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UAWOS - Unmanned Airborne Water Observing System

Deliverable 3.2:

Riverbed Geometry Surveying Protocol

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3. Overview and Summary

This document summarizes the contactless airborne riverbed geometry surveying workflow developed in UAWOS. The document constitutes deliverable D3.2 of the Horizon Europe project "UAWOS – Unmanned Airborne Water Observing System", contract number 101081783.

The UAWOS riverbed geometry surveying workflow uses a combination of near infrared (NIR) lidar and water penetrating radar (WPR) or sonar/echosounder. NIR lidar is used to map the elevation of the exposed portions of the riverbed, while WPR or sonar/echosounder are used to map the submerged portions of the riverbed. Commercial drone-borne NIR lidar solutions are available on the market and UAWOS uses established and mature products such as the DJI Zenmuse L2. For WPR and sonar/echosounder surveying, UAWOS has developed new drone payloads as described in UAWOS deliverables D2.2 and D2.3.

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 UAV riverbed geometry surveys.

4. Purpose of Riverbed Geometry surveying

Riverbed geometry is the most important input parameter for river hydraulic models used in flood forecasting and infrastructure planning. Riverbed geometry determines conveyance and thus the relationship between river discharge and river water level. Riverbed geometry can change in time due to erosion and sedimentation processes in the river and must therefore be re-surveyed at regular intervals. This requires a lot of resources. Denmark, for example, spends on the order of 200 million Danish kroner per year on geometry surveys of rivers and streams. Near-infrared lidar is the method of choice for contactless mapping of land surface elevation. It can be deployed from airplanes or drones and mature commercial solutions are available (e.g. DJI Zenmuse L2). However, NIR lidar cannot be used to map the geometry of the submerged portion of the river. If river water is clear and transparent, drone-borne green lidar is an option (e.g. Astralite Edge, TDOT green). However, these payloads are very expensive and do not perform in turbid and vegetated rivers. Under such conditions, tethered sonar (or echosounder) or water penetrating radar can be used as described in detail in Bandini et al., 2023, 2018. The main limitation for water penetrating radar (WPR) is electric conductivity of the water. Depending on the bottom type and depth of the river, WPR will be able to map riverbed geometry up to a water electric conductivity of ca. 300-400 micro Siemens per centimeter. If the water is more conductive, WPR is not an option. The main limitation of sonar/echosounder is the tethered arrangement, which is limited to relatively slow flowing rivers. Moreover, sonar performance is sensitive to submerged vegetation, which can be partly addressed by using multiple frequencies. Postprocessing effort is higher for WPR datasets compared to sonar/echosounder datasets. The UAWOS riverbed geometry surveying workflow uses a combination of NIR lidar for the exposed portions of the riverbed and sonar or WPR for the submerged portions, depending on site conditions. An example of a complete riverbed geometry survey is described in detail by Coppo Frias et al., 2024.

Utilizing Unmanned Aerial Vehicles (UAVs) for riverbed geometry surveys greatly enhances efficiency and cost-effectiveness. Riverbed geometry surveying consists of two different parts. One part is mapping the riverbanks (dry portion) in order to produce a high-resolution Digital Elevation Model (DEM). The other part is collecting bathymetry cross sections of the river with the desired spacing. Traditionally, mapping the riverbanks has only been feasible using manned aircraft. The traditional approach for collecting bathymetry cross sections has entailed deploying ground personnel on both sides of the river, suspending a line across the river and dragging the bathymetry sensor across. Alternatively, boat-based solutions have also been deployed at certain locations where possibly. UAVs provide a more economical alternative to the traditional combination of manned aircraft surveys in conjunction with on-site ground personnel 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 riverbed geometry 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 riverbed geometry 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 riverbed geometry surveying setup and the different hardware components. The centerpiece is the UAV carrying both a radar altimeter and a GNSS receiver. In areas with good GNSS coverage, the UAV can be directly linked up to an RTK network provider. In areas with sub-optimal GNSS coverage, a local base station is employed for providing RTK corrections to the UAV via Starlink.

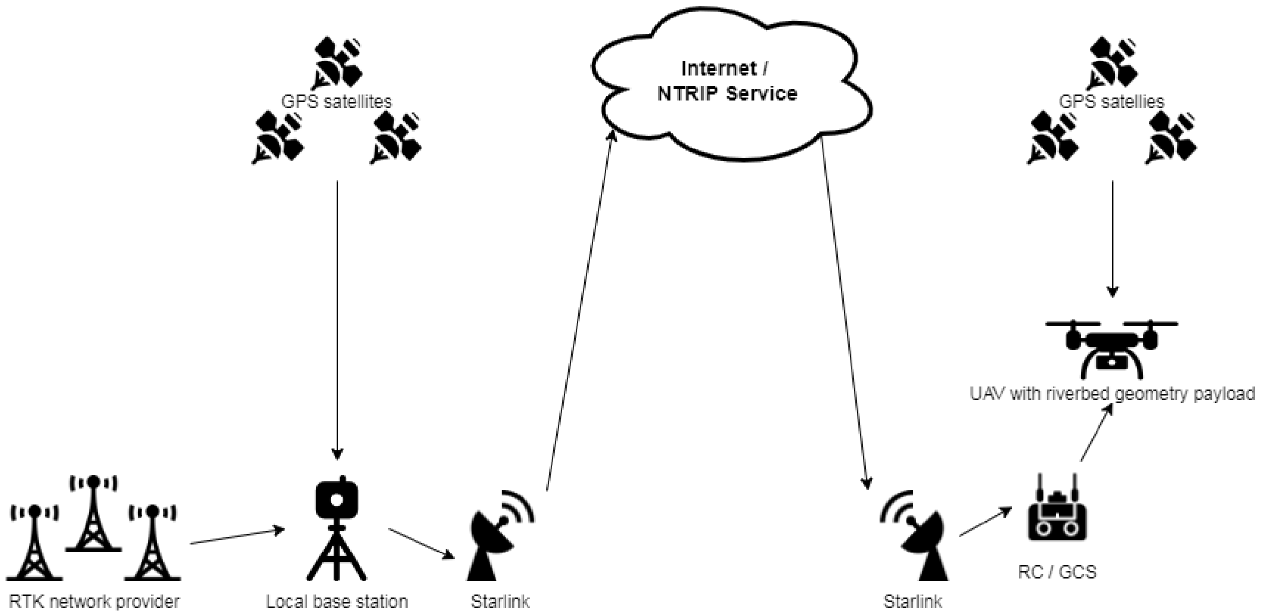

Figure 1 - Overview of riverbed geometry survey setup

5. Surveying specifications

5.1. LiDAR - DTM

5.1.1. Accuracy

The LiDAR surveying workflow provides lidar returns including ranges and angles, which are first processed into point cloud data and can subsequently be processed into a gridded digital surface model (DSM). Subsequently, vegetation elements, buildings etc. can be removed from the DSM to obtain a bare-earth digital terrain model (DTM). The point cloud spatial resolution and accuracy is variable depending on LiDAR equipment, flight altitude, flight velocity, GNSS setup and ground control point (GCP) utilization. Typically, the processed DEM provides a vertical accuracy of 10 cm or better. 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

The productivity which can be expected is highly dependent on the survey area characteristics. 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 1.0-4.0 km/hour can be expected.

5.1.3. Flight parameters

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

Altitude: 50-120m, depending on payload and desired spatial resolution

Velocity: Max. 10 m/s

Terrain-follow: Not required, but can be desired in areas with a highly variable terrain profile

Coverage: Grid based pattern (lawnmower) with a sideways overlap of 50% or more (recommended).

5.2. WPR - Bathymetry

5.2.1. Accuracy

The expected accuracy is 10cm or better.

5.2.2. Productivity & Scale

The productivity which can be expected is highly dependent on the survey area characteristics. Challenging accessibility to takeoff locations is a primary factor that can hamper a high productivity. The actual flight time for performing a cross section is typically a few minutes. Accessibility, flight route endpoint adjustments and data verification are accountable for most of the time spent on performing a WPR cross section. Based on practical experience from a variety of rivers a productivity of 0.75-2.0 cross sections/hour can be expected.

