Guidelines for Siting and Operating Surface-water Velocity Radars

The goal ... To collect channel velocity and cross-section data on Monday and operationally transmit real-time stage, velocity, area, and discharge on Tuesday regardless of:

- How surface-water velocities were measured (LSPIV or radar)
- The hydraulic conditions that existed on Monday

Introduction

The United States Geological Survey (USGS) and Environment and Climate Change Canada (ECCC) are exploring the use of velocity radars to measure surface-water velocities and compute real-time mean-channel velocity and discharge in streams and rivers. Velocity radars can deliver real-time discharge at new stations where stage-discharge, index-velocity, or slope-discharge ratings are not available; extend ratings; corroborate indirect measurements; and provide an alternative for measuring discharge at sites with complex ratings. The ultimate goal of this effort is to transition the use of surface-water velocity radars from a proof-of-concept to an operational mode and to more clearly determine operational limitations.

Backstory

These guidelines are an extension of the non-contact methods initiated by HYDRO 21 (Costa et al., 2006). The USGS Hydrologic Instrumentation Facility (HIF), Project Chiefs from 6 USGS Water Science Centers (WSCs), and two vendors (Stalker and Hydrological Services of America; HSA) participated in proof-of-concept testing. Fourteen (14) sites, which exhibited different hydraulic flow regimes, were identified and collocated with existing USGS streamgages. Laboratory testing was conducted in parallel with field deployments by the HIF (Fulford, 2015) and the Switzerland Federal Institute of Metrology (METAS). Testing at the HIF and METAS was conducted in the spring 2015 using standard methods including flumes, carriage-tow tanks, and tuning forks with known frequencies. Stalker and HSA offered their units gratis in exchange for an assessment on their performance. Similarly, OTT Hydromet (OTT) offered their radar for testing; however, the unit is still under development.

Quick Start Guide

You'll need to acquire a small amount of velocity and channel data beyond what a normal field trip demands. Data should be collected at the cross section-of-interest and in the vicinity of the radar footprint. Keep in mind that the radar's ability to return a surface-water velocity is influenced by (1) the quality of scatterers or waveforms on the water surface, (2) the air gap or the distance between the bridge deck and the water surface, and (3) the potential noise imposed by wind drift, eddies, secondary flows, and macro turbulence.

Follow the same principles used to site a conventional streamgage (Site Selection, p. 9; Turnipseed and Sauer, 2010):

- Straight channels with parallel streamlines
- Streambed free of large rocks, weeds, obstructions that would create turbulence/slack water
- Sections that are parabolic, trapezoidal, or rectangular
- Avoid variable flow conditions downstream of piers or channel obstructions (Please note it is important they we target surface scatterers to achieve sufficient radar returns, but highly turbulent conditions should be avoided)
- Velocities greater than .5 to 1 feet per second (fps) and depths greater than 0.5 feet (ft)
- Avoid sections influenced by tributaries or contributing drainage

Collect the following streamflow and channel data at the cross section-of-interest:

- Station number and measurement number
- Date of measurement
- Width
- Area
- Mean-channel velocity
- Gage height
- Discharge
- Lat/long of the starting and ending edge of water
- Lat/long of the vertical termed the “y-axis”, where the maximum in-stream or maximum surface-water velocity is measured
- At the y-axis, record the surface-water velocity and point velocities near the water surface, close to the channel bottom, 0.2D, 0.3D, 0.4 D, 0.5D, 0.6D, 0.7D, 0.8D, 0.9D using a current meter, FlowTracker, or Stationary Moving Bed Analysis with an ADCP
- Confirm the location of the y-axis by repeating this procedure to the left and right of the y-axis
- Water depth at the y-axis
- Wind speed and direction

To estimate the stationing of the y-axis, rely on the location of the maximum-surface water velocity; it generally coincides at the same vertical as the maximum-instream velocity

Develop a stage-area rating using AreaComp (https://hydroacoustics.usgs.gov/indexvelocity/AreaComp.shtml)

Generally, data collection and radar deployments point should be upstream of bridges or structures to avoid eddies, secondary flows, and macro turbulence

Wind dominated reaches complicate data collection by requiring a way to remove wind effects from recorded surface velocities

Velocity radars can be deployed by hand or fixed on bridges, light cableways, or cable stays
Purpose

This document was designed to (1) evaluate whether radars can accurately measure surface-water velocities, (2) compute the mean velocity and discharge at a channel cross-section, (3) identify the environmental and hydraulic factors that influence surface-water velocity measurements, and (4) establish a protocol for transitioning the proof-of-concept to an operational streamgage platform.

