WATER RESOURCES RESEARCH, VOL. 42, W07422, doi:10.1029/2005WR004430, 2006

Use of radars to monitor stream discharge by noncontact methods

J. E. Costa,[1] R. T. Cheng,[2] F. P. Haeni,[3] N. Melcher,[4] K. R. Spicer,[1] E. Hayes,[5]
W. Plant,[6] K. Hayes,[6] C. Teague,[7] and D. Barrick[7]

Received 13 July 2005; revised 2 March 2006; accepted 3 April 2006; published 27 July 2006.

[1] Conventional measurements of river flows are costly, time-consuming, and frequently dangerous. This report evaluates the use of a continuous wave microwave radar, a monostatic UHF Doppler radar, a pulsed Doppler microwave radar, and a ground-penetrating radar to measure river flows continuously over long periods and without touching the water with any instruments. The experiments duplicate the flow records from conventional stream gauging stations on the San Joaquin River in California and the Cowlitz River in Washington. The purpose of the experiments was to directly measure the parameters necessary to compute flow: surface velocity (converted to mean velocity) and cross-sectional area, thereby avoiding the uncertainty, complexity, and cost of maintaining rating curves. River channel cross sections were measured by ground-penetrating radar suspended above the river. River surface water velocity was obtained by Bragg scattering of microwave and UHF Doppler radars, and the surface velocity data were converted to mean velocity on the basis of detailed velocity profiles measured by current meters and hydroacoustic instruments. Experiments using these radars to acquire a continuous record of flow were conducted for 4 weeks on the San Joaquin River and for 16 weeks on the Cowlitz River. At the San Joaquin River the radar noncontact measurements produced discharges more than 20% higher than the other independent measurements in the early part of the experiment. After the first 3 days, the noncontact radar discharge measurements were within 5% of the rating values. On the Cowlitz River at Castle Rock, correlation coefficients between the USGS stream gauging station rating curve discharge and discharge computed from three different Doppler radar systems and GPR data over the 16 week experiment were 0.883, 0.969, and 0.992. Noncontact radar results were within a few percent of discharge values obtained by gauging station, current meter, and hydroacoustic methods. Time series of surface velocity obtained by different radars in the Cowlitz River experiment also show small-amplitude pulsations not found in stage records that reflect tidal energy at the gauging station. Noncontact discharge measurements made during a flood on 30 January 2004 agreed with the rated discharge to within 5%. Measurement at both field sites confirm that lognormal velocity profiles exist for a wide range of flows in these rivers, and mean velocity is approximately 0.85 times measured surface velocity. Noncontact methods of flow measurement appear to (1) be as accurate as conventional methods, (2) obtain data when standard contact methods are dangerous or cannot be obtained, and (3) provide insight into flow dynamics not available from detailed stage records alone.

Citation: Costa, J. E., R. T. Cheng, F. P. Haeni, N. Melcher, K. R. Spicer, E. Hayes, W. Plant, K. Hayes, C. Teague, and D. Barrick (2006), Use of radars to monitor stream discharge by noncontact methods, *Water Resour. Res.*, *42*, W07422, doi:10.1029/2005WR004430.

1. Introduction

[2] Quantification of streamflow is essential for economic, social, and political security. Streams and rivers provide water for important uses including drinking water, irrigation, navigation, power generation, and recreation. Too much water presents problems for public safety as rivers overflow their banks, breach levees, and inundate critical infrastructure such as hospitals and fire stations. Flow data are essential for computation of loads for water quality. The amount of water available for different uses, and the basis for predicting the frequency of damaging floods, is dependent upon accurate measurements of the rate of flow in rivers under widely varying conditions.

[3] The basic method for measuring streamflow in the United States using current meters has been virtually unchanged for over a century. Direct measurements are

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[1] U.S. Geological Survey, Vancouver, Washington, USA.
[2] U.S. Geological Survey, Menlo Park, California, USA.
[3] U.S. Geological Survey, Storrs, Connecticut, USA.
[4] U.S. Geological Survey, Tucson, Arizona, USA.
[5] U.S. Geological Survey, Stennis Space Center, Mississippi, USA.
[6] Applied Physics Laboratory, University of Washington, Seattle, Washington, USA.
[7] CODAR Ocean Sensors, Mountain View, California, USA.