5.2.3. Flight parameters

Altitude: As close to the water surface as possible. For optimal results the distance between the WPR payload and the water surface should not exceed 0.5m.

Velocity: Max. 2 m/s

Terrain Follow: TTF (True Terrain Follow) with altimeter.

Coverage: Dual pass cross section

5.3. Sonar - Bathymetry

5.3.1. Accuracy

The expected accuracy is 10cm or better.

5.3.2. Productivity & Scale

The productivity which can be expected is highly dependent on the survey area characteristics. Challenging accessibility to takeoff locations is a primary factor that can hamper a high productivity. The actual flight time for performing a cross section is typically a few minutes. Accessibility, flight route endpoint adjustments and data verification are accountable for most of the time spent on performing a sonar cross section. Based on practical experience from a variety of rivers a productivity of 0.75-2.0 cross sections/hour can be expected.

5.3.3. Flight parameters

Altitude: 2m above water surface (ultimately defined by length of cable suspending the sensor)

Velocity: Max. 1 m/s

Terrain Follow: TTF (True Terrain Follow) with altimeter

Coverage: Single pass cross section

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.

BVLOS operations have the potential to enhance riverbed geometry surveying productivity substantially.

This Riverbed Geometry Surveying Protocol is based UAV operation in the ‘open’ category.

6.2. Equipment

This Riverbed Geometry 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 multirotor

Any RTK-enabled multirotor UAV with sufficient payload capacity for the chosen sensors is appropriate. The riverbed geometry surveying protocol recommends the DJI M300 RTK as a reference 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.

Figure 2 - DJI M300 RTK without payload

6.2.2.LiDAR payload

Any standard grade LiDAR which fulfills the following requirements can be utilized:

Ranging accuracy: 3 cm @ 100m or better

Vertical system accuracy: 5 cm @ 50m or better

Number of returns: 3 or more

This Riverbed Geometry Surveying Protocol recommends using the DJI L1 or DJI L2 LiDAR system. Using one of the recommended LiDAR systems ensures seamless setup and deployment due to them being inherently designed for deployment on the recommended UAV multirotor, the DJI M300 RTK. The DJI L1/L2 payloads are designed for aerial mapping, integrating a Livox LiDAR module, a high-precision IMU, and a camera for RGB data collection. They capture high-density point cloud data, making them suitable for topographic surveys.

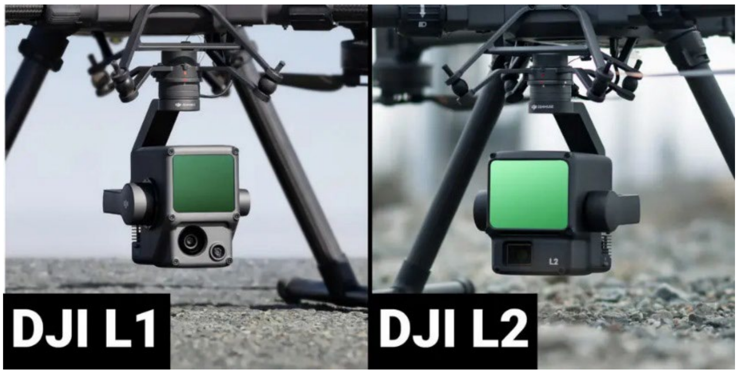

Figure 3 - DJI L1 and L2

6.2.3. Bathymetry Payloads

Any bathymetry payload which can deliver a bottom profile with a precision of 10 cm or better can by utilized.

This Riverbed Geometry Surveying Protocol recommends using SkyHub as payload controller in conjunction with Radar Systems Zond AERO LF GPR (described in UAWOS D2.2) as WPR sensor and/or Echologger ECT 400s (described in UAWOS D2.3) as Sonar sensor. This allows for seamless integration and full compatibility between the recommended UAV, GCS, TFF Radar Altimeter and Rover GPS.

SkyHub is an onboard computer and payload interface, which is compatible with all bathymetry 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 4 - SkyHub payload controller

Figure 5 - DJI M300 RTK with Radar Systems Zond AERO LF GPR

Figure 6 - Echologger ECT 400s Payload

6.2.4.TTF Radar Altimeter

Any true terrain following system that allows for cm precise terrain following capabilities at very low altitudes (less than 1m) above water and ground surfaces can be utilized.

This Riverbed Geometry Surveying Protocol recommends the True Terrain Following kit for DJI drones from SPH Engineering (described in UAWOS D2.2 and UAWOS D2.3).

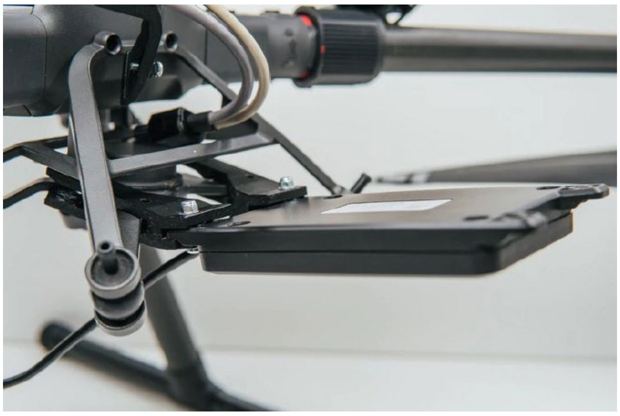

Figure 7 - **True Terrain Following kit for DJI drones from SPH Engineering**

6.2.5.GCS

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

- Terrain follow capability (DEM based)
- True Terrain Follow (TTF)
- 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 Riverbed Geometry 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, Radar Systems Zond AERO LF GPR and Echologger ECT 400s).

6.2.6.Rover GPS

Any multi-band, RTK/PPK enabled rover GPS 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 GPS. The Emlid Reach M2 is fully compatible with the recommended payload equipment (SkyHub, Radar Systems Zond AERO LF GPR and Echologger ECT 400s).

Figure 8 - Emlid Reach M2

6.2.7.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 Riverbed Geometry Surveying Protocol recommends the Emlid RS3 as local base station.

Figure 9 - Emlid RS3

6.2.8. 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 GPS, which requires two mobile broadband modems, one at the base station, and one at the GCS.

If reliable 4G LTE coverage is available in the survey area, a high-quality 4G LTE router is recommended RC/GCS internet connectivity. Practical experience has shown that carrying a high-quality 4G LTE router in a backpack is an excellent solution, supporting a high degree of mobility often required by ground crew. This Riverbed Geometry Surveying Protocol recommends using a 4G LTE router from Teltonika. Positive experience has been achieved with Teltonika RUT951 and Teltonika RUTX12.

Often riverbed geometry surveys has to be performed in remote locations and/or at locations which do not have reliable mobile broadband connectivity from common ISPs. For those situations this Riverbed Geometry 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. Practical experience has shown that the wifi network created by Starlink has limited range, which can be cumbersome. Therefore, at the RC/GCS it is recommended to use a high quality router as a repeater/extender in conjunction with the Starlink.

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

Figure 10 - Starlink receiver and router

7. Desktop Reconnaissance

The purpose of desktop reconnaissance is:

- Decide if onsite reconnaissance is required
- Decide upon equipment setup

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

- Takeoff locations for VLOS 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

Completing a riverbed geometry survey entails performing a LiDAR survey which can be performed at a high flight altitude. In many situations there are not any obstacles that constitute a hazard for LiDAR flights and VLOS can often be maintained at large distances due to the flight altitude.

If there is no existing up to date and precise digital reference data (orthomosaic, satellite imagery, DEM or similar) of the survey area, then it is recommended to initially perform planning and execution of the LiDAR survey. Thereafter, post process the LiDAR survey data in order to attain up to date and precise digital reference data. If one of the recommended LiDAR payloads are utilized both point cloud data and RGB imagery can be collected simultaneously. This allows for the creation of both a high-quality DEM and orthomosaic.

Once up to date and precise digital reference data is available it is recommended to initiate planning of bathymetry flights.

As part of the desktop reconnaissance it is recommended, if possible, to attain information regarding the expected water depth, flow velocity and electric conductivity of the river to be surveyed. These parameters impact which bathymetry sensors can be expected to deliver usable data. If these parameters cannot be established, it is recommended to perform planning for both WPR and sonar as the decision regarding which sensor to deploy will have to be made on-site.

