

# River Discharge Measurements By Using Helicopter-Mounted Radar

N.B. Melcher, J.E. Costa, F.P. Haeni, R.T. Cheng, E.M. Thurman, M. Buursink,  
K.R. Spicer, and E. Hayes

United States Geological Survey

W.J. Plant, W.C. Keller, and K. Hayes

Applied Physics Laboratory, University of Washington

**Abstract.** The United States Geological Survey and the University of Washington collaborated on a series of initial experiments on the Lewis, Toutle, and Cowlitz Rivers during September 2000 and a detailed experiment on the Cowlitz River during May 2001 to determine the feasibility of using helicopter-mounted radar to measure river discharge. Surface velocities were measured using a pulsed Doppler radar, and river depth was measured using ground-penetrating radar. Both radars were mounted on a helicopter and flown over the rivers in a series of approximately 1-minute passes at heights of 2–15 m. Surface velocities were converted to mean velocities, and horizontal registration of both velocity and depth measurements enabled the calculation of river discharge. The magnitude of the uncertainty in velocity and depth indicate that the method error is in the range of 5 percent. The results of this experiment indicate that helicopter-mounted radar can make the rapid, accurate discharge measurements that are needed in remote locations and during regional floods.

## 1. Introduction

The production of accurate river discharge data for streamflow-gaging stations depends on defining the stage-discharge relations during high flows (Rantz and others, 1982a). Traditionally, the U.S. Geological Survey (USGS) has relied on direct measurement of the cross-sectional area and mean velocity using a cable-suspended weight and vertical-axis current meter to define the stage-discharge relation.

During regional flooding, river conditions may make it impossible to access the gage, find a suitable cross section, or utilize conventional river contact equipment. Consequently, current-meter measurements often are not available to accurately define the highest discharges.

Concerns about the costs, safety, and accuracy of traditional methods have been the incentive for exploring new technologies for making river discharge measurements during high-flow conditions (Melcher and others, 1999; Cheng and others, 2001), including the use of radar.

Previous studies using radar to measure river characteristics have involved different low-frequency radar antennas mounted from a bridge, crane, or helicopter, but these investigations focused on ice thickness and characteristics (Arcone, 1991; O'Neill and Arcone, 1991) or water depth and channel form alone (Spicer and others, 1997; Okamoto, 1999). Other studies tried to measure surface velocity by using simple continuous-wave high-frequency radars (Yamaguchi and Niizato, 1994) and pulsed Doppler radars (Plant and Keller, 1990). The first effort to compute a river discharge by using both high-frequency (velocity) and low-frequency (channel cross section) radars was successfully completed in 2000 (Costa and others, 2000). Following this

successful proof-of-concept experiment, a second experiment was conceived to measure discharge from the air by using non-contact methods. The goals of these experiments were to measure surface velocity and channel cross-section geometry and then compute a flow discharge with only data collected from the radar antennas mounted on the helicopter.

## **2. Principles of the Radar Measurements**

Surface currents can be measured using microwave Doppler radars by measuring the Doppler shift in the signal scattered back to the radar antenna from a rough water surface. Backscatter from such a surface is explained by Bragg scattering and composite surface theory (Plant, 1990). Backscattering is a resonance phenomenon that is caused only by short surface waves, called Bragg waves, on the order of one-half the radar wavelength. These waves are traveling in the plane of incidence of the radar signal. Such surface waves travel at a speed that is determined by the sum of their intrinsic phase speed and the current at the surface on which they are traveling. The surface waves generated by the helicopter downwash, including the Bragg waves, always travel radially outward from the helicopter. Thus, a Doppler radar mounted on the helicopter with antennas directed both upstream and downstream (Figure 1) might be able to separate the intrinsic phase speed of the waves from the surface current. Because the Bragg waves travel away from the antennas on both sides of the helicopter, their phase speeds always produce negative Doppler shifts. By contrast, the Doppler shift produced by the surface current is negative for the antenna looking downstream but positive for the antenna looking upstream. Subtracting Doppler shifts from the antennas on either side of the helicopter yields a result that is directly proportional to the surface velocity, assuming the antennas look directly upstream and downstream.

