HORIZON-CL6-2022-GOVERNANCE-01-07: "New technologies for acquiring in-situ observation datasets to address climate change effects"

Action acronym: **UAWOS**
Full title: **Unmanned Airborne Water Observing System**
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UAWOS - Unmanned Airborne Water Observing System

Deliverable 3.1:
WSE Surveying Protocol

Date: 31 January 2024
Lead Author: Henrik Grosen

1. Change Record

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V3	Henrik Grosen, Sune Nielsen, Peter Bauer-Gottwein	31 January 2024	UAWOS_D3.1 - WSE Surveying Protocol_v3.docx

2. Table of Contents

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.

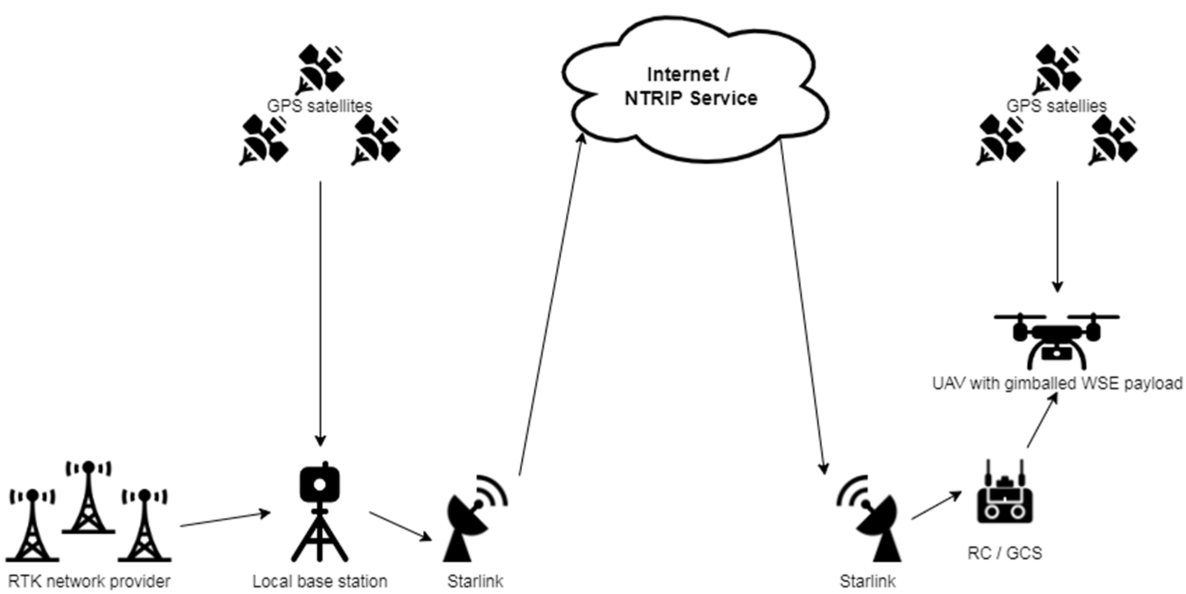

Figure 1 - Overview of WSE survey setup

5. Surveying specifications

5.1. 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.

5.2. Productivity & Scale

The productivity which can be expected is highly dependent on the survey area 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.

5.3. 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.

BVLOS operations have the potential to enhance WSE surveying productivity substantially.

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

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 Multirotor

Any RTK-enabled multirotor UAV with sufficient payload capacity for the chosen sensor is appropriate. The WSE 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.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 3 - Gremsy T3V3

6.2.3.Payload

Any radar altimeter sensor which fulfills the following requirements can by 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 4 - 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 5 - Geolux LX-80

6.2.4.Ground Control Software

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)
- 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).

6.2.5.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 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 WSE 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 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 does 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 8 - Starlink receiver and router

7. Desktop Reconnaissance

The purpose of desktop reconnaissance is:

- Decide if onsite reconnaissance is required
- Decide if a 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 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.