Often riverbed geometry 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 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 utilized. Meticulous planning is often highly beneficial when planning riverbed geometry surveys due to challenging site characteristics combined with flights at an extremely low altitude.

8.1. LiDAR Routes

Planning the LiDAR routes should be performed in accordance with common best practices and accommodate equipment specific requirements such as calibration flight patterns.

Depending on the river layout, two different approaches can be considered. If the river consists of several narrow branches with rapidly changing morphology, or similar, it is recommended to employ a grid mapping mission (lawnmover pattern). Conversely, if the river is wide and without significant branches, then it is recommended to only map the riverbanks in a dual pass corridor flight mission. This significantly reduces survey time compared to mapping the entire area of a wide river. The L1 LiDAR recommended in this protocol is only suitable for mapping dry areas.

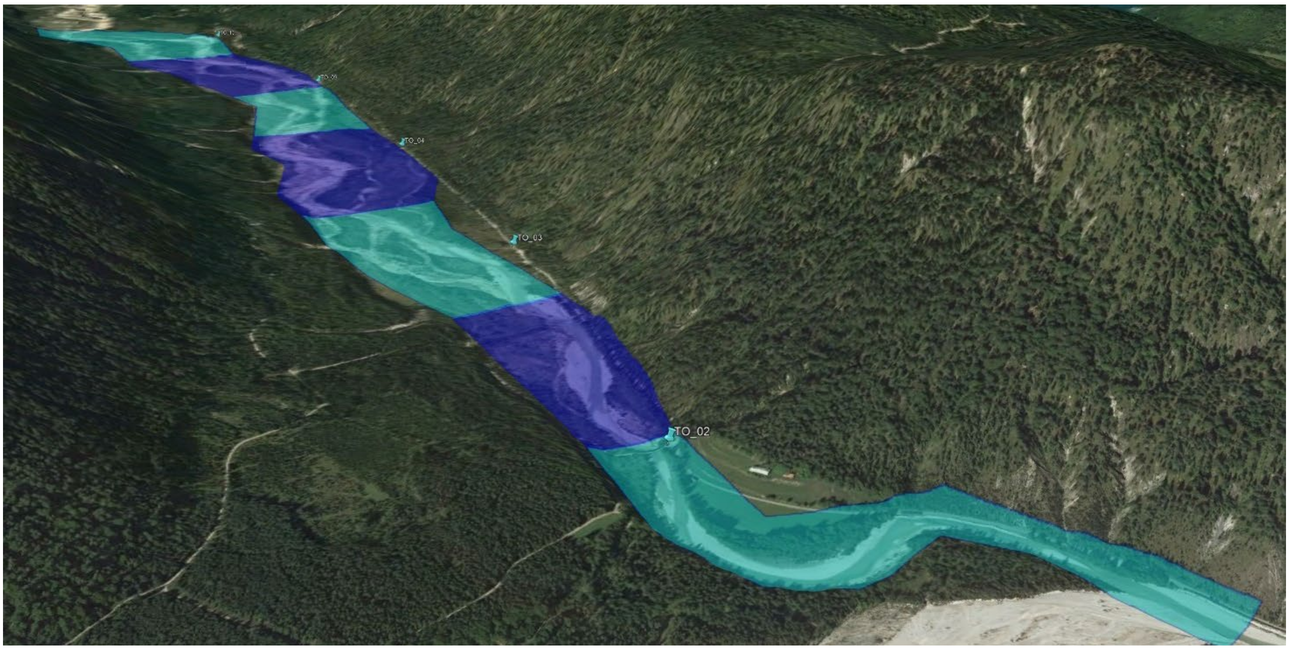

Figure 11 – Area of interest divided into flight zones/polygons for optimal VLOS

Figure 12 - LiDAR Grid Mapping Mission

8.2. WPR Routes

For WPR route planning it is highly recommended add an up to date and precise digital reference as a custom layer or background map in the GCS prior to initiate route planning.

WPR routes must be flown at a very low altitude. TTF is essential during these flights. They cannot be safely performed using AGL heights from a barometer or elevation model.

There are three factors which impact the WPR data quality (signal to noise ratio):

1) Distance from WPR sensor to water surface
2) Water depth
3) Electric conductivity of the water

Consult UAWOS D2.2 for description of WPR capabilities.

The minimum recommended altitude using the recommended equipment is 0.4m (from the TTF sensor to the water surface). Under optimal conditions it may be possible to acquire satisfactory data quality at a flight altitude of 1.0m. Often it will necessary to reduce the flight altitude towards 0.4m. The planned flight routes can be created at any low altitude, since the actual flight altitude is controlled by the TFF system, which is specified during flight execution.

The maximum recommended flight speed is 2 m/s with 1 m/s being preferable.

It is recommended to plan a WPR cross-section as a waypoint flight mission as follows:

Waypoint 1 – 2: Used to reduce flight altitude to survey altitude. This can be placed in the center of the river.

Waypoint 2 – 3: Survey line to the far side riverbank. Keep a safety margin to the riverbank, depending on terrain, vegetation etc.

Waypoint 3 – 4: Specify the UAV to reverse a few meters. This is performed to enhance safety by reducing risk of vegetation entanglement near the riverbank.

Waypoint 4: Specify a 180-degree yaw action.

Waypoint 4 – 5: Survey line to the near side riverbank. Keep a safety margin to the riverbank, depending on terrain, vegetation etc.

Waypoint 5 – 6: Specify the UAV to reverse a few meters. This is performed to enhance safety by reducing risk of vegetation entanglement near the riverbank.

Waypoint 6: Specify a 180-degree yaw action.

Waypoint 6 – 7: Survey line to the starting location.

Waypoint 7 – 8: Used to ascend from flight survey altitude to comfortable altitude.

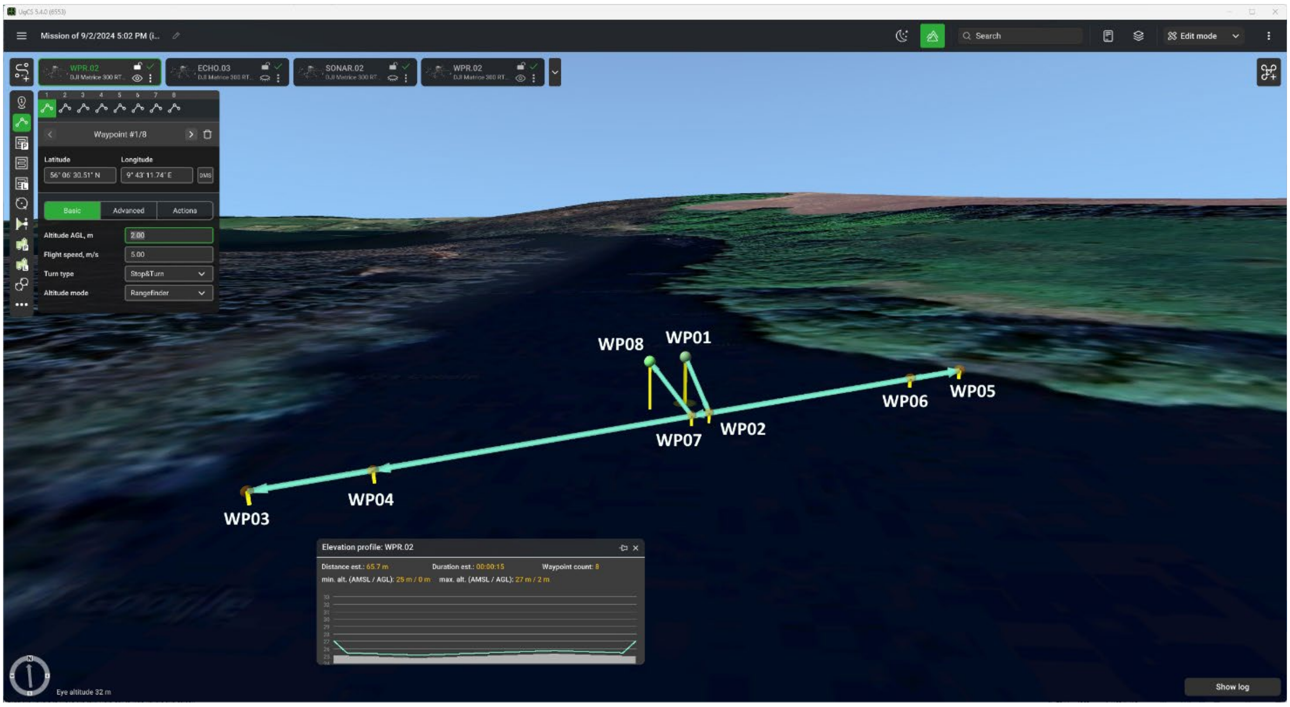

Figure 13 - WPR flight route example

Using a precise digital reference as a custom layer or background map in the GCS is essential to create flight routes with a high degree of accuracy. Regardless of the digital reference precision, it is recommended to evaluate/adjust waypoint 3 + 4 and waypoint 5 + 6 on site prior to initiating the flight route.

