Measuring stream discharge by non-contact methods: A proof-of-concept experiment

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Abstract. This report describes an experiment to make a completely non-contact open-channel discharge measurement. A van-mounted, pulsed doppler (10GHz) radar collected surface-velocity data across the 183-m wide Skagit River, Washington at a USGS streamgaging station using Bragg scattering from short waves produced by turbulent boils on the surface of the river. Surface velocities were converted to mean velocities for 25 sub-sections by assuming a normal open-channel velocity profile (surface velocity times 0.85). Channel cross-sectional area was measured using a 100 MHz ground-penetrating radar antenna suspended from a cableway car over the river. Seven acoustic doppler current profiler discharge measurements and a conventional current-meter discharge measurement were also made. Three non-contact discharge measurements completed in about a 1-hour period were within 1 % of the gaging station rating curve discharge values. With further refinements, it is thought that open-channel flow can be measured reliably by non-contact methods.

1. Introduction

The basic method by which flow in open channels is measured at streamgaging stations has not changed for over 100 years. A current meter with rotating propeller or cups is lowered into the river and may be stabilized by a heavy lead weight when depth or velocity is large. The velocity of flow at a point is proportional to the rate of rotation of the rotor during a measured period of time (Rantz, 1982). Multiple depth and velocity measurements are taken across the channel, and these sub-areas summed to calculate the total stream discharge. These discharge values are used to define a relation between the stage (depth) and rate of flow (discharge), referred to as a rating curve.

Discharge data collected under ideal conditions, using a properly rated current meter and following accepted practices, are generally considered to be within 5 % of the true value (Sauer and Meyer, 1992). During floods, direct measurement of flow with a current meter or any other instrument that must be placed in the water could introduce high measurement errors, and safety hazards. Debris can snag equipment and cables, jeopardizing the safety of technicians suspended over the water on cableways. At times conditions are sufficiently hazardous that no current-meter measurement can be made. When discharge measurements are not available, the stage-discharge relation is defined by indirect methods, which are less accurate than direct measurements. Lower-quality high-flow data mean less accurate estimates of flood-frequency and flood-inundation areas.

Procedures used in this experiment may not be those we expect to be used in the future, but the experiment is important as a proof of concept because of its future potential, increased safety, and to dispel the belief that open-channel flow cannot be measured with remote sensing data alone (e.g. Schultz, 1996).

In cooperation with the Applied Physics Laboratory of the University of Washington, the U.S Geological Survey devised an experiment using radar technology that would allow the direct measurement of river discharge without any instrument having to touch the water. Lessons learned from this experiment would hopefully identify directions for future efforts to reinvent methods of streamgaging that would be safer, more efficient, and less expensive than present. With non-contact radar technologies there is no reason why streamflow information should be degraded as flow rate or stage increases. In this experiment, accuracy of the non-contact discharge estimate was assessed by concurrent measurement of discharge by a conventional current-meter measurement, an acoustic doppler current profiler (Simpson and Oltmann, 1993), and a long-term stage-discharge rating curve for the site.

2. Use of Radar for Non-Contact Discharge Measurements

Measurements of stream discharge require information about the mean velocity in a number of sub-sections across the river, and knowledge of the geometry of the cross-section of the river at the measuring location. Microwave doppler radar offers a remote means of measuring water-surface velocities of rivers using Bragg scattering from short waves produced by the turbulence associated with open-channel flow (Plant and Keller, 1990). When the transmitted radar signal is scattered from the rough water surface, a doppler shift is produced by the centimeter-length surface waves that backscatter. In the absence of stream current, these centimeter waves have a speed that is precisely known and produces a positive and

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a negative doppler shift depending on the travel direction of the waves. For scattering from river turbulence, these two contributions are nearly equal and their mean is zero in the absence of water current. Downstream flow that transports these surface waves imparts an added doppler shift, which is measured by spectrally analyzing the received signal. This method is similar to HF radar methods used to map surface velocity of coastal currents (Paduan and Graber, 1997), and has been tested by the Applied Physics Laboratory at the University of Washington and the U.S. Geological Survey on several streams in Washington State (W. J. Plant, unpublished data). It is possible to identify and remove wind-effects on surface velocity in the radar spectra, but there will be some point when wind effects will be so great as to preclude the use of radar to measure surface velocity.