Velocity radars can be deployed by hand (figure 1) or fixed on bridges (figure 2), light cableways or cable stays (figure 3).

Methods

Channel, velocity and discharge data should be co-collected using methods consistent with Turnipseed and Sauer (2010) or Office of Surface Water Hydroacoustics webpage (http://hydroacoustics.usgs.gov/index.shtml).

Site Selection

Channel, velocity and discharge data measured at USGS streamgages will be used to validate the radar-derived data; however, when siting a surface velocity radar, the same hydrodynamic conditions used to site a conventional streamgage (Site Selection, p. 9; Turnipseed and Sauer, 2010) should be followed, which include:

- Straight channels with parallel streamlines
- Streambed free of large rocks, weeds, obstructions that would create turbulence/slack water
- Sections that are parabolic, trapezoidal, or rectangular
- Avoid variable flow conditions downstream of piers or channel obstructions (Please note it is important they we target surface scatterers to achieve sufficient radar returns, but highly turbulent conditions should be avoided)
- Velocities greater than .5 to 1 fps and depths greater than 0.5 ft
- Avoid sections influenced by tributaries or contributing drainage

Data Needed to Compute Discharge

It is important to note the stationing or location of the vertical ("termed the y-axis") in a cross section where the maximum-instream or maximum-surface water velocity occurs. Generally, the maximum-surface-water velocity occurs at the same vertical as the maximum-instream velocity. The y-axis is also where all velocity and depth data should be collected to translate surface velocities into a mean-channel velocity. Velocity data can be collected using current meters, ADCPs, and ADVs. The following data will be recorded at each measured cross section:

- Station number and measurement number
- Date of measurement
- Width
- Area
- Mean-channel velocity
- Gage height
- Discharge
- Lat/long of the starting and ending edge of water
- Lat/long of the vertical (termed the "y-axis") where the maximum in-stream or maximum surface-water velocity is measured
- At the y-axis, record the surface-water velocity and point velocities near the water surface, close to the channel bottom, 0.2D, 0.3D, 0.4D, 0.5D, 0.6D, 0.7D, 0.8D, 0.9D using a current meter, FlowTracker, or Stationary Moving Bed Analysis with an ADCP
- Confirm the location of the y-axis by repeating this procedure to the left and right of the y-axis; to estimate the stationing of the y-axis, rely on the location of the maximum-surface water velocity; it generally coincides at the same vertical as the maximum-instream velocity
- Water depth at the y-axis
- Wind speed and direction
- Stage-area rating using AreaComp (https://hydroacoustics.usgs.gov/indexvelocity/AreaComp.shtml).

Y-axis Stability

The y-axis, which contains the maximum in-stream or surface-water velocity, should be recorded at the cross section-of-interest. Research indicates the y-axis is quite stable and does not vary with changing hydraulic conditions (Fulton, 2011; Fulton and Ostrowski, 2008; Chiu et al., 2001; Chiu and Chen, 1999; Fulton, 1999). It should be noted that y-axis rarely coincides with the channel thalweg in open or engineered channels. Generally, the location of the y-axis and the parameters used to compute discharge (see Surf Board link, https://my.usgs.gov/confluence/pages/viewpage.action?pageId=552933693) remain constant for a cross-section regardless of variations in stage, velocity, flow, flow, channel geometry, bed form and material, slope, or alignment; however, field verification of these parameters must be conducted periodically and a stage-area rating must be maintained. Although used for verification and confirmation, historical data such as stage, velocity, and discharge, which are commonly collected for a range of low and high flow events, is not needed, but it is advised. By following the procedures listed below, real-time mean-channel velocity and discharge can be computed straight away.