8.3. Sonar Routes

For sonar route planning it is highly recommended add an up to date and precise digital reference as a custom layer or background map in the GCS prior to initiate route planning.

Sonar routes must be flown at a low altitude. TTF is essential during these flights. They cannot be safely performed using AGL heights from a barometer or elevation model.

A restrictive parameter for sonar flights is the flow velocity of the river at the cross-section. If the sonar sensor is equipped with housing attachment the maximum flow velocity is 1.5 m/s. If no housing is equipped, the maximum flow velocity is 0.8 m/s.

Consult UAWOS D2.3 for description of sonar capabilities.

Figure 14 – Sonar sensor with housing equipped

During sonar routes the sonar payload must be submerged in the water, while being attached to the UAV with a cable. The sonar payload is dragged in the water surface across the river. There is no safety release mechanism if the payload becomes entangled during flight. Therefore, it is highly recommended plan the cross-section flight at a location that is free of obstacles and vegetation that can induce a chance of entanglement.

The maximum recommended flight altitude for sonar flights is 2m. Ultimately the maximum flight altitude is defined by the length of cable suspending the sensor. The planned flight routes can be created at any low altitude, since the actual flight altitude is controlled by the TFF system, which is specified during flight execution.

The maximum recommended flight speed is 1 m/s.

It is recommended to plan a sonar cross-section as a waypoint flight mission as follows:

Waypoint 1: Placed at the far side. Altitude and location should be specified to safe values with no risk of entanglement, ex. 5 m. It is recommended to displace this waypoint a few meters horizontally from the survey line, against the stream flow direction.

Waypoint 2: This waypoint defines the beginning of the survey line at the far side. Keep a safety margin to the riverbank, depending on terrain, vegetation etc.

Waypoint 3: This waypoint defines the end of the survey line at the near side. Keep a safety margin to the riverbank, depending on terrain, vegetation etc.

Waypoint 4: Placed at the near side. Altitude and location should be specified to safe values with no risk of entanglement, ex. 5 m. It is recommended to displace this waypoint a few meters horizontally from the survey line, against the stream flow direction.

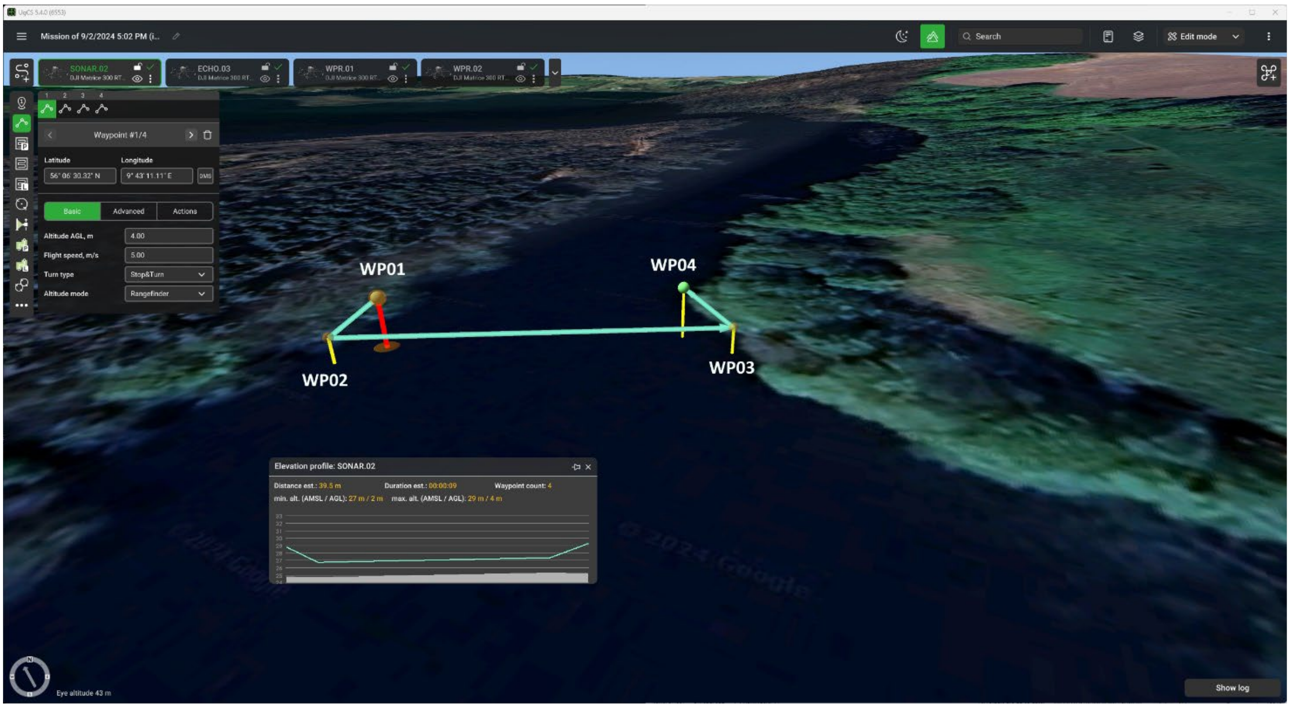

Figure 15 – Sonar flight route example

9. Flight Execution

9.1. LiDAR Flights

LiDAR flights should be conducted according to commonly recommended best practices.

In mountainous regions it is recommended to pay enhanced attention to VLOS conditions due to steep elevation changes.

It is recommended to employ strobe lights if available to increase UAV visibility, even in daylight conditions.

Ensure that the UAV has RTK fix during data collection.

Figure 16 – DJI M300 RTK with L1 LiDAR. Crew is waiting for the morning fog to clear

Figure 17 - FPV camera feed from DJI M300 RTK during LiDAR flight

9.2. DJI M300 RTK Preparation for Low Altitude TTF Flights

In order to prepare the DJI M300 RTK for low altitude flights using the recommended TTF system (6.2.4) it is highly recommended to complete the following actions.

All downward facing sensors (for the vision/collision avoidance system) must be disabled in DJI Pilot 2 App. It is also required to cover the disabled sensors with electrical tape. If these actions are not taken, TFF flights will be interrupted by numerous "avionics errors" from the flight controller.

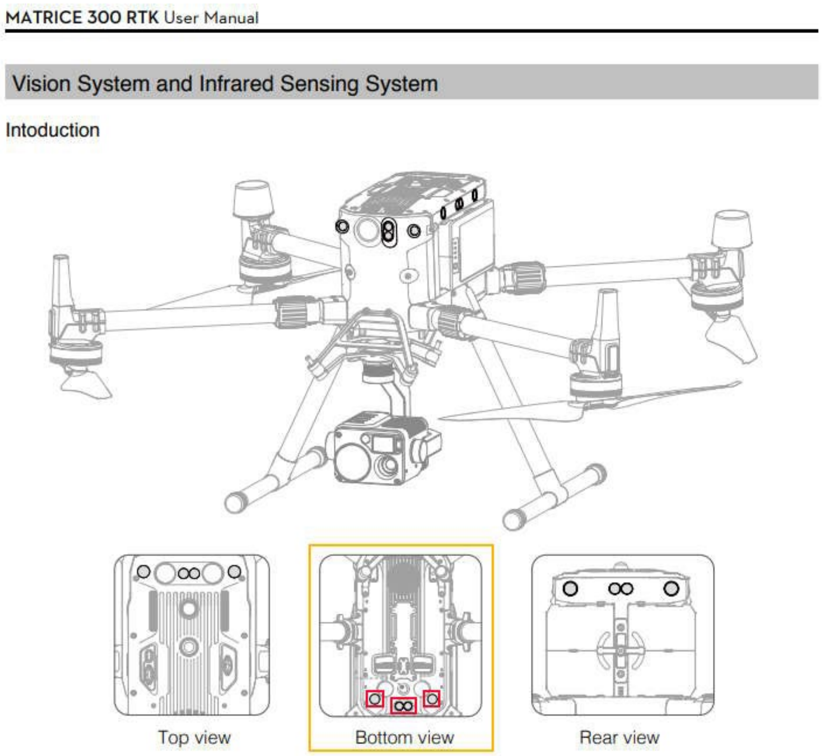

Figure 18 - All four sensors on the bottom must be disabled and covered with tape.