Measurements of channel cross-sectional area in streams with low specific conductance-water can be obtained from a conventional ground-penetrating radar system (60-300 MHz) with an antenna suspended above the water surface from a bridge or cableway. Ground-penetrating radar (GPR) produces a continuous high-resolution profile of the water surface and stream bottom by measuring the travel time of an electromagnetic pulse between a transmitter, a reflective boundary, and a receiver. The velocity of the electromagnetic pulse varies with the dielectric constant of the penetrated materials, and changes at the boundaries between air, water, and river-bottom sediment. GPR has been used to detect the water-streambed interface on rivers and lakes in Connecticut (Beres and Haeni, 1991), and to measure and monitor changes in cross-sections of four unstable streams draining the slopes of Mount St. Helens in Washington (Spicer and others, 1997).

The velocity of radar waves in impure freshwater is partly controlled by water conductivity and suspended-sediment concentration. Previous studies showed that GPR can accurately determine stream channel geometry with sediment concentrations as high as 10,000 mg/l (Spicer and others, 1997), but conductivity of about 1,000 microSiemens/cm or greater can completely absorb radar energy, so no discernable signals are returned (Olhoeft, 1984). High conductivity water would preclude the use of GPR in estuaries and some rivers. During the non-contact discharge measurement on the Skagit River, conductivity was measured to be 70 microSiemens/cm.

3. A Proof of Concept Experiment

On April 21, 1999, the U.S. Geological Survey and the Applied Physics Laboratory of the University of Washington collaborated to conduct a non-contact discharge experiment at the Mount Vernon streamgaging station on the Skagit River, Washington, about 100 km north of Seattle (Fig. 1).

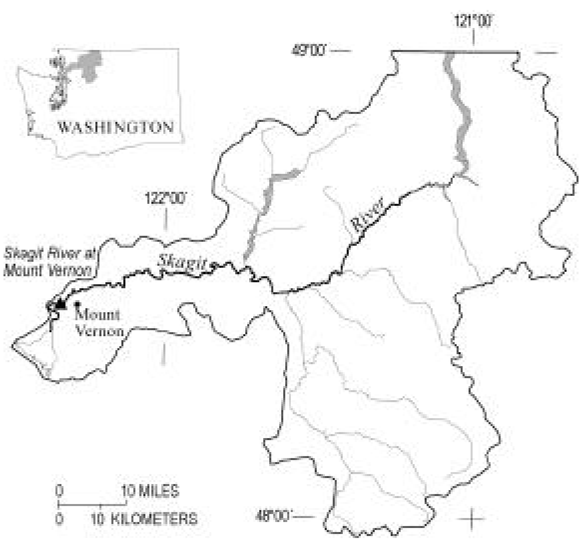

Fig. 1. Location of Skagit River streamgaging station.

The Skagit River at Mount Vernon drains an area of about 8,000 km^2 in NW Washington and Canada, and was selected as the site for the experiment because (a) it is a USGS stream-gaging station with continuous record from 1940 to present; (b) it is located close to the University of Washington and the USGS District offices in Tacoma, WA and Portland, OR; (c) the site has a cableway for suspending the GPR antenna to measure channel geometry, (d) it has a clear riverbank for sending and receiving radar signals to measure surface velocity; and (e) the site is a National Weather Service Flood-Forecast location used to issue watches and warnings to nearly 30,000 people on the downstream floodplain of the Skagit River.

At the Mount Vernon gaging station, the channel is confined between two flood-control levees and is 183 m wide. Surface-velocity data were collected by a van-mounted pulsed doppler radar system operating at a frequency of 10 GHz.

The radar measures the doppler shift of the backscatter in consecutive cells whose length in the range direction is 7.5 m and whose width varies with range, averaging about 10 m. Doppler shifts are collected with the antenna directed 15 degrees to either side of the cross-channel direction. Adding and subtracting the doppler shifts measured in the same range cell for the upstream and downstream look directions yields the along- and cross-stream components of surface velocity. All data were collected from a van-mounted antenna located at a single point on the south levee about 25 m from the edge and about 9 m above the river. The total time required to scan and process the data averaged about 15 minutes for each of three measurements that were conducted on April 21, 1999 (Fig. 2).