Measure Channel Geometry

If the channel has not been surveyed, it is recommended that the cross section be surveyed and include the wetted perimeter and above-water points-of-interest in the floodplain. The stage-area rating is used to compute area, which is required to compute discharge. Horizontal and vertical control should be surveyed relative to the gage datum using a total station survey, GPS receiver, or an equivalent. The program AreaComp (Lant and Mueller, 2012) can be used to generate a synthetic stage-area rating, when estimating areas above the water surface during the day of the siting.
Current meters or ADVs

When wading is possible, measure velocities and compute discharge in accordance with Turnipseed and Sauer (2010). Select the y-axis from the 25 - 30 verticals comprising the measurement that exhibits the greatest velocity value based on either the maximum-surface velocity; 0.2D and 0.8D velocities; or 0.6D velocity. At the y-axis, measure the surface velocity using handheld or portable velocity radar concurrently with point velocities immediately below the water surface to the channel bottom at an interval that can be used to adequately define the velocity distribution along the selected vertical. Depending on water depth, this should include a minimum of 6 point velocities (near the channel bottom, 0.2D, 0.4D, 0.6D, 0.8D, close to the water surface while minimizing air entrainment); however, it is preferred that the surface velocity, point velocities near the water surface and close to the channel bottom, 0.2D, 0.3D, 0.4D, 0.5D, 0.6D, 0.7D, 0.8D, 0.9D be collected. Repeat this procedure to the left and right of the y-axis.

ADCPs

When wading is not possible, velocity data should be collected at the y-axis using a Stationary Moving Bed Analysis (SMBA) either by boat, light cableway, tethered from a bridge, or river banks. Surface velocities should be collected concurrently with the ADCP measurement using handheld or portable velocity radar. Repeat this procedure to the left and right of the y-axis. Discharge should be computed using QRev or an equivalent. When coupled with a GPS receiver, the lat/long of the y-axis should be recorded or established using VMT (Parsons, 2012). Process the velocity distribution in WinRiver II by choosing:

Select Playback

“Reprocess Selected Transect”

Select Configure

“Averaging Data” to identify the number of ensembles to average to reduce noise

Select View

“Tabular, Earth Velocity Magnitude and Direction” and “Graphs, Profile, Velocity”

The depth and velocity data can be copied to a text file.

Surface velocity Radars

Velocity radars are used to measure surface velocities and do not penetrate the water surface. Typically, the vertical containing the maximum-surface velocity will contain the maximum-instream velocity. Velocities should be measured relative to bridge stationing or geo-referenced using a GPS receiver. 20 to 25 surface-water velocities are needed to adequately identify the maximum-surface water velocity and y-axis. The velocity radar can be pointed upstream (preferred) or downstream from a bridge or walkway. It should be oriented parallel to flow lines and tilted (from horizontal) at a nominal 45-degree incidence angle. It should be noted that different radar units operate at different incidence angles. It’s important to note when collecting velocity data to avoid wind-dominated reaches, eddies, secondary flows, and macro turbulence.

Compare Radar-derived Discharges to Conventional Methods

Conventional methods including stage-discharge and index-velocity ratings, current meters/ADVs/mid-section method, and ADCPs are widely accepted as industry-standards (table 1). As a result, they will be used as a periodic benchmarks and should be conducted in conjunction with the radar-derived discharges for comparison purposes. Real-time radar results from the Tanana River at Nenana, AK (Heather Best) and Rio Grande at Embudo, NM (Jay Cederberg) are presented in figures 12 and 13, respectively.

Table 1 Method summary.

<table>
<thead>
<tr>
<th>Field Methods</th>
<th>Computation Methods</th>
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</thead>
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<tr>
<td>Conventional</td>
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<tr>
<td><strong>ADCP</strong></td>
<td>QRev, WinRiver II or RiverSurveyor</td>
</tr>
<tr>
<td><strong>ADV</strong></td>
<td>Mid-section Method</td>
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<tr>
<td><strong>Current-meter</strong></td>
<td>Mid-section Method</td>
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<td><strong>Surface-water velocity</strong></td>
<td>Surface Method</td>
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</tbody>
</table>
Challenges

Surface velocity radars will not work at every site, particularly where wind drift is dominant and surface-water velocities are less than 0.5 fps and the surface-water scatterers (small wave forms) are ill-defined.