9.3. WPR Flights

For all WPR routes, the prepared route must be adjusted at the endpoints (near riverbanks) before the route is flown. This adjustment is performed to ensure a safe distance from vegetation and other obstacles during execution of the flight route. This adjustment is crucial even when planning is performed based on an up to date and precise digital reference since river water level, morphology and debris can change on a very short timeframe.

Steps for route adjustments:

1. Load prepared route in the GCS software
2. Take off with the UAV, and manually fly at a safe altitude above the cross-section survey line. Ensure that the UAV location is visible in the GCS alongside the prepared route. While flying above the cross-section survey line, monitor the UAV FPV camera feeds to identify if there is unexpected obstacles/debris at the cross-section survey line. If obstacles are present, relocate to an obstacle free location.
3. Using the UAV FPV camera feeds, establish a safe placement for the waypoint defining the far side endpoint of the cross-section survey line. This should be as close to the riverbank as possible without inducing an increased risk of obstacle collision/entanglement. The waypoint in the prepared route is moved to this location (waypoint 3 and if necessary, waypoint 4).
4. Using the UAV FPV camera feeds, establish a safe placement for the waypoint defining the near side endpoint of the cross-section survey line. This should be as close to the riverbank as possible without inducing an increased risk of obstacle collision/entanglement. The waypoint in the prepared route is moved to this location (waypoint 5 and if necessary, waypoint 6).

Once the WPR flight route has been adjusted, the TTF flight altitude values are specified, and the automated flight is executed.

Ensure that the UAV has RTK fix during data collection.

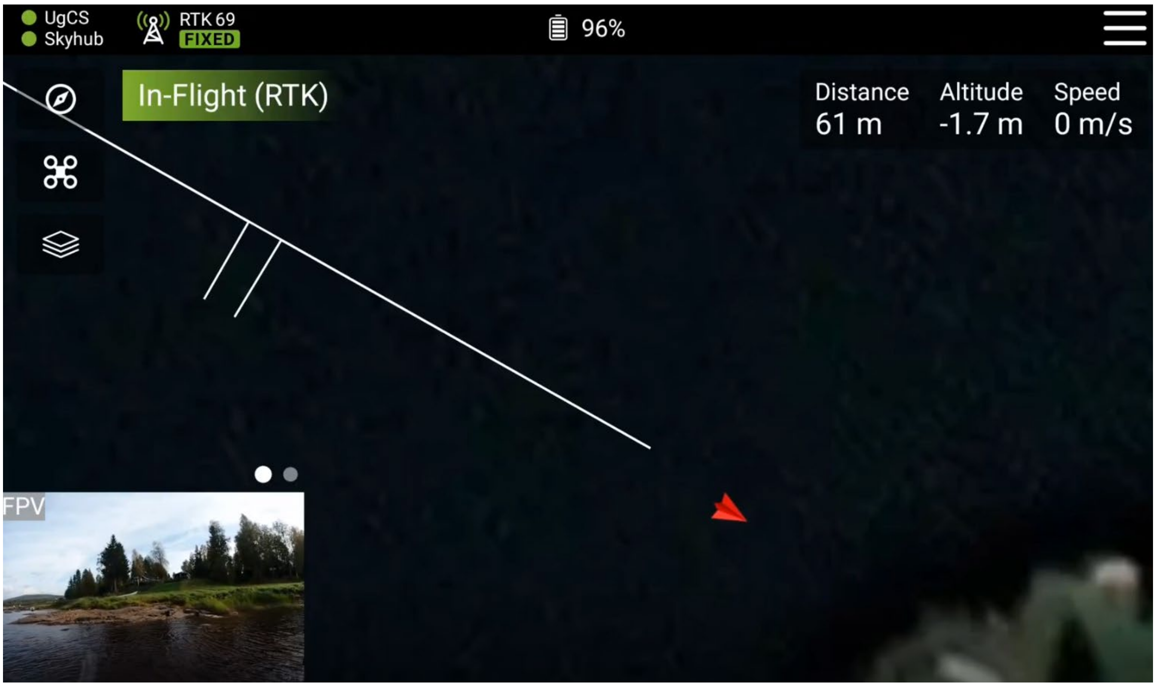

Figure 19 – WPR route adjustment. UAV location is displayed with a red arrow icon.

It is recommended to perform on-site verification that collected data includes a bottom profile. This can be achieved during flights using the UgCS CPM software. For the WPR payload, it is possible to show either “Trace” or “Profile”. It is recommended to use the “Profile” for visualizing the WPR return signal.

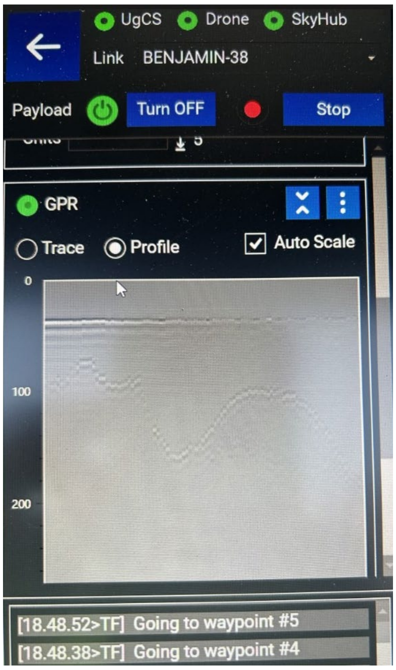

Figure 20 - WPR "Profile" shown during flight. The river geometry is being shown.

Alternatively, verification can be performed by downloading the collected data from the SkyHub payload controller and visualizing the data using the PRISM software provided by the manufacturer.

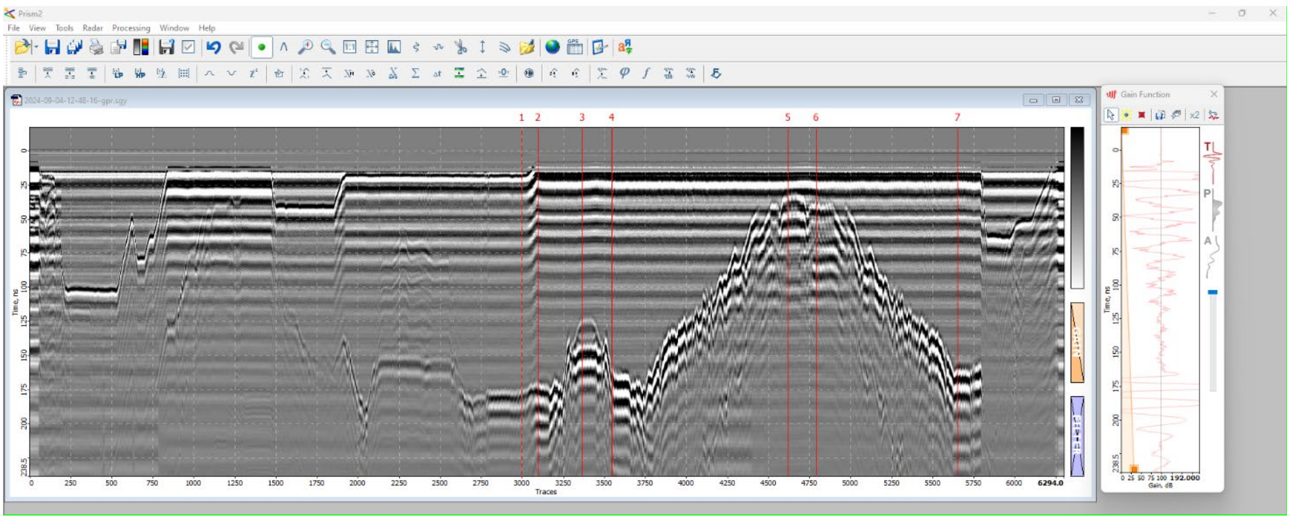

Figure 21 - WPR data visualized using Prism2 software

If no bottom profile is present, it may be necessary to change the WPR configuration and/or reduce the flight altitude. If the lack of bottom profile is due to too large water depth or too high electric conductivity it will be necessary to perform the cross section with the sonar payload.

