relay UAV, Relay System, GCS, and payload configuration.
2. Load prepared route in the Survey UAV GCS software.
3. Take off with the Relay UAV and position it at an appropriate altitude and location to maintain line-of-sight and stable C2 link between the GCS and the Survey UAV. Ensure directional antennas are aligned and that Relay UAV H20 feed provides visual coverage of the survey area. Optionally engage the H20 tracking capability on the Survey UAV.
4. Take off with the Survey UAV and execute the prepared route.
5. During flight execution, continuously monitor payload output, Survey UAV FPV feed, Relay UAV feed, and link performance. Manual abort shall be initiated if link quality degrades, payload data becomes unreliable, or obstacle clearance cannot be confirmed.

Ensure that the Survey UAV has RTK fix during data collection.

Perform verification of WSE data as described in Section 9.1. If required, adjust flight parameters or repeat the flight.

10.5. Failsafes

For BVLOS WSE Flights the Survey UAV must support standard RTH failsafe procedures.

Upon C2 link loss, the Survey UAV shall initiate RTH.

Upon GPS link loss, the Survey UAV shall initiate hover state. This enables the Survey UAV Operator to engage manual control or another appropriate recovery procedure.

11. Post-survey data processing steps

Prior to initiating data processing, gather the following files/information:

- Raw radar data
- River centerline
- Radar antenna specifications
- Offset distance between rover GNSS antenna reference point and radar antenna reference point

If the survey was not completed with RTK georeferenced radar data, then the following files are required in addition, for PPK processing:

- Base station GNSS rinex data for the full survey duration
- Rover GNSS rinex data for the full survey duration

If PPK is employed and the base station was not connected to a local GNSS network service provider:

- Acquire GNSS rinex data and antenna specifications for the nearest antenna from the local GNSS network service provider
 - Alternatively, download orbit and clock data from NASA CDDIS, typically available within one week
- Compute the precise position of the base station using the GNSS observations from the local GNSS network service provider, or alternatively using the orbit and clock data from NASA CDDIS

If PPK is employed, perform PPK processing:

- Compute precise rover positions using the precise base station position

The raw radar data processing consists of the following steps:

- Parse the raw radar data and locate the largest peak (highest return power) for each radar measurement
- Using the radar antenna specification, compute the distance to the largest peak of each measurement
- If PPK is employed, correlate GNSS timing with radar timestamps and interpolate the GNSS position for each measurement
- Deduct the peak distance and radar antenna to rover GNSS antenna offset from the position altitude to get the water level value

The water level values are processed using the following steps:

- Relate each measurement to the local vertical reference (e.g. DVR90, EPSG:5799 for Denmark)
- Filter all measurements according to return power, distance to centerline and altitude deviation
- Define an appropriate moving window along the centerline, with 10-20cm incremental steps. For low gradient rivers a moving window size of 50-100m is often suitable.
- For each window, outliers are filtered out and the mean, median and confidence interval is computed

The resulting datasets are saved as CSV files.