Unlike microwaves, low-frequency electromagnetic waves will penetrate both air and water. The ground-penetrating radar (GPR) method sends out pulses of waves at 100 MHz and determines the time to their reflection. Reflections occur wherever there are changes in the dielectric constant of the material through which the wave travels. Thus, reflections occur at the water surface and at the bottom of the river. Taking into account that waves of this frequency travel approximately nine times slower in water than they do in air, the depth of the river can be determined from the time difference between the surface and bottom reflections.

## **3. Initial Experiment**

An initial test of the feasibility of helicopter-mounted radar measurements of river velocity and depth was completed at the Lewis River near Woodland, Wash., the Cowlitz River at Castle Rock, Wash., and the Toutle River near Castle Rock, Wash., on September 13, 2000 (Figure 2). For this test, Federal Aviation Administration approval was secured for mounting radar antennas on the exterior of a leased Bell 206B Jet Ranger helicopter. Several passes were made over each river to determine if reliable velocity and depth data could be produced using radar equipment and if the equipment could be used to make multiple measurements on different rivers in a short period of time. Initial testing was done during this experiment to determine the importance of helicopter altitude, position, attitude, and equipment synchronization. Concurrent baseline data were collected at all three sites by using conventional methods. The results of this initial experiment indicated that this method could be used to measure river velocity and depths. Interpretable radar signals could be

obtained with the helicopter flying 3 to 5 m above the water surface. The helicopter completed several passes at each site and traveled the full loop of 100 km to all three sites in less than 60 minutes. These initial tests indicated that depth and velocity data must be accurately synchronized in time and position. A record of helicopter position and attitude also must be maintained in order to produce accurate results.

## **4. Main Experiment**

### **4.1 Helicopter Flights**

A subsequent experiment was conducted using the same helicopter and radar equipment near the USGS streamflow-gaging station on the Cowlitz River at Castle Rock, Wash., on May 1, 2001, during a normal flow period. Differential global positioning system (DGPS) equipment was installed in the helicopter to ensure accurate positioning as the helicopter flew from one side of the river to the other.

Two orange, wooden posts were mounted on each bank to enable the pilot to minimize yaw and stay on line with the selected cross sections. Observers were stationed at each cross section to document and record the measurements on video and to provide radio instructions to the pilot.

An initial set of measurements involving 16 passes across the river was made between 1408 PDT and 1641 PDT. After refueling, 14 additional river passes were flown between 1839 PDT to 1900 PDT. The flights were made at various altitudes and speeds in order to determine their effects on the measurements. A brisk west wind made it necessary to collect all data by flying from the east bank to the west bank. Figure 1 shows the helicopter with two microwave antennas mounted on each side and the large GPR antenna mounted underneath.

### **4.2 Data Collection and Processing**

For these experiments, the distance between the river surface and the channel bottom was measured using standard GPR equipment made by MALÅ GeoScience AB<sup>1</sup>. The radar signal was transmitted via an unshielded 100 MHz antenna, and data were recorded on a laptop computer. The GPR data were collected in MALÅ GeoScience AB RD3 format, but were converted to SEG Y format (Society of Exploration Geophysicists, 2002) so that they could be processed through Promax, a seismic processing software package. In Promax, the water surface reflection was picked semi automatically as a reflector horizon. This horizon was then used to flatten the water-surface reflection and remove the effect of variable helicopter elevation. A background removal filter was applied to the data before and after the horizon flattening. The primary purpose of this filter was to remove interference induced by the helicopter engine and radio. In addition, a trace mixing filter was applied to the data to enhance both the water-surface and the river-bottom reflections.

To produce GPR profiles of accurately positioned traces and water depth, DGPS data were incorporated into the SEG Y radar trace headers using Matlab. Profiles were then plotted using a process called rubber sheeting, which plots traces according to their true position along the profile. The rubber-sheeted profiles were plotted with total profile length as the horizontal axis. Figure 3 shows a representative example of the GPR profiles. The cross-section geometry was determined by the distance between the first water surface reflection and the first river-bottom reflection. Because the cross-section

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<sup>1</sup> Use of trade names is for purpose of identification only and does not constitute endorsement by the U.S. Geological Survey.

geometry did not change during the experiment, this GPR-derived channel cross section was used to compute discharge.