Environmental Factors

The scatterer size and quality is a function of the frequency of the transmitted radar and environmental factors such as wind drift, turbulence, and rain. The length of these small-scale surface waves or Bragg waves is computed using equation 1:

\[ b = \frac{\lambda}{2 \sin \theta} \]

Eq. 1

Where,

- \( b \) = wavelength of the water wave or Bragg wave, Gigahertz; GHz
- \( \lambda \) = wavelength of the transmitted radar signal; GHz
- \( \theta \) = the incidence angle
- \( \theta = \frac{c}{v} \)

Where,

- \( c = \) speed of light = 3E8 meters per second, m/s
- \( v = \) frequency in hertz; Hz

Given,

K-band radar transmission frequency = 24 GHz = 24E9 Hz

Incidence angle = 45 degrees

\[ b = \frac{3E8 \text{ m/s} \times 100 \text{ cm/m} / 24E9 \text{ Hz} / (2 \times \sin 45 \text{ degrees})}{0.88 \text{ cm}, \text{ which represents the small-scale surface waves that serve as scatterers.}} \]

A wind-drift correction algorithm was developed and applied to the Red River of the North at Grand Forks, ND (Chris Laveau). The results are illustrated in figures 10 (raw discharge) and 11 (corrected discharge for wind drift).

Duration of Sampling and Filtering

The duration of sampling has an impact on radar returns and should be optimized in the field based on the spectrum returned from the radar (figure 12). Typically, sample durations range from 40 seconds to 2 minutes. A number of filtering schemes to reduce measurement noise such as high- and low-pass filters, moving averages, LOESS, Savitsky-Golay filter, and Kalman filter are being investigated.

Data Quality

Regardless of the equipment selected, velocity variations associated with turbulence create noise in the data, which complicates the analysis. The objective is to minimize scatter in the velocity data collected at the y-axis by reducing the standard deviation of the velocity data.

When using current meters or ADVs, turbulent flows that can dominate in natural and artificial channels are accompanied by local eddies (Rantz et al., 1982) that can result in variations in the velocity in any direction. It changes rapidly in time and space and is scale-dependent. Pierce (1941) reported that the velocities recorded by current meters in laboratory flumes were greater in magnitude (relative to the mean velocity) for lower velocities when compared to higher velocities. At high velocities, variations have a minor effect on current-meter observations. It’s customary to observe velocity at a point by current meter for a period that ranges from 40 to 70 seconds (Rantz et al., 1982).

When using ADCPs it is important to minimize noisy data related to ADCPs, this is achieved by collecting an even number of (reciprocal) transects with a minimum of 720 seconds total exposure time be made during steady-flow conditions. The measured discharge will be the average of the discharges from all valid reciprocal transects. Reciprocal transects should always be made to reduce potential directional biases. For policy detail, see OSW Technical Memorandum 2011.08. If using a TRDI product, the Correlation Profile should be reviewed to ensure the quality of the measurement is sufficient (reviewing the signal-to-noise ratio, SNR) to ensure the SNR is greater than 128. After locating the y-axis and to provide for redundancy, velocity data should be collected at the y-axis using a an SMBA either by boat or tethered from a bridge or river banks.
When using surface velocity radars and depending on variations in velocities with time, each vertical should be sampled for 40 seconds to 2 minutes. Please note if measurements are collected downstream of a bridge and depending on stage, piering can create secondary flow patterns that can influence the velocity distribution at the y-axis and ultimately the parameters used to compute discharge. It’s preferred that all radar and hydroacoustic measurements be collected upstream of bridges. Using ADCPs downstream of a bridge to compare discharge rates is acceptable. Diagnostic tests, which are run for current meters or acoustic instruments, are not available for velocity radars. However, tuning forks can be used to validate the velocities reported by a radar (equations 2 and 3). By striking the tuning fork and placing the tuning fork in front of the radar antenna, the recorded velocity is measured using the Doppler shift.

\[ v = \frac{f_{\text{Doppler Shift}} \times c}{2 \times f_{\text{radar}}} \]  
Eq. 2

Where,

\[ v = \text{velocity recorded by the radar, feet per second; fps} \]

\[ f_{\text{Doppler Shift}} = \text{Doppler shift associated with tuning fork frequency; Hz} \]

\[ c = \text{speed of light, miles per second; mi/s} \]

\[ f_{\text{radar}} = \text{radar frequency, gigahertz; GHz} \]

Given,

\[ f_{\text{Doppler Shift}} = 1055 \text{ Hz tuning fork frequency} \]

\[ c = 186,000 \text{ mi/s} \]

\[ f_{\text{radar}} = 24.150 \text{ GHz} \]

\[ v = \frac{1055 \text{ Hz} \times 186,000 \text{ mi/s} \times 5,280 \text{ ft/mi}}{(2 \times 24.150 \text{ GHz} \times 10^9 \text{ Hz/1 GHz})} = 21.5 \text{ fps} \]  
Eq. 3

Some portable and fixed-mount radars (Sommer Messtechnik) produce spectra, which offer a quantitative tool that serves as a “spin test” for electromagnetic instruments and can be used to qualify the value of surface-water velocity estimate. Figures 14 through 16 offer examples of good, fair, and poor spectra that can be used to assess the quality of the measurement.