9.4. Sonar Flights

It is highly recommended to perform a thorough cross-section check prior to executing sonar flights. For wide cross-sections, having a second UAV operator follow the sonar-equipped UAV with a camera UAV can increase awareness of potentially dangerous situations.

During sonar routes the sonar payload must be submerged in the water, while being attached to the UAV with a cable. The sonar payload is dragged in the water surface across the river. There is no safety release mechanism if the payload becomes entangled during flight.

Therefore, it is highly recommended to only perform sonar cross-section flights at locations that are free of obstacles and vegetation that can induce a risk of entanglement.

For all sonar routes, the prepared route must be adjusted at the endpoints (near riverbanks) before the route is flown. This adjustment is performed to ensure a safe distance from vegetation and other obstacles during execution of the flight route. This adjustment is crucial even when planning is performed based on an up to date and precise digital reference since river water level, morphology and debris can change on a very short timeframe.

Steps for route adjustments:

1. Load prepared route in the GCS software
2. Take off with the UAV (without the sonar payload attached), and manually fly at a safe altitude above the cross-section survey line. Ensure that the UAV location is visible in the GCS alongside the prepared route. While flying above the cross-section survey line, monitor the UAV FPV camera feeds to identify if there are any unexpected obstacles/debris at the cross-section survey line. If obstacles are present, relocate to an obstacle free location.
3. Using the UAV FPV camera feeds, establish a safe placement for the waypoint defining the far side endpoint of the cross-section survey line. This should be as close to the riverbank as possible without inducing an increased risk of obstacle collision/entanglement. The waypoint in the prepared route is moved to this location (waypoint 2 and if necessary, waypoint 1).
4. Using the UAV FPV camera feeds, establish a safe placement for the waypoint defining the near side endpoint of the cross-section survey line. This should be as close to the riverbank as possible without inducing an increased risk of obstacle collision/entanglement. The waypoint in the prepared route is moved to this location (waypoint 3 and if necessary, waypoint 4).

Once the sonar flight route has been adjusted:

1. Specify the TTF flight altitude values
2. Mount the sonar payload to the UAV according to the manufacturer's guidelines
3. Measure the distance between the sonar payload and the TTF altimeter according to the manufacturer's guidelines
4. Enter the measured length in the skyhub.config for the specific payload
5. Execute the automated flight route.

Ensure that the UAV has RTK fix during data collection.

Figure 22 – Sonar Payload attached to DJI M300 RTK

It is recommended to perform on-site verification that collected data includes a bottom profile. This can be achieved during flights using the UgCS CPM software. For the sonar payload, the calculated distance from the sonar to the bottom is displayed. This numerical value should always be shown.

Alternatively, verification can be performed by downloading the collected data from the SkyHub payload controller and visualizing the data ex. using free software like PlotJuggler.

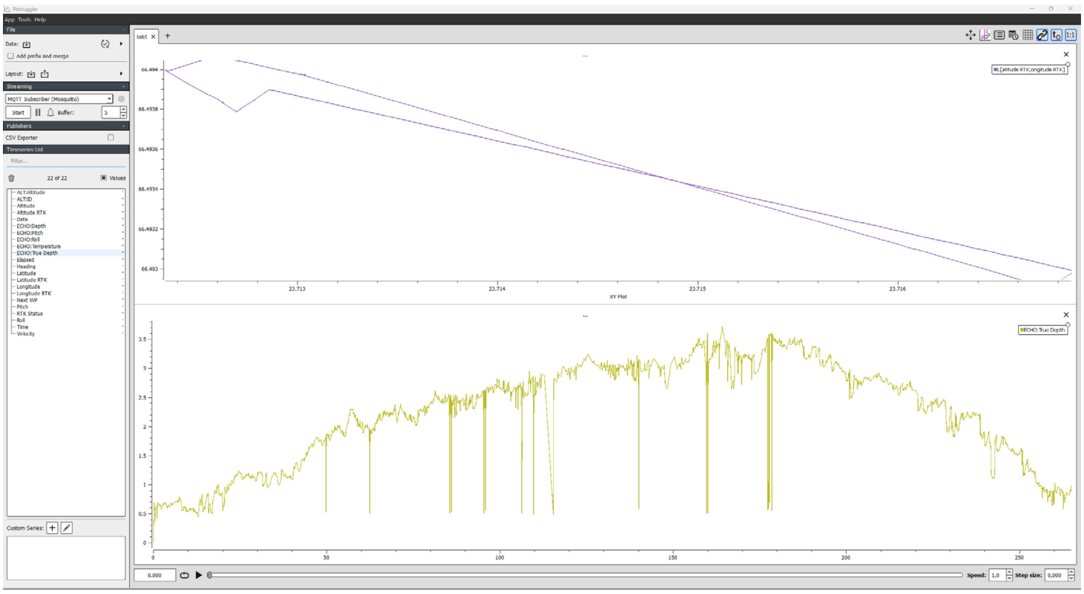

Figure 23 - Sonar data visualized using PlotJuggler

10. Post-survey data processing steps

10.1. LiDAR Data

LiDAR data should be processed according to commonly accepted best practices.

The overall recommended workflow is as follows:

- Download the raw LiDAR data from the SD-Card (DJI L1 & L2)
- Import the data into DJI Terra by selecting "LiDAR Point Cloud"
- Process the data to generate a point cloud in LAS format

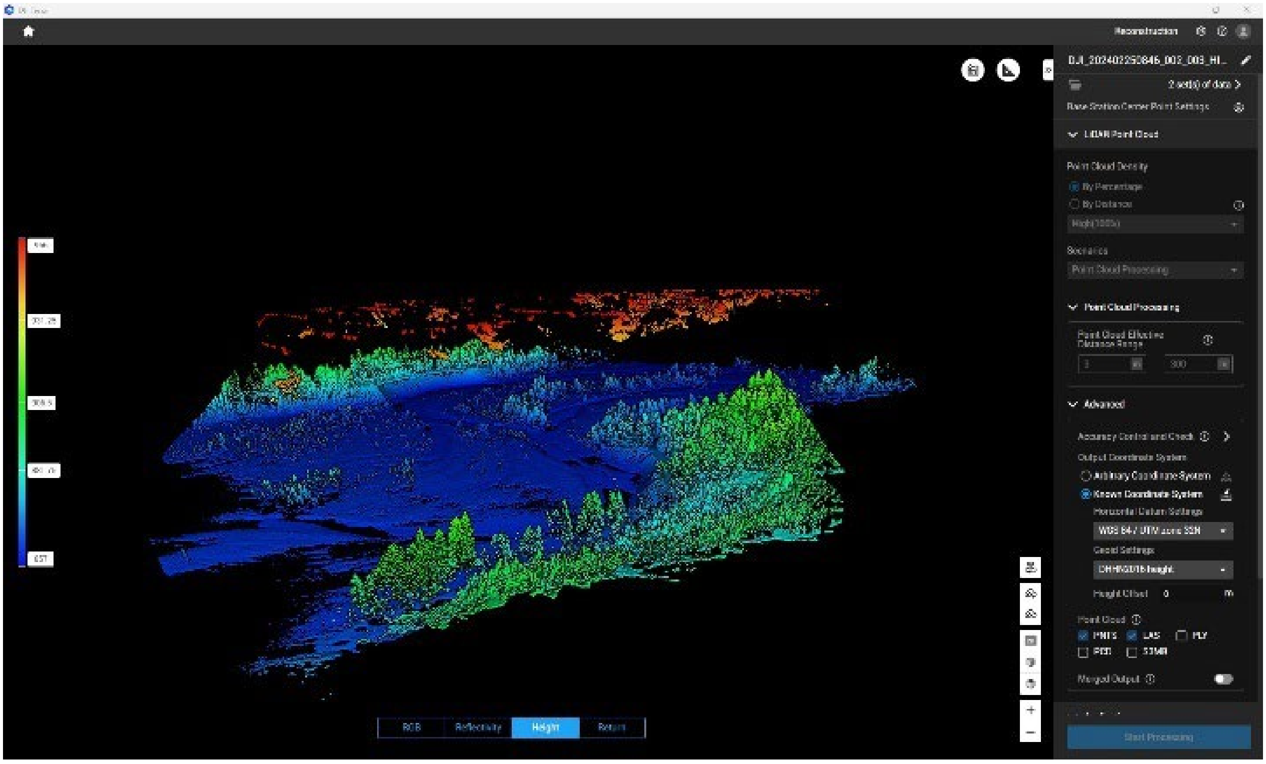

Figure 24 – Unfiltered point cloud in DJI TERRA.

