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UAWOS - Unmanned Airborne Water Observing System

Deliverable 3.3:

Flow Velocimetry Surveying Protocol

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3. Overview and Summary

This document summarizes the contactless airborne flow velocimetry surveying workflow developed in UAWOS. The document constitutes deliverable D3.3 of the Horizon Europe project “UAWOS – Unmanned Airborne Water Observing System”, contract number 101081783.

The UAWOS flow velocimetry surveying workflow uses a 24 GHz doppler radar sensor described in detail in Zhou et al., 2024. For flow velocimetry surveying, UAWOS has developed new drone payloads as described in UAWOS deliverable D2.4.

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 flow velocimetry surveys.

4. Purpose of Flow Velocimetry Surveying

In-situ reference techniques for river flow velocimetry are Acoustic Doppler Current Profiling (ADCP, Gordon, 1989) and electromagnetic, acoustic or mechanical point velocity measurements using probes (e.g. OTT MFPro), These techniques require the operator to be in contact with the water, either wading through the river or deploying a boat. Such procedures are time-consuming and expensive and can be risky during extreme conditions. This motivated the development of contactless techniques for monitoring river flow velocity.

Stationary Doppler radar sensors deployed on bridges etc. have become a common contactless monitoring option for river flow velocity (e.g. OTT SVR 100). At the same time, airborne contactless monitoring options were developed to increase flexibility, spatial resolution and coverage. The most widely used airborne surface velocimetry technique is image cross correlation from optical video coverage of the flow (Manfreda and Dor, 2023; Strelnikova et al., 2023). Such workflows provide high-resolution surface velocity fields and high accuracy. However, limitations include the need for trackable features in the flow (bubbles, debris, or artificial seeding), the need for sufficient illumination, and complex processing workflows, including the need to stabilize videos and stitch individual video scenes, when the river is wide. Recently, video-velocimetry using thermal video coverage has also been successfully demonstrated, exploiting natural temperature patterns that can be tracked in rivers (Legleiter et al., 2024).

Airborne doppler radar is an alternative to image velocimetry, which is particularly attractive for larger rivers. As described in detail in Zhou et al., 2024, airborne doppler radar provides surface velocity measurements which are representative of an elliptic footprint on the water surface. The size of the footprint depends on the flight height but is typically a few square meters. Doppler radar thus provides much lower spatial resolution than image velocimetry, but data processing effort is significantly reduced and processing of velocity estimates in real-time is straightforward. Doppler radar is suitable for both large and small rivers, as the spacing of velocity samples can be adjusted according to river width to provide appropriate resolution of the lateral surface velocity profile in the river, which is required for the estimation of river discharge.

Figure 1 provides an overview of the flow velocimetry surveying setup and the different hardware components. The centerpiece is the UAV carrying both a doppler radar sensor 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.