Surface velocity was measured by using a pulsed Doppler radar developed by the Applied Physics Laboratory of the University of Washington. The design of this radar is described by Plant and others (1998). The system transmits 50 nsec pulses of 10 GHz radiation every 25  $\mu$ sec and receives the backscattered power in 64-range bins that are spaced 7.5 m apart. The received signal is downshifted, and its Doppler shift is measured and recorded. This range-gated system was used in order to investigate the maximum distance from the helicopter from which the signal could be detected.

In order to obtain accurate surface currents, effects of the helicopter pitch, roll, and yaw had to be removed from the Doppler shift. To this end, an Attitude and Heading Reference System (AHRS) was mounted in the tail of the helicopter, and its output was recorded along with the microwave data. This instrument yielded the pitch, roll, and heading of the helicopter. The track of the helicopter across the river was obtained from a DGPS that was mounted in the cockpit of the helicopter. These data were then used to calculate yaw. In addition to the track, helicopter ground speed and position from the DGPS also were recorded. Because they were recorded on different data acquisition systems, these data were used during subsequent analysis to collocate the depth and surface-velocity measurements.

### 4.3 Conventional Discharge Measurements

From 0840 PDT to 1025 PDT, river discharge was measured from a small boat attached to a tag line along the flight-path cross section by using standard USGS procedures. The measurement, made by using a Price AA current meter and a depth calibrated reel with sounding weight, yielded a discharge of  $226 \text{ m}^3\text{s}^{-1}$  ( $7,970 \text{ ft}^3\text{s}^{-1}$ ; median time of 0930 PDT). A second boat carried an acoustic Doppler current profiler (ADCP), which was used to measure velocity profiles at 31 positions across the river. Surface velocity values were then obtained by extrapolating the trend of the ADCP velocity profiles to the surface of the river. Results compared well with current-meter measurements obtained as close to the surface of the river as possible (Figure 4).

## 5. Results

These experiments provide insight into some of the operational conditions necessary to measure river discharge by using helicopter-mounted radar. The ideal helicopter speed for these measurements was about 3 knots, and the ideal elevation for data collection and safety was about 3–5 m above the water surface. The radar results were sensitive to the helicopter heading and flow direction. Discharge changed by about 0.5 percent for each degree of error in measured flow direction and by about 2 percent for each degree of error in heading. A good GPR signal was obtained using a 100 MHz unshielded antenna. By using the single best GPR profile combined with an average of eight pulsed-Doppler surface velocity data runs, these experiments produced mean velocity, mean depth, and resultant discharge values within 2.4 percent of values obtained by conventional methods. Safe collection of helicopter-derived discharge data is dependent on a careful reconnaissance and selection of river cross sections that have open banks for maneuvering on both sides of the river.

Comparisons of the radar-produced velocity and cross-sectional area data with the baseline data produced by ADCP, sounding weight, and current meter are shown in figures 4

and 5. Figure 4 shows the average of the radar-derived velocity measured during eight crossings of the river, each of which was less than one minute long. These eight passes were used because they were the runs during which the DGPS and radar systems were working at the same time. The error bars show the standard error of these eight runs. Asterisks in the figure are surface-velocity measurements from the current meter, and the x's are extrapolations of the ADCP measurements to the water surface. Figure 5 shows manually selected depths derived from the single best GPR measurement when the helicopter was 3 and 5 m above the water, compared to depths measured using a sounding weight and the ADCP.

Radar-measured surface velocity values were converted to mean velocity for each subsection across the river by multiplying the radar-measured surface values by 0.85 (Rantz and others, 1982b). The GPR and Doppler radar measurements were then registered with each other using the DGPS data. Mean velocity values every 3 m across the river were multiplied by the corresponding depths and integrated to obtain discharge. Cross-sectional mean depth, mean velocity, and computed discharge by the helicopter-mounted radar method are compared with those obtained by conventional methods in Table 1. The magnitude of the uncertainty in velocity and depth indicate that the method error is in the range of 5 percent. The results of these tests are encouraging; however, due to the time and complexity of processing GPR signals, further research and an integrated data acquisition system are needed to produce reliable real-time results for future application.

## 6. Conclusions

The investigated techniques described in this report have important operational applications for flooding conditions if the helicopter is operated under suitable conditions. The equipment eventually needs to be consolidated into compact, easily mounted units for rapid deployment during floods or for routine measurements in remote areas. A limited number of radar systems could provide service to large regions provided that helicopters and operational personnel are available. These experiments have demonstrated the feasibility of making a large number of discharge measurements rapidly and within reasonable accuracy limits of conventional methods. The successful application of the method has the potential to significantly improve discharge estimates of large floods, and the method could be used to quickly measure the physical properties of rivers for many other uses.