- Import the LAS point cloud into CloudCompare and apply desired filters to remove vegetation and non-ground points
- In CloudCompare, convert the processed point cloud into a raster format using the "Rasterize" tool
- Adjust the raster resolution, ensuring it matches the point cloud resolution, and export the data as a DTM
- Import the DTM into QGIS and ensuring/specify that the desired Coordinate Reference System is set
- Use the Raster Calculator in QGIS to specify the desired visualization

Summary of recommended tools and usage:

- **DJI Terra**: LiDAR point cloud generation.
- **CloudCompare**: Point cloud correction, cleanup, filtering and conversion to raster.
- **QGIS**: Georeferencing and visualization.

10.2. WPR Data

The WPR survey produces the following output: (1) the radargram, typically in seg-y format and (2) position log file including trace numbers, typically in csv format. The radargram is a 2-dimensional data structure. It consists of a few hundred to a few thousand traces (radar echo curves). Each trace has a few thousand samples. Each sample contains the energy of the echo for the specific time interval (bin) corresponding to the sample. As the radar signals travel at a given speed in water ($v_w = \frac{c}{\sqrt{\varepsilon}}$, where c is the speed of light in vacuum and ε is the dielectric permittivity of water, which is ca. 81), each time bin can be translated into a range, considering that the time is a two-way travel time.

WPR processing proceeds in the following steps:

1. Read and display seg-y radargram. This can be done with commercial software or with open-source code, for instance in python.
2. Enhance contrast in the radargram using background removal, filtering, and gaining steps.
3. Identify the time bin corresponding to the water surface
4. Pick the river bottom return from the radargram. This can be done semi-automatically, but typically requires some manual cleaning/postprocessing
5. Export picks as pairs of points trace number / depth
6. Subtract depth from water surface elevation to obtain river bottom elevation.
7. Translate trace number to position using position log file
8. Project points on a reference cross section line and translate position into cross section coordinate.
9. Export final result as csv file

10.3. Sonar Data

The sonar survey produces the following output: (1) the sonargram, typically in seg-y format and (2) position log file including trace numbers, typically in csv format, (3) a log file with automatically picked depth estimates for each position. The sonargram can be processed in the same way as explained above for the radargram, changing the speed of light in water to the speed of sound in water (ca 1500 m/s), which depends significantly on water temperature and salinity. However, in most cases the automatic picking algorithm that comes with the sensor performs well and depth estimates can be used directly.

In this case, sonar processing proceeds in the following steps:

1. Translate depth to riverbed elevation by subtracting depth and cable length from the drone altitude.
2. Project points on a reference cross section line and translate position into cross section coordinate.
3. Export final result as csv file

10.4. Merging LiDAR and WPR/Sonar Data

For most applications, merged riverbed cross sections are required, i.e. cross sections spanning across both the dry and submerged portions. To get there, we need to merge the lidar and WPR/Sonar datasets. To this end, we extract lidar elevation from the gridded DTM along the chosen cross section reference line and then merge the points with the WPR/sonar points along the reference line. To fill potential gaps (especially around the fringes of the water surface, where the water is too deep for lidar, but too shallow for WPR/sonar) and produce regularly spaced elevation samples, one can fit a spline function to the merged dataset and then predict riverbed elevation at any point using the spline.

11. Output data formats and example output

11.1. LiDAR output

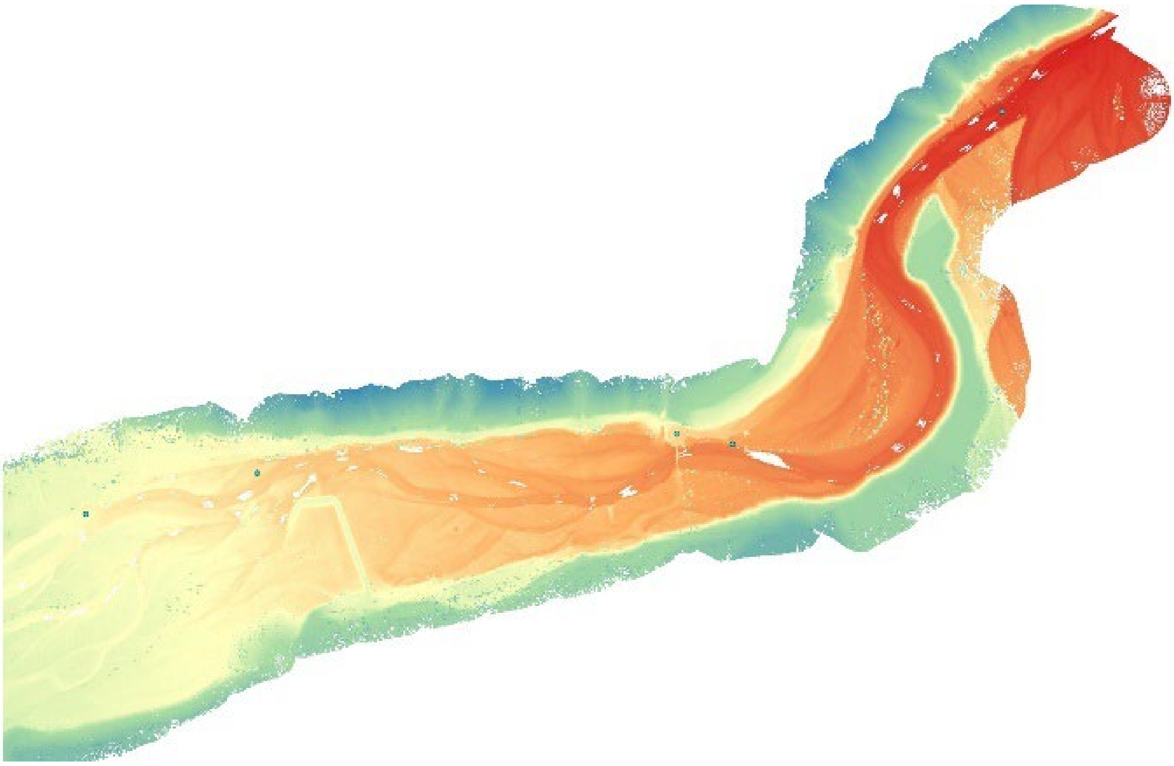

Figure 25 - DTM

11.2. WPR output

Example output of WPR surveys can be found on the UAWOS data repository at https://data.dtu.dk/projects/UAWOS/164815. The figure below shows a processed radargram for one of the cross sections of Torne River in Sweden.