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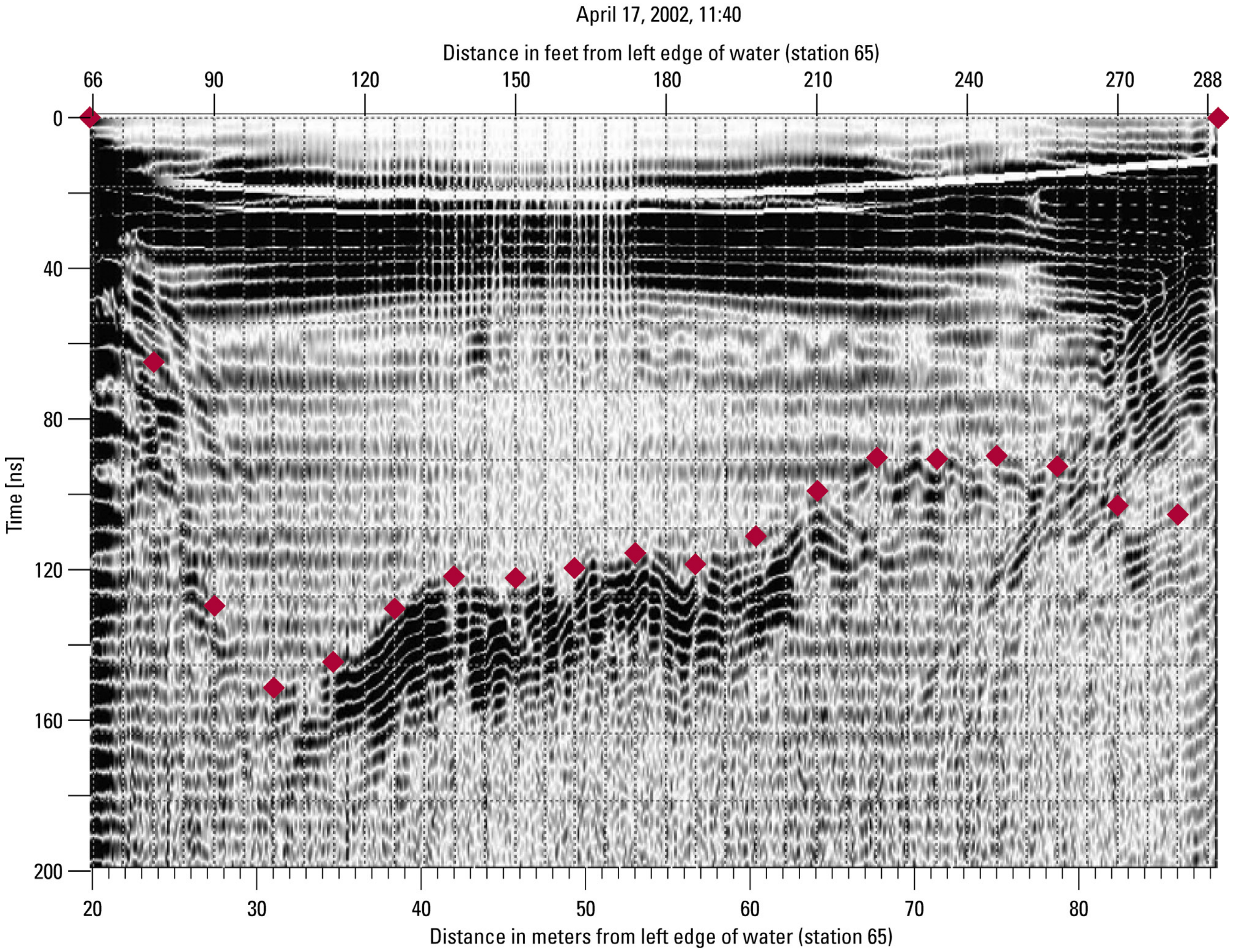

Figure 1. GPR output. Interpreted channel bottom is marked with red dots, measured at the San Joaquin River near Vernalis, California, on 17 April 2002.

made at regular intervals across the river with mechanical meters from bridges, cableways, or boats [*Rantz*, 1982]. More recently, some direct discharge measurements have been made using acoustic Doppler current profilers (ADCPs) that record water velocity through most of the water column by measuring the Doppler shift in the frequency of the acoustic signals reflected from materials suspended in, and moving with, the river flow. ADCPs are rapidly replacing mechanical meters in many situations [*Morlock*, 1996]. The use of instruments based on the Doppler principle for measuring water velocity and computing discharge is common within the U.S. Geological Survey, but still require human operators and expensive instrumentation placed in contact with the water.

[4] Under some conditions, direct measurement of discharge by current meter or ADCP is unreliable, unsafe, or impossible. These include floods where flow conditions or debris are dangerous to personnel in boats, and rapidly changing unsteady flows. Rivers at flood stage are dangerous to measure because of high velocities and drifting logs, stumps, and debris. Time consuming direct measurement methods are increasingly subject to error and/or failure as stream depth, velocity, and bed instability increase [*Sauer and Meyer*, 1992]. In situations when direct measurements are not made, discharge is determined indirectly by surveying high-water marks left by the flow and applying indirect discharge procedures such as the slope-area method [*Benson and Dalrymple*, 1967]. Accuracies of indirect discharge methods are far less than direct measurements, yet many times estimates of flows that are not directly measured are critical for identification of flood hazard areas, the frequency with which flooding occurs, or the mass flux of sediment or contaminants.