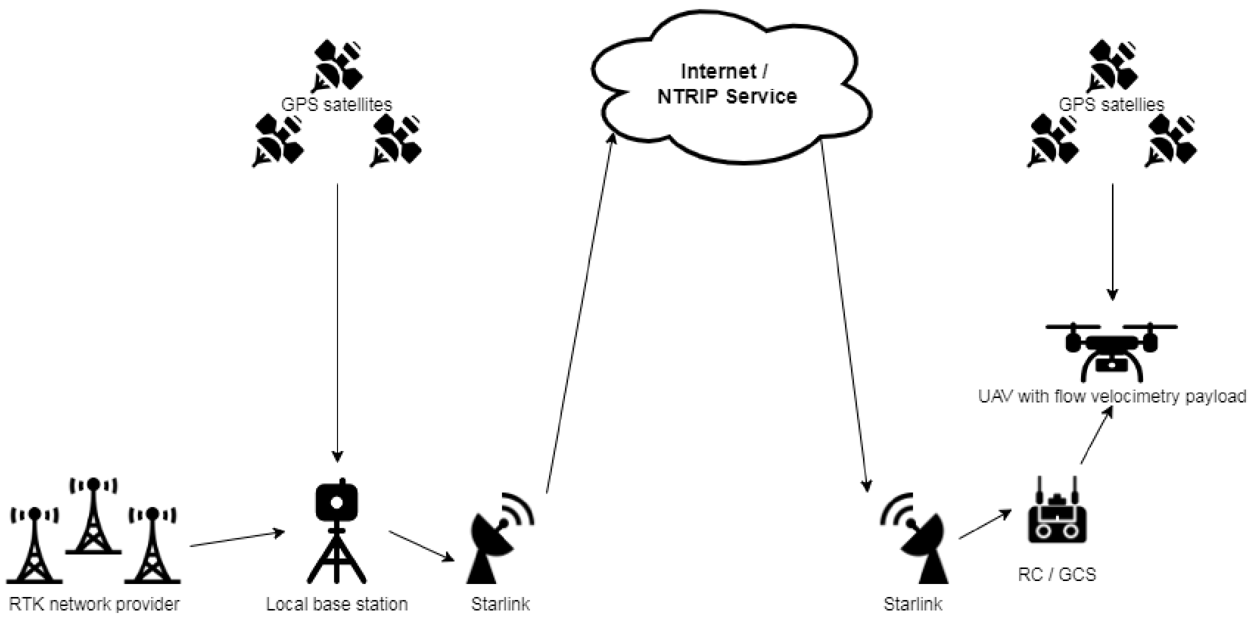

Figure 1 - Overview of flow velocimetry survey setup

5. Surveying Specifications

5.1. Doppler Radar – Flow Velocimetry

5.1.1. Accuracy

The expected accuracy is 0.1 m/s or better.

5.1.2. 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 between 5-20 minutes. Accessibility and flight route endpoint adjustments are accountable for most of the time spent on performing a flow velocimetry cross section. Based on practical experience from a variety of rivers a productivity of 0.75-1.5 cross sections/hour can be expected.

5.1.3. Flight Parameters

Altitude: 4.0 m

Velocity: 20 seconds hovering points

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

Coverage: Dual 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 flow velocimetry surveying productivity substantially.

This Flow Velocimetry Surveying Protocol is based on UAV operation in the ‘open’ category.

6.2. Equipment

This Flow Velocimetry 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 flow velocimetry 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. Doppler Radar Payload

This Flow Velocimetry Surveying Protocol recommends using SkyHub as payload controller in conjunction with Geolux RSS-2-300W Doppler Radar (described in UAWOS D2.4). 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 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 3 - SkyHub payload controller

Figure 4 - DJI M300 RTK with Geolux RSS-2-300W Doppler Radar

6.2.3.TTF Radar Altimeter

Any true terrain following system that allows for cm precise terrain following capabilities at low altitudes (4.0 m) 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).

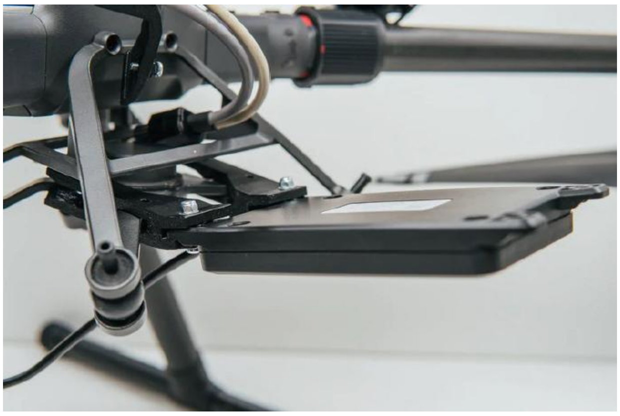

Figure 5 - True Terrain Following kit for DJI drones from SPH Engineering

6.2.4.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 Flow Velocimetry 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 RSS-2-300W Doppler Radar).

6.2.5.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 Flow Velocimetry Surveying Protocol recommends the Emlid Reach M2 as rover GPS. The Emlid Reach M2 is fully compatible with the recommended payload equipment (SkyHub and Geolux RSS-2-300W Doppler Radar).

Figure 6 - Emlid Reach M2

6.2.6.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 Flow Velocimetry Surveying Protocol recommends the Emlid RS3 as local base station.

Figure 7 - Emlid RS3

6.2.7.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 flow velocimetry 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 Flow Velocimetry 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 8 - Starlink receiver and router

7. Desktop Reconnaissance

The purpose of desktop reconnaissance is:

- Decide if onsite reconnaissance is required
- Decide if pre-survey 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 flights 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

If no existing up-to date and precise digital reference data (orthomosaic, satellite imagery, DEM or similar) of the survey area is available, then it is recommended to perform a pre-survey. The purpose of a pre-survey is to attain a precise up to date digital reference of the survey area. This can be achieved by creating a GCP georeferenced orthomosaic or LiDAR point cloud of the area. If applicable, the pre-survey can with advantage be performed as part of a riverbed geometry survey (described in UAWOS D3.2).