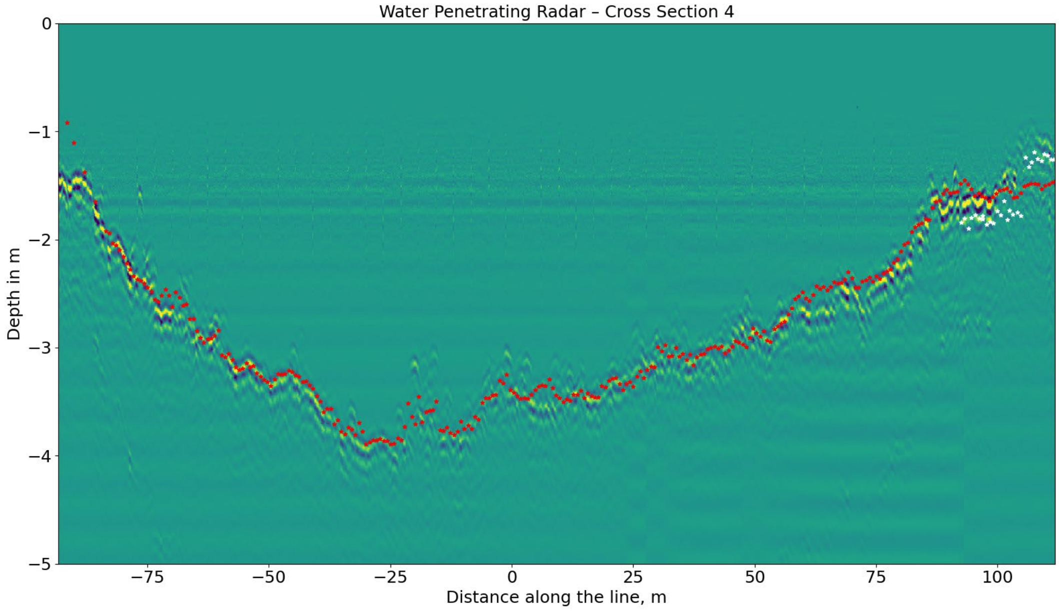

Figure 26 - Processed WPR radargram for cross section 4 of Torne River.
Red dots are ADCP ground truth, white dots along the right edge are RTK ground truth

11.3. Sonar output

Example output of sonar surveys can be found on the UAWOS data repository at https://data.dtu.dk/projects/UAWOS/164815. The figure below shows a processed sonar dataset for one of the cross sections of Roenna Å in Southern Sweden.

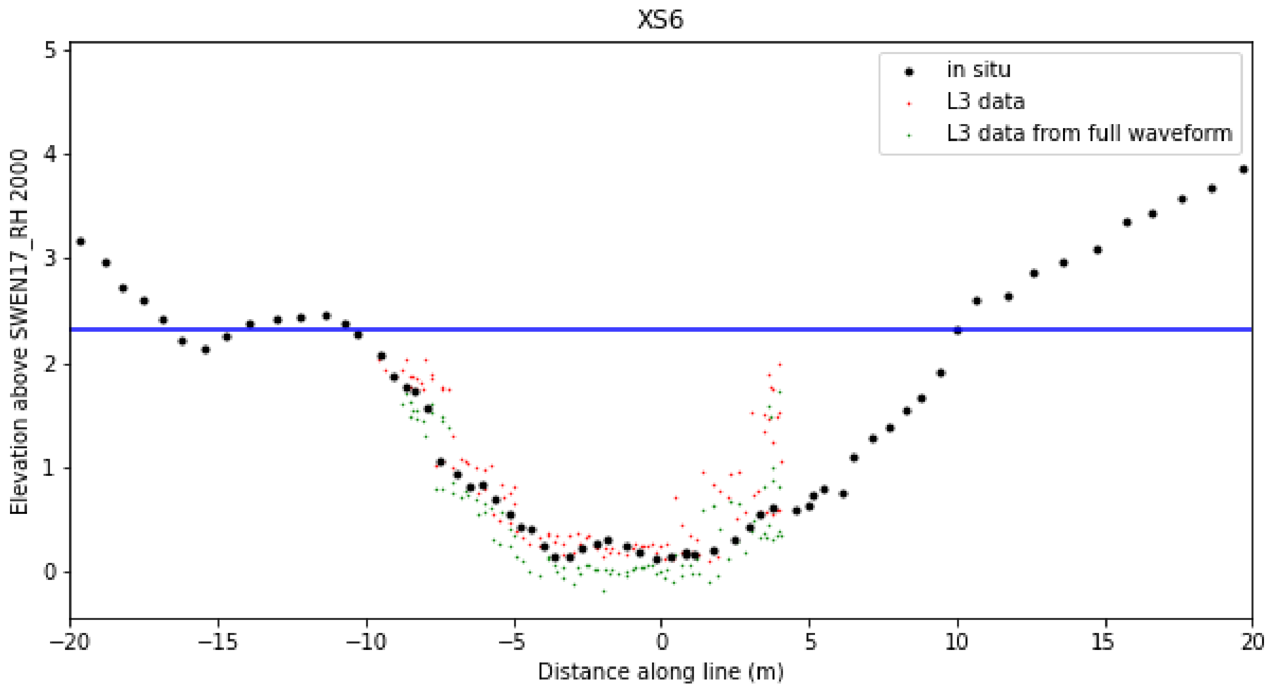

Figure 27 - Sonar bathymetry for cross section 6 of Roenne Å.
Black dots are RTK ground truth, red dots are bathymetry points delivered by the automatic picker that is integrated with the sensor and green points are bathymetry points picked from the sonargram.
The blue line is the water surface elevation.

11.4. Merged lidar and WPR/Sonar

An example of a full cross section consisting of merged lidar and WPR data is shown below. Note significant deviations around cross section coordinate -30 (high grass on the land, which is not penetrated by the lidar) and around cross section coordinate +10 (high aquatic vegetation prevented WPR data acquisition there).

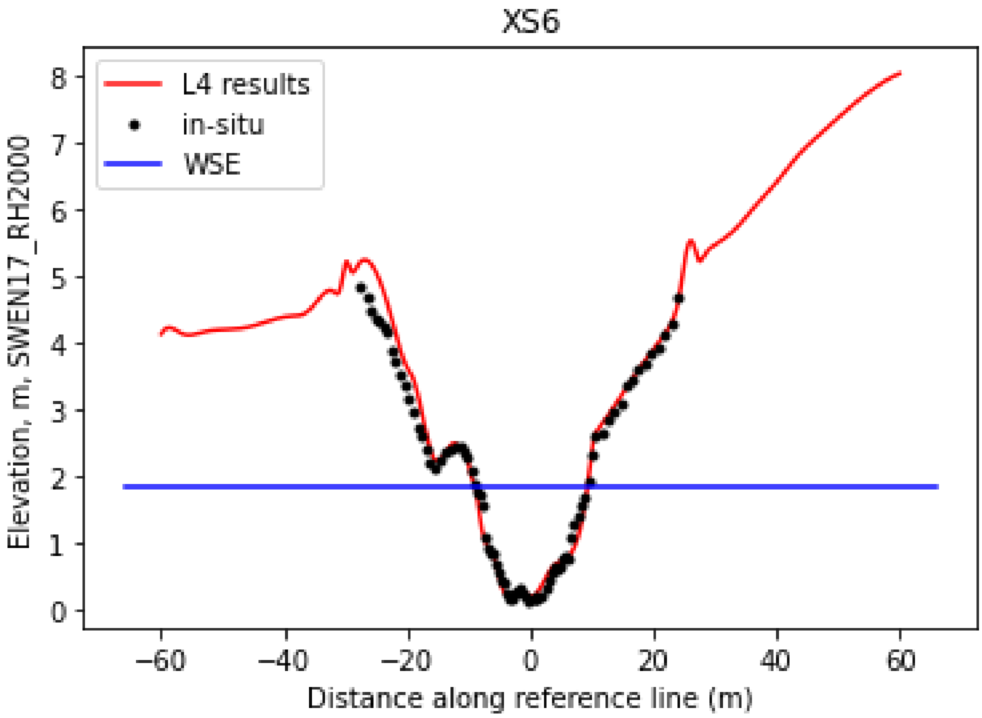

Figure 28 - Cross section 6 of Roenne Å.
Black dots are in-situ RTK observations, blue line is water surface elevation.
Red line is interpolated from merged lidar and WPR datasets, using a spline function.

12. References

Bandini, F., Kooij, L., Mortensen, B.K., Caspersen, M.B., Thomsen, L.G., Olesen, D., Bauer-Gottwein, P., 2023. Mapping inland water bathymetry with Ground Penetrating Radar (GPR) on board Unmanned Aerial Systems (UASs). J Hydrol (Amst) 616, 128789. doi:https://doi.org/10.1016/j.jhydrol.2022.128789

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