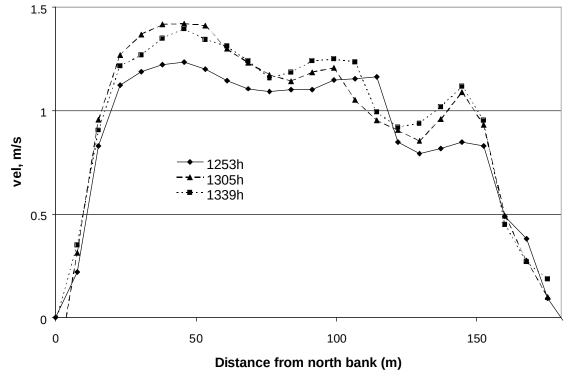

Fig. 2. Surface-velocity profiles measured by 10 GHz radar used in the computation of discharge.

In this non-contact discharge experiment, three radar surface-velocity data sets were collected between 1247h and 1345h on April 21, 1999. A current meter discharge measurement took 2 hours to complete between 1530h – 1730h on the same day, and seven acoustic doppler current profiler (ADCP) measurements were made between 1042h – 1316h.

Channel geometry data were collected with a conventional ground-penetrating radar system. The unit is battery powered, portable, and was deployed using methods similar to those developed in a previous investigation (Spicer and others, 1997). The unshielded transmitting and receiving antennas were suspended from the cablecar using nylon rope and were connected to the system control electronics with fiber optic cables. Although the transmitter and receiver antennas are broadband, the rated center frequency of the antennas is about 100 MHz. Analysis of the radar reflections yielded a signal center frequency of about 150 MHz. The data were processed by filtering out extraneous low and high frequency noise outside the frequency band of interest. Noise that was present as horizontal bands from trace to trace was removed using a horizontal filter. The antennas were positioned above the free surface of the river, and moved from bank to bank at a constant rate of about 0.33 m/s while the GPR data were logged on a laptop computer. Cableway stationing was marked in the GPR data file to indicate antenna location relative to stream channel cross-section position. Because of sag in the cable, the antennas were suspended about 3 m above the water surface at the edge of the river, and about 0.3 m above the water surface in the middle of the river. It took about 8-10 minutes to complete one GPR measurement for water depth distribution (Fig. 3).

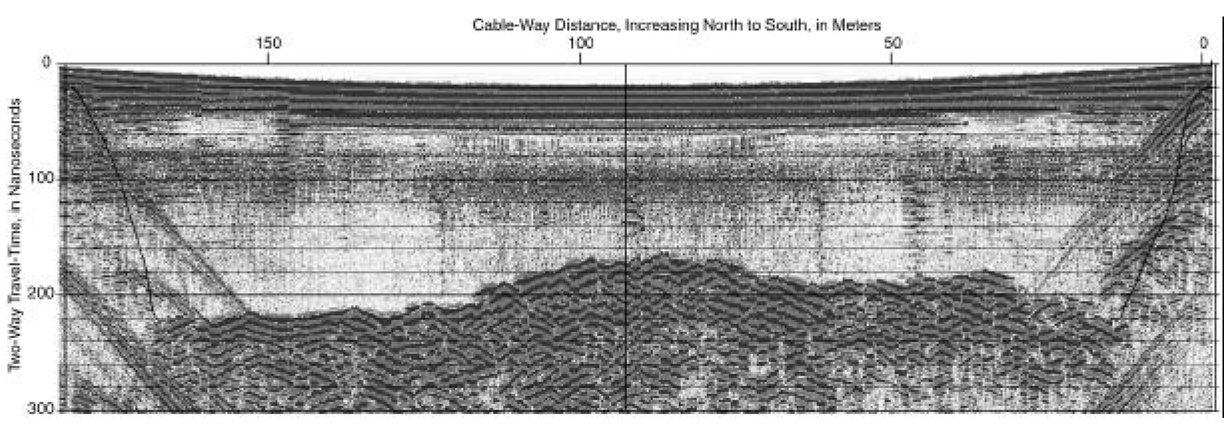

Figure 3. GPR-generated channel cross-section, Skagit River at Mount Vernon, WA. South bank is the left side; channel banks marked by thin drawn lines on the figure.

Two assumptions were needed to compute stream discharge in the Skagit River by non-contact radar methods: surface velocity was converted to mean velocity, and the velocity of radar waves in the river and air was estimated to convert GPR signal travel time to depth. Surface velocity points across the river were converted to mean velocity for each subsection by assuming a normal depth-velocity profile and multiplying radar surface velocity by 0.85 (Rantz, 1982). This assumption allowed computations of mean velocity in 25 subsections across the river for each of three radar experiments. When needed, surface velocity was extrapolated between the radar sampling points to match subsections.