12. Output data formats and example output

```

1 Folder: Entry, PacketID, TS, Com, Lat, Alt, SDR, MaxIndex, MaxPower, CompIndex, CompPower, RadarClass, ML, Decid, ProjName, X, ProjDecid, Y, ML, Decid, StageClass, StageIndex, StageChain, MaxIndex, MediaIndex, MediaIndex, DstIndex, MeanConfFlow, MeanConfFlgH, MeanConfFlow, MeanConfFlgH
2 *800,20231123_165559,1,2136,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
3 *801,20231123_165559,1,2139,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
4 *802,20231123_165559,1,2137,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
5 *803,20231123_165559,1,2134,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
6 *804,20231123_165559,1,2132,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0157,381,75,2874891995953,101,261904761045,75,1202151004354,35,5562377939869,39,84620362929876,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
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9 *807,20231123_165559,1,2129,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
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11 *809,20231123_165559,1,2127,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
12 *810,20231123_165559,1,2126,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
13 *811,20231123_165559,1,2125,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
14 *812,20231123_165559,1,2124,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
15 *813,20231123_165559,1,2123,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
16 *814,20231123_165559,1,2122,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
17 *815,20231123_165559,1,2121,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
18 *816,20231123_165559,1,2120,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
19 *817,20231123_165559,1,2119,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
20 *818,20231123_165559,1,2118,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1
21 *819,20231123_165559,1,2117,16,9895335666667,9,6325161726211,56,1797819244868,98,7128055276765,0,0156,382,74,821228411322,561,890761904761,75,23973072251065,35,85249880776876,59,657285677361,-39,9361,539267,216762134,6226270,317090618,19,7178677913894,1

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Figure 15 - Example output, CSV format

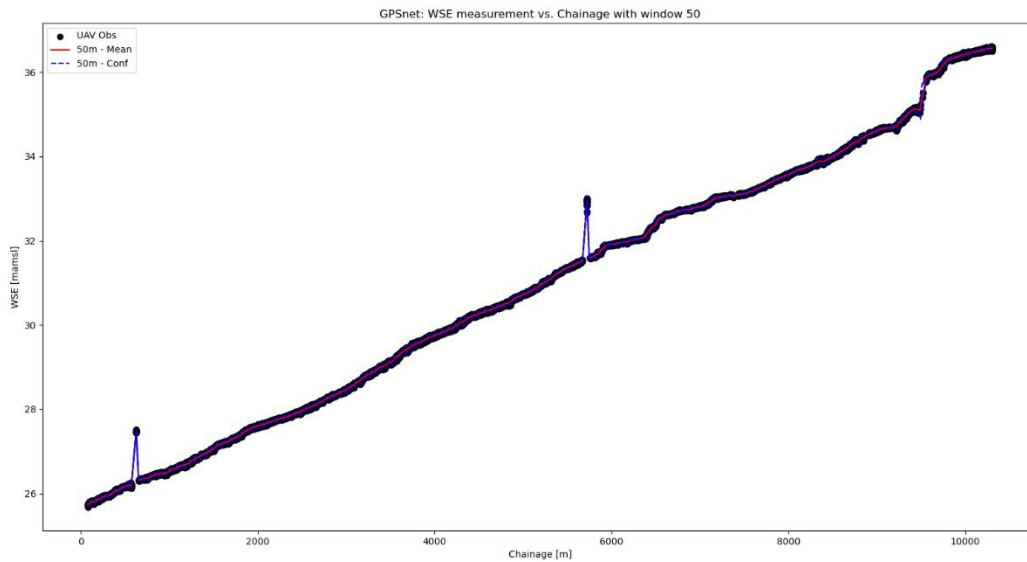


Figure 16 - Example output, Graph

13. References

- [1] F. Bandini *et al.*, “Unmanned Aerial System (UAS) observations of water surface elevation in a small stream: Comparison of radar altimetry, LIDAR and photogrammetry techniques,” *Remote Sens Environ*, vol. 237, 2020, doi: 10.1016/j.rse.2019.111487.
- [2] F. Bandini *et al.*, “Unmanned aerial vehicle observations of water surface elevation and bathymetry in the cenotes and lagoons of the Yucatan Peninsula, Mexico | 无人机观测墨西哥尤卡坦半岛天然井及泻湖的水面高程及深度测量 | Observations de l’élévation de la surface de l’eau et de la bathymétrie par drone ,” *Hydrogeol J*, vol. 26, no. 7, pp. 2213–2228, 2018, doi: 10.1007/s10040-018-1755-9.
- [3] L. Jiang, F. Bandini, O. Smith, I. K. Jensen, and P. Bauer-Gottwein, “The value of distributed high-resolution UAV-borne observations of water surface elevation for river management and hydrodynamic modeling,” *Remote Sens (Basel)*, vol. 12, no. 7, 2020, doi: 10.3390/rs12071171.
- [4] F. Bandini *et al.*, “A Drone-Borne Method to Jointly Estimate Discharge and Manning’s Roughness of Natural Streams,” *Water Resour Res*, vol. 57, no. 2, 2021, doi: 10.1029/2020WR028266.
- [5] J. Liu *et al.*, “Spatio-temporally varying Strickler coefficient: A calibration approach applied to a Danish river using in-situ water surface elevation and UAS altimetry,” *J Hydrol (Amst)*, vol. 613, p. 128443, Oct. 2022, doi: 10.1016/J.JHYDROL.2022.128443.