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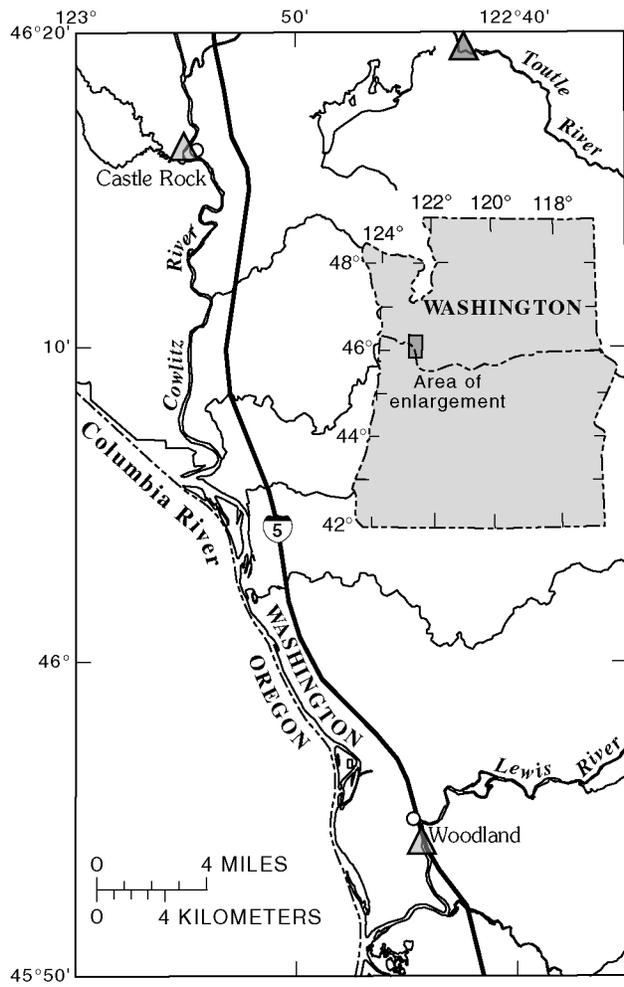
**Table 1.** Comparison of cross-sectional mean velocity and discharge from radar and conventional methods (current-meter measurement and stage-discharge rating curve)

Method	Mean Velocity	Mean Depth	Discharge
Sounding weight/ Current meter (0930 PDT)	1.67 m/s*	1.49 m*	226 m <sup>3</sup> s <sup>-1</sup>
Rating curve (stage-discharge relation) (0930 PDT)			222 m <sup>3</sup> s <sup>-1</sup> *
(1630 PDT)			222 m <sup>3</sup> s <sup>-1</sup>
Radar (1630 PDT)	1.63 m/s	1.52 m	223 m <sup>3</sup> s <sup>-1</sup>
Deviation from baseline data	-2.3 %	+2.0 %	+0.4 %