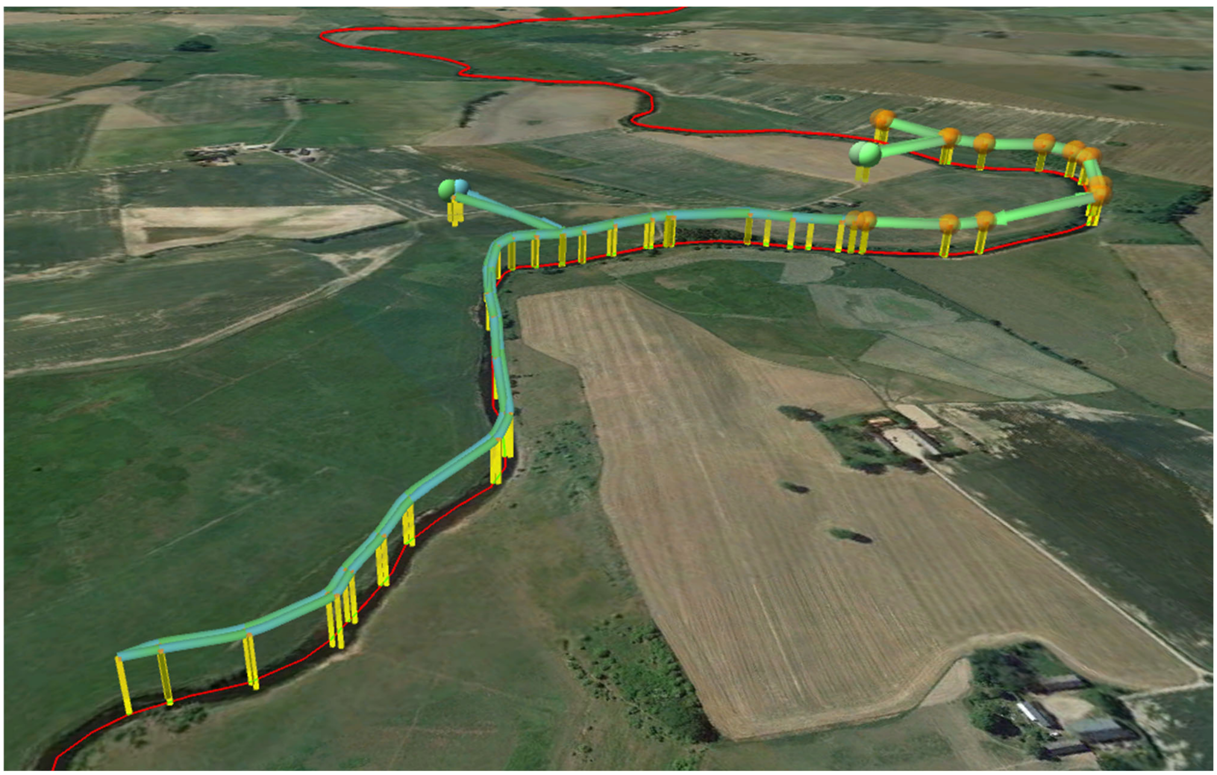

Figure 9 - Flight routes example

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.

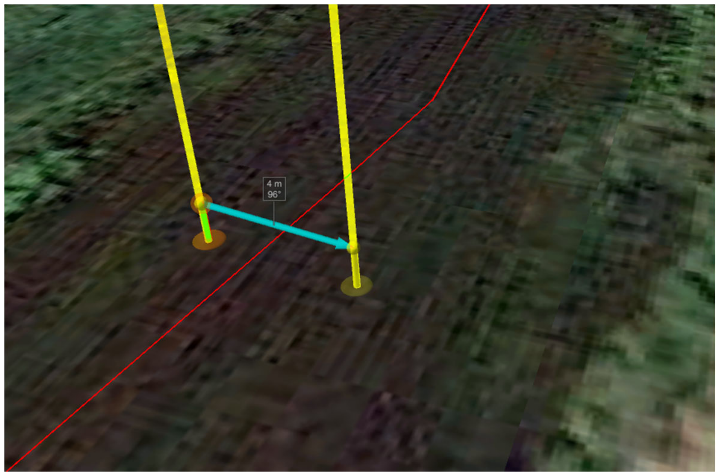

Figure 10 - 2m offset from centerline in a narrow river

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.