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

Often flow velocimetry 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 flow velocimetry surveys due to challenging site characteristics combined with flights at a low altitude.

For flow velocimetry 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.

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

There are two main factors which impact doppler radar data quality:

1) Roughness of the water surface. Low water surface velocity often entails low water surface roughness. During the planning phase it is recommended to consider this aspect. If a desired cross section is suspected to exhibit low water surface roughness, then it is recommended to consider an alternative location with a higher degree of water surface roughness. This could be at a location where the river is narrower or has a different bottom type.
2) Downwash from UAV propellers impacts the collected data. At 4m flight altitude, the recommended UAV, the M300 RTK produces downwash to a degree which can be removed in post processing. It is not recommended to plan flow velocimetry surveys using a UAV that produces a higher degree of downwash compared to the M300 RTK.

The recommended flight altitude using the recommended equipment is 4.0m (from the TTF sensor to the water surface). 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.

Initially define a cross section line. Then define two additional lines in parallel with the cross-section line offset by 4.4m upstream and downstream. The flow velocimetry flight consists of two flight lines which must be placed directly above the 4.4m offset lines. The main flight line is the one offset 4.4m in the upstream direction. The secondary flight line is the one offset 4.4m in the downstream direction. The main flight line is flow first (outbound) and the secondary flight line is flow last (homebound).

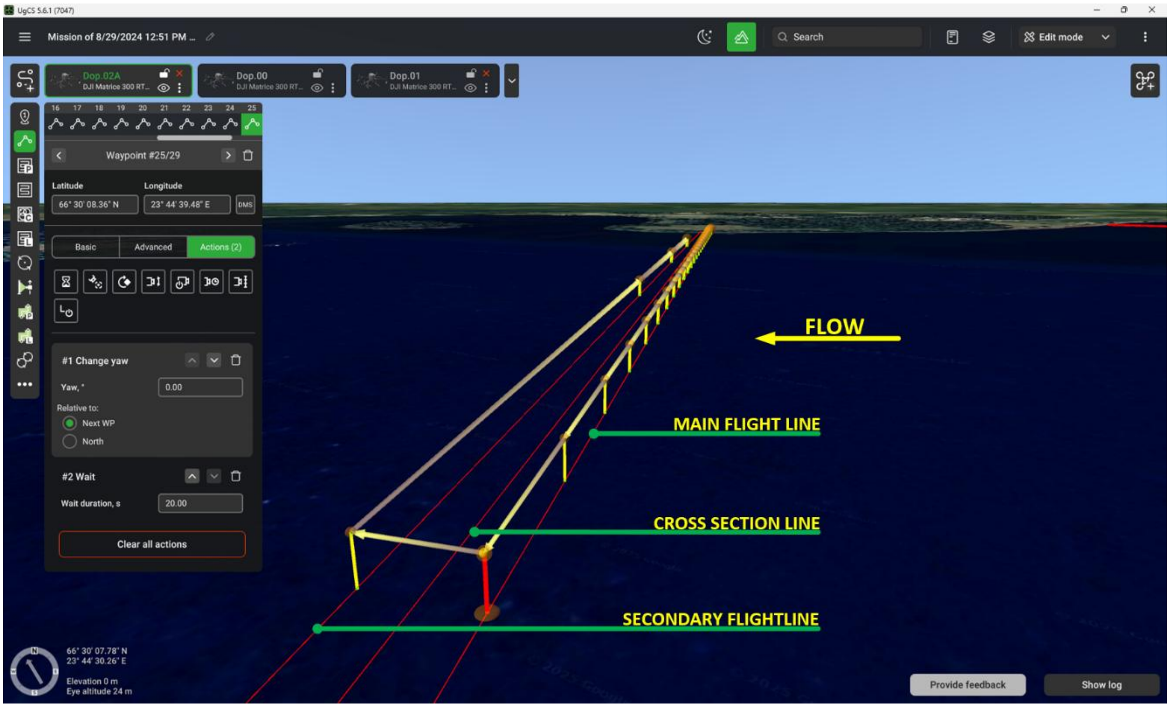

Figure 9 – Flow velocimetry flight route example.

The minimum distance to the shoreline shall be at least 2m in order to obtain usable data. Depending on the quality and precision of the available digital reference, and vegetation conditions at the cross-section location, it may be necessary to increase the distance to the shoreline.

The main flight line shall consist of a number of evenly spaced waypoints at which the UAV must hover for at least 20 seconds while facing the doppler radar towards the cross-section line.