Based on previous work using GPR to measure channel geometry on four rivers in southwestern Washington state (Spicer and others, 1997), a single value of 0.04 m/ns (0.13 ft/ns) was used as a representative radar signal velocity in impure freshwater. This radar wave speed was used to calculate water depth at those points where direct measurements of depth were obtained. The GPR generated river-bottom cross-section is shown in Figure 4, along with two plots of the same cross-section measured directly with a sounding weight from the cableway. We assumed that the channel remained stable throughout the entire day of the experiment.

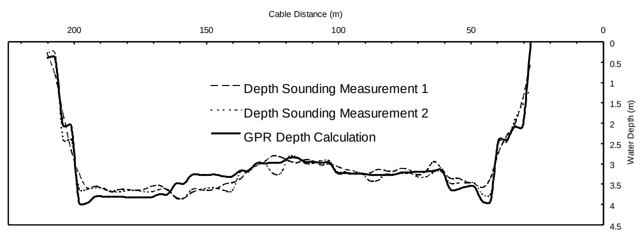

Figure 4. GPR-derived cross section, compared to two sounding-weight cross-sections, Skagit River at Mount Vernon, WA.

4. Results

The non-contact discharge experiments took place in the afternoon of April 21, 1999. Field conditions were ideal with sunny weather, a slowly declining hydrograph, and no wind. Three surface-velocity microwave radar readings were made between 1247h and 1345h (Fig. 5a). The GPR cross-section measurement took place between 1345h and 1403h (Fig. 5b).

Cross-sectional area was measured from the GPR profile to be 598 m^2 at 1345h, compared to sounding weight measurements of 572 m^2 at 0930h, and 547 m^2 about 7 hours later at 1630h when the water surface had dropped by 0.10 m (Fig. 4). Using the GPR-generated cross-section, and three radar-generated surface velocity data sets, converted to mean velocity, three non-contact discharge values were calculated between 1247h – 1345h. Non-contact discharge values were 518, 517, and 520 m^3/s, while the gaging station rating curve values were 518, 518, and 515 m^3/s (Table 1). At the same time, an acoustic doppler current profiler (ADCP), mounted in a boat, was used to make discharge measurements (Fig. 5b). Each traverse to make a discharge measurement with the ADCP took between 6-8 minutes, and seven passes were made between 1042h and 1316h on April 21. Measured discharges ranging from 526 m^3/s to 511 m^3/s, and average discharge for the seven measurements was 520 m^3/s. A conventional current meter discharge measurement was begun at 1530 and ended at 1730, and produced a discharge of 527 m^3/s (Table 1).

Method	**Time**	Discharge (m^3/s)	Discharge from rating curve (m^3/s)
ADCP	1042	526	527
	1130	521	524
	1156	511	521
	1252	525	518
	1300	517	518
	1312	523	515
	1316	514	515
Mean		**520**	**520**
Current meter	1630	527	504
Non-contact radar	1253	518	518
	1305	517	518
	1339	520	515
Mean		**518**	**517**

Table 1. Summary of discharge measurements.

Figure 5. Photo of pulsed doppler radar system for acquiring surface-velocity data (a); GPR antenna suspended from the cableway across the Skagit River with boat-mounted ADCP measuring discharge concurrently (b).

5. Conclusions

The results of this proof-of-concept experiment indicate that it is possible to measure the actual discharge of the river within the accuracy standards of conventional procedures, using non-contact methods. To accomplish this, it was necessary to (a) convert surface-velocity to mean velocity for 25 points across the surface of the river, by assuming surface velocity times 0.85 equaled mean velocity in each subsection; and (b) convert radar-signal travel times to depth, by assuming the average speed of a radar pulse in impure freshwater to be 0.04 m/ns.

These results demonstrate the feasibility of using non-contact methods for river discharge measurements; they also show that additional research on non-contact stream-discharge measurements is warranted. The U.S. Geological Survey is beginning to work with private contractors to design new specialized equipment, and implement a series of additional non-contact experiments that avoids the need for a bridge or cableway over the river. The goal is to make non-contact discharge measurements with radar from a single point on the side of a river, and from two points on opposite sides of the river.

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