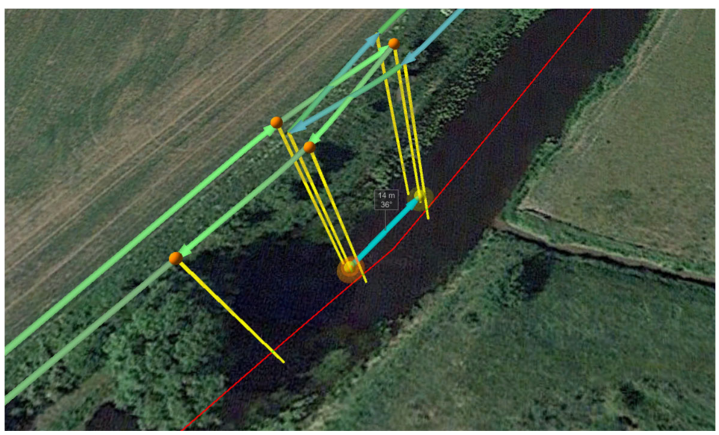

Figure 11 - 15m overlap between flight routes

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.

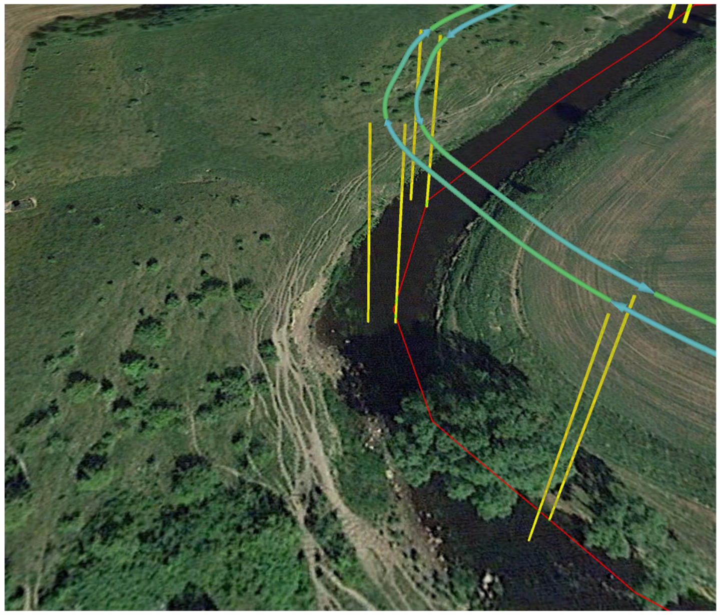

Figure 12 - Offsetting WP in sharp turns

9. 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.

10. Output data formats and example output

```
,Folder,Entry,PacketID,TS,Lon,Lat,Alt,SDU,MaxIndex,MaxPower,CompIndex,CompPower,RadarDist,WL,Geoid,Projected_X,Projected_Y,WL_Geoid,ShapeDist,ShapeIndex,ShapeChain,MeanWindow,MedianWindow,StdWindow,MeanConfLow,MeanConfHigh,MedianConfLow,MedianConfHigh
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Figure 13 - Example output, CSV format

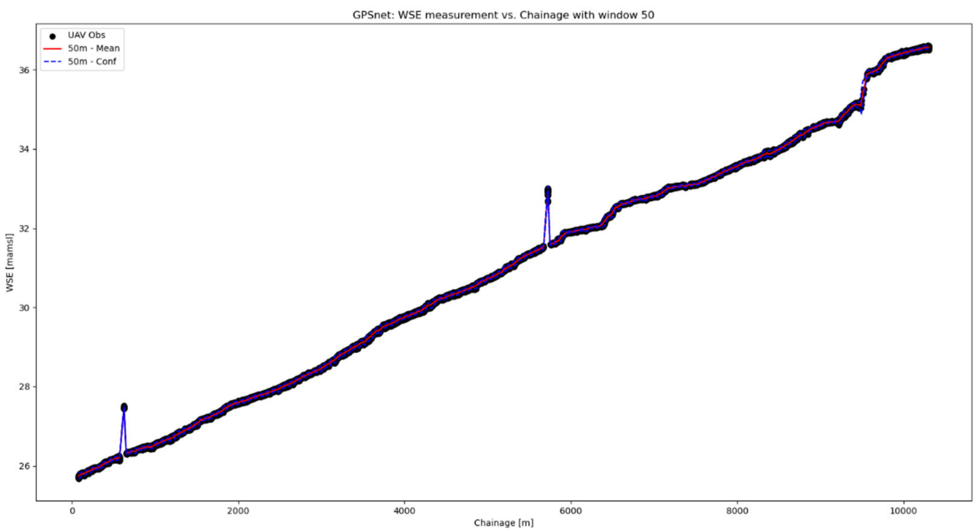

Figure 14 - Example output, Graph

11. 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.

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