Figures

**Figure 1**
Handheld radar (Stalker Pro II SVR) deployed from a bridge used to measure surface-water velocities concurrently while measuring point velocities with a FlowTracker at the y-axis in a cross section.

**Figure 2**
Fixed-mount radar (Sommer RQ30 and Stalker Surface Velocity Sensor) deployed from a bridge near upstream of USGS streamgage 05082500 Red River of the North at Grand Forks, ND and used to measure surface-water velocities and compute discharge. Courtesy of Chris Laveau.
Cable stay deployment (Sommer RQ30), where little or no infrastructure exists at USGS streamgages 385309104561101 Middle Waldo and 385254104560401 Lower Waldo. The radars are used to measure surface-water velocities and compute discharge. Data is transmitted via 3G and Iridium modems.

Figure 4
Good surface scatterers (Green for go!) and minimal wind drift. Poor surface scatterers (Red for stop!) downstream of piering. Fixed-mount radars (Sommer RQ30 and Stalker Surface Velocity Sensor) deployed from a bridge upstream of the USGS streamgage 08279500 Rio Grande at Embudo, NM. The radars are installed at the y-axis of the cross section and are used to measure surface-water velocities and compute discharge. Courtesy Jay Cederburg.

Figure 5
Good surface scatterers (Green for go!) and minimal wind drift. Poor surface scatterers (Red for stop!) caused by wind drift. Wind drift creates noise in the radar returns and must be corrected prior to transmitting surface-water velocities. Upstream of the USGS streamgage 15515500 Tanana River at Nenana, AK. Courtesy Heather Best.
Good surface scatterers (Green for go!) and minimal wind drift upstream of the pier, where the radar is pointing. Poor surface scatterers (Red for stop!) located downstream and adjacent to the pier caused by secondary flows and eddies. Fixed-mount radar (Sommer RQ30) deployed from a bridge upstream of the USGS streamgage 06192500 Yellowstone River near Livingston, MT. The radars are installed at the y-axis of the cross section and are used to measure surface-water velocities and compute discharge. Courtesy Steve Holnbeck.
Good surface scatterers (Green for go!) associated with pancake ice. Fixed-mount heterodyne radar (APL-UW RiverScat) is pointing upstream near USGS streamgage 01538700 Susquehanna River at Bloomsburg, PA.

Figure 8
Good surface scatterers (Green for go!) near the USGS streamgage 05056678 Tolna Coulee near Tolna, ND. Courtesy Chris Laveau.

Figure 9
Poor surface scatterers (Red for stop!) and significant wind drift near USGS 06751490 North Fork Cache La Poudre River at Livermore, CO.

Figure 10
Raw discharge data, Red River of the North, Grand Forks, ND (PROVISIONAL).

**Figure 11**

Wind-drift corrected discharge data, Red River of the North, Grand Forks, ND (PROVISIONAL).

**Figure 12**
Stage-discharge rating and instantaneous radar-derived discharge, Tanana River at Nenana, AK (PROVISIONAL). Unsure if noise is from wind or hydraulic features such as boils.

Figure 13

Stage-discharge rating, radar-derived discharge and measured discharge, Rio Grande at Embudo, NM (PROVISIONAL).

Figure 14
Good spectra with a sharp peak and no velocities from opposite directions. Courtesy Wolfram Sommer (Sommer Messtechnik).

Figure 15
Fair spectra with small velocities from opposing directions, yet a significant peak in the direction of flow. Courtesy Wolfram Sommer (Sommer Messtechnik).

Figure 16
Poor spectra with velocities from a variety of directions and multiple peak velocities. The radar will recognize a velocity, but it will not be very accurate. Courtesy Wolfram Sommer (Sommer Messtechnik).

References


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- Field Radar Guidelines Quicksheet (printable)