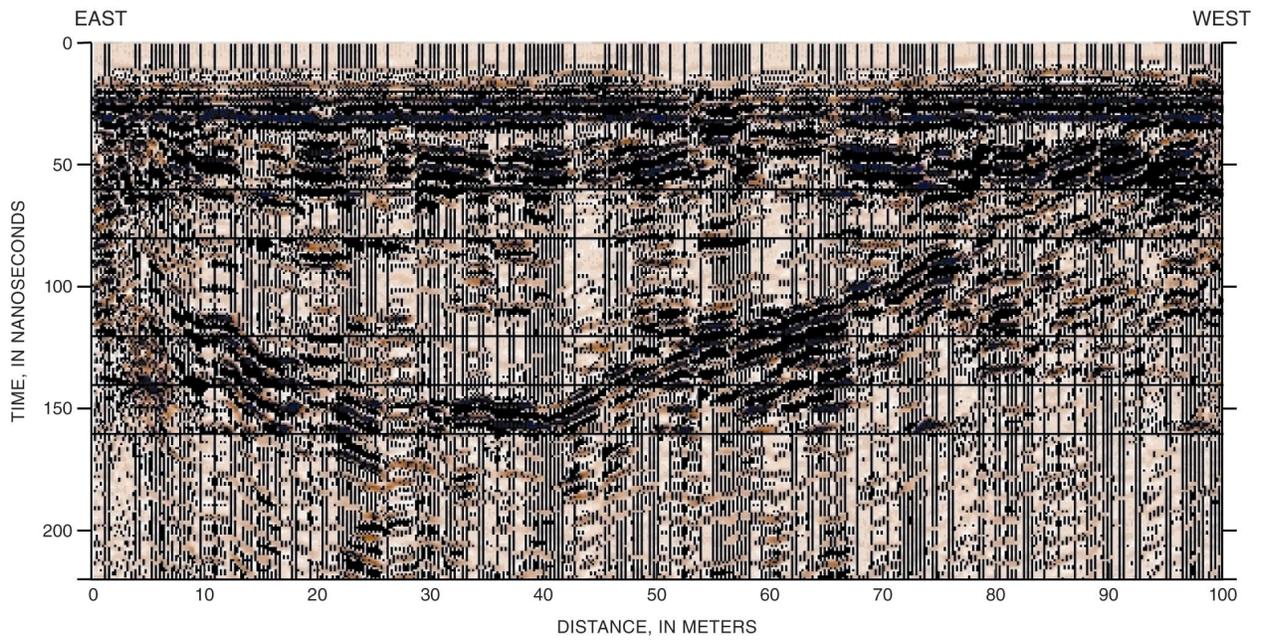
\* Baseline data



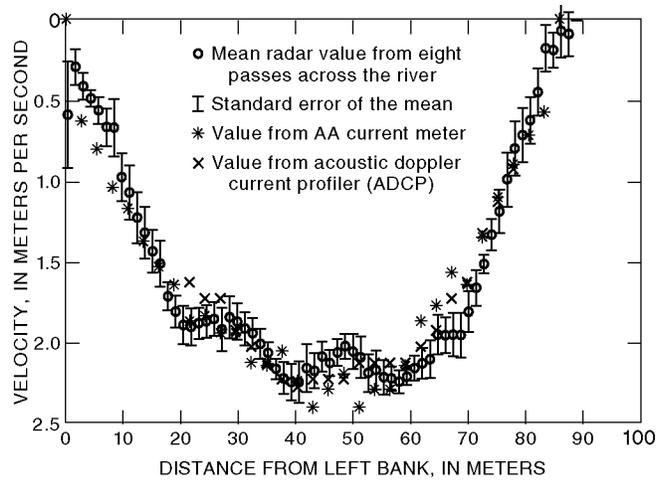
**Figure 1.** The helicopter at the Cowlitz River. Two microwave antennas are located just below the cabin on each side. The GPR antenna is the large white structure below the helicopter.



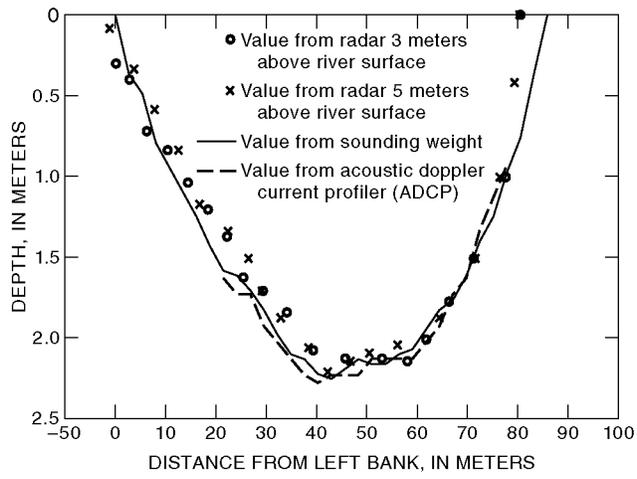
**Figure 2.** Location of river sites investigated in this report



**Figure 3.** Computer processed, 100 MHz GPR channel cross section of the Cowlitz River at Castle Rock, Wash., obtained from a helicopter flying 3–5 m above the river. East bank is on the left side.



**Figure 4.** Surface velocities determined by the Doppler radar, by the AA current meter, and by the acoustic Doppler current profiler, Cowlitz River near Castle Rock, Wash.



**Figure 5.** River depth derived from two ground penetrating radar profiles, the sounding weight, and the acoustic Doppler current profiler, Cowlitz River near Castle Rock, Wash.