The minimum distance between hover waypoints is 2m.

Practical experience has proven that the recommended UAV, the M300 RTK can, with safety margin, handle up to 25 hovering waypoints on the main flight line. If the river is less than 54m wide, then reduce the number of hovering waypoints. If the river is wider than 54m, then space the 25 hovering waypoints evenly across the main flight line.

After the last hovering waypoint on the main flight line, the next waypoint is placed on the secondary flight line.

The secondary flight line shall consist of 3 hovering waypoints at which the UAV must hover for at least 20 seconds while facing the doppler radar towards the cross-section line. It is recommended to place the 3 waypoints at 75% (halfway between the river center and far-side shoreline), 50% (center of the river) and 25% (halfway between the river center and near-side shoreline).

The recommended GCS, UgCS supports the necessary yaw and hold/wait actions in order to plan and execute flow velocimetry flight routes.

9. Flight Execution

9.1. 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 (6.2.3) 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.

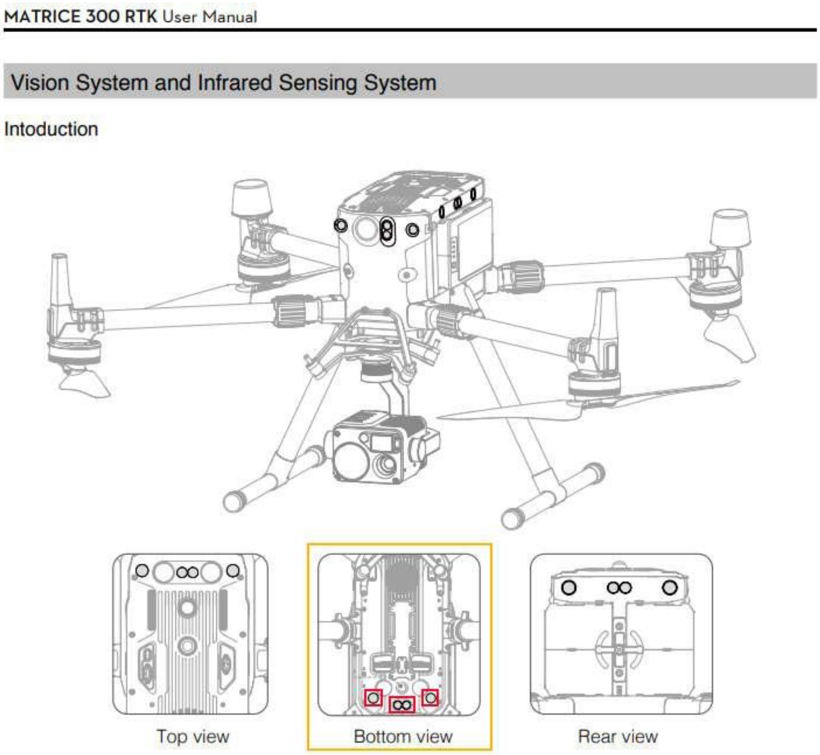

Figure 10 - All four sensors on the bottom must be disabled and covered with tape.

9.2. Doppler Radar Flights

For flow velocimetry routes it is recommended to adjust/verify 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. If the route is planned using a precise and up to date digital reference and there is no vegetation or other obstacles at the riverbanks which can pose a hazard, then endpoint adjustment/verification can be omitted. When performing this decision be aware that at some locations, water surface level, morphology and debris can change in a very short timeframe.

If the flow velocimetry route is flown in conjunction with a bathymetry route, either WPR or sonar route (described in UAWOS D3.2), then it is recommended to perform endpoint adjustment prior to executing the bathymetry route, and then reuse those endpoints adjustments for the flown velocimetry route.

If the flow velocimetry route is flown as standalone, then following steps are recommended for endpoint adjustment:

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.
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.

For flow velocimetry route endpoint adjustments, the hovering waypoints closest to the riverbanks can be moved further away from the riverbank if possible given the requirement of minimum 2m spacing between hovering waypoints can be maintained. If this is not possible, then hovering waypoints close to the riverbanks has to be removed. Thereafter, the neighboring hover waypoint can optionally be moved closer to the riverbank if desired. If waypoints are removed, then be aware that predefined yaw actions may be removed as well and will need to be added to another waypoint.

Once the flow velocimetry flight route has been adjusted, the TTF flight altitude of 4.0m is specified and the flight is executed. Ensure there is sufficient battery capacity remaining to conduct the flight in one go.

Ensure that the UAV has RTK fix during data collection. This is important to achieve a high degree of stability at hovering waypoints which is required for optimal data collection.

During flight execution it is recommended to verify that the doppler radar output is displaying a value. This can be performed using the UgCS CPM software or UgCS app on the remote controller.

If no value is displayed it can be due to too low water surface roughness/velocity. In such case, it is recommended to consider an alternative location with a higher degree of water surface roughness.

Figure 11 – Remote Controller View: Doppler radar payload in flight along the main flight line. Output in lower left corner reports surface velocity value. Barometric altitude in upper right corner is not in effect due to TFF mode.

10. Post-survey Data Processing Steps

10.1. Doppler Radar Data

The doppler radar survey produces the following output:

1) Doppler radar spectrum file in SEG-Y format
2) Doppler radar data file in CSV format
3) Position log file including trace numbers in CSV format
4) Rover GNSS raw observation file
5) Local base station raw observation and navigation files

The doppler spectrum is a two-dimensional data structure. It consists of a few hundred to a few thousand traces (radar echo curves). Each trace has 4,096 samples, with each sample containing the energy of the echo at a specific frequency bin. The doppler shift observed in the radar signal corresponds to the velocity of the water surface relative to the sensor.

The following describes the steps for processing acquired doppler radar data.

For in depth description of processing details please refer to Zhou et al., 2024.

For python code and addition processing description please refer to Zhou, Z. [Software].

Doppler radar processing consists of the following steps:

1. Perform PPK processing is necessary. Ideally RTK should be active during all doppler radar data acquisition since the data quality may be lower without. RTK status can be inspected in the position log file. PPK processing is performed using the position log, local base station raw observations and the rover GPS raw GNSS observations. Various software solutions can perform this task, ex. Emlid Studio.
2. Segregate doppler radar traces according to flown waypoints using the python code example: ‘Plot_altitude_vs_traces_vs_distance_example.py’
3. Apply Gaussian model fitting using the python code example: ‘Reselect_traces_Gaussian_fitting.py’

11. Output Data Formats and Example Output

11.1. Doppler Radar Output

Example output of doppler radar 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.

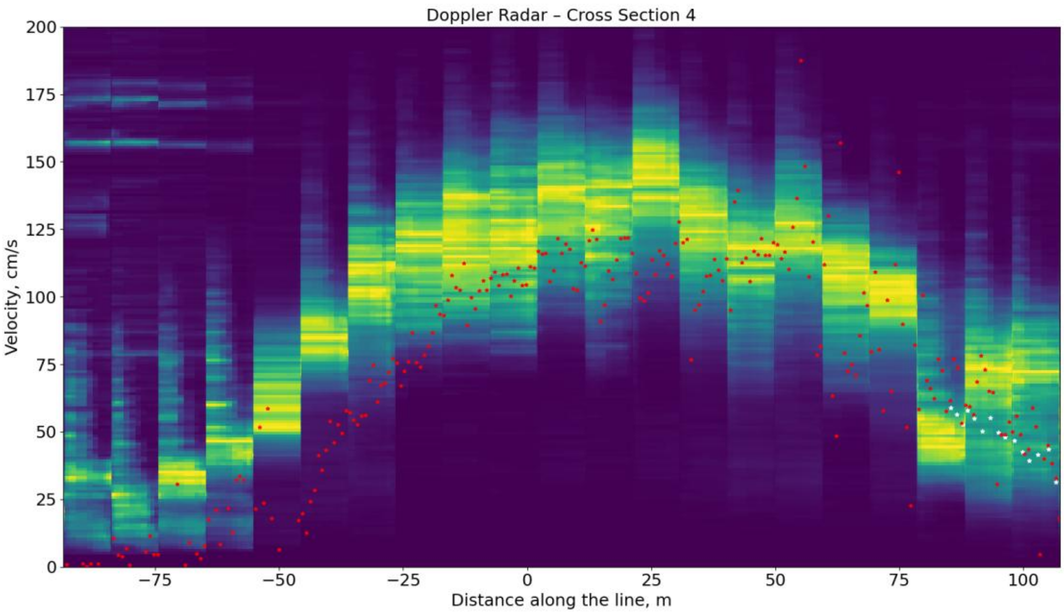

Figure 12 - Processed doppler radar velocimetry radargram for cross section 4 of Torne River. Red dots are ADCP ground truth, white dots along the right edge are OTT MFPro ground truth

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