[5] In an effort to solve some of these problems the U.S. Geological Survey began a project to investigate new and emerging technologies that might have the potential of developing into the basis for a more inexpensive, accurate, safe, and robust method of stream gauging. The ideal stream gauge of the future was conceived as one that would (1) directly measure the variables that determine discharge (channel geometry and flow velocity), so a rating curve would no longer be needed, (2) measure these variables continuously, and (3) not place any instruments in contact with the water, thus greatly extending the range for high-flow measurements and making them more accurate and safe.

[6] This paper describes a method by which river channel cross section and mean flow velocity (the two variables necessary to compute river flow) can be measured over

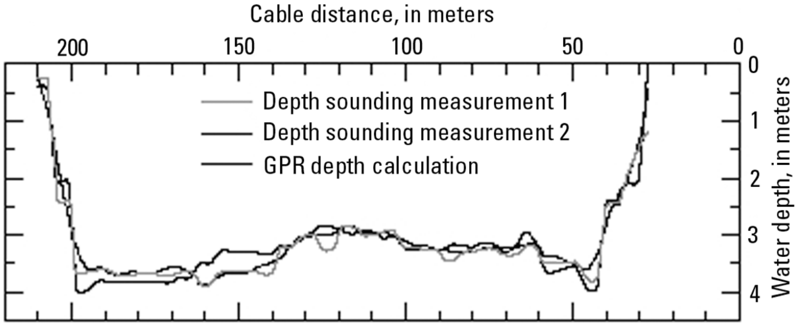

Figure 2. Comparison of two sounding weight measurements of the cross section of the Skagit River near Mount Vernon, Washington, with GPR measured cross section.

extended time periods without putting any instruments into the water. The hypothesis is that surface velocity is highly correlated with discharge, and channel cross sections can be measured in real time by radar. It reviews (1) a radar method to measure the cross-sectional area of river channels without touching the water, (2) the difficulties of measuring surface velocity with water contact instruments, (3) methods to measure the surface velocity of rivers using different kinds of radars, (4) the basis for converting measured surface velocity to mean flow velocity, and (5) the results of two experiments designed to continuously measure river flow by noncontact methods.

2. Noncontact Measurements of Stream Discharge

2.1. Channel Cross Section

[7] Channel cross-section geometry is routinely measured during conventional discharge measurements. This typically involves making depth soundings at 20–30 points across the river, connecting the points, and integrating for area. Alternatively, cross sections can be measured with a fathometer or acoustic device, both of which require floating instruments across the river from one side to the other.

[8] Several possible techniques for measuring channel cross section by noncontact means have been considered. These include visible and infrared lasers, electromagnetic induction techniques, and VHF and UHF radar techniques. The conclusion reached was that the most promising technology to record channel cross section without touching the water is radar operating at Megahertz frequencies, specifically ground-penetrating radar. Several unrelated studies in the past have offered hints on how to scan the bed of a river or shallow coastal areas continuously and record the shape of the channel cross section without having the antennas in the water [e.g., *O'Neill and Arcone*, 1991; *Spicer et al.*, 1997; *Okamoto*, 1999; *Bell*, 1999].

[9] Ground-penetrating radar (GPR) involves transmission of an electromagnetic pulse with carrier frequency in the MHz range toward the ground from a transmitting antenna at the surface. Some of the radiated electromagnetic energy is reflected back to the receiving antenna from interfaces of materials having different dielectric properties. GPR systems are light, portable, digital, and can provide real-time images of the subsurface.

[10] To obtain noncontact cross-section data, the GPR unit can be operated from a bridge or cableway that allows the antenna to be moved across the river while suspended above the water surface. Electromagnetic waves are transmitted through air, water, and channel bed material and backscattered waves are measured by the receiving antenna. The intensity of the reflected signal is controlled by the dielectric constant of the materials through which it passes. At the interfaces where the dielectric constant changes, distinct echoes can be seen in the profiles (Figure 1).

[11] A comparison of channel cross sections of the Skagit River, Washington, sequentially measured on the same day by conventional sounding weight and by GPR is shown in Figure 2. Note that even with the simple process of measuring depth by a tape and weight, results are not identical from one measurement to another. In 11 measurements comparing cross-sectional areas measured by sounding weights and by GPR, the GPR areas differed from sounding weight areas by −4.8% to +3.5%, with an average difference of only +1.15% [*Costa et al.*, 2000].

[12] Conductivity and temperature have a small effect on the speed of an electromagnetic wave in impure fresh water, but energy is attenuated and dispersed in water that has high conductivity (Figure 3). Values greater than about 500 μS/cm (microsiemens per centimeter) are sufficient to absorb most of the energy and prevent most reflections. We have found conductivities greater than 300–400 μS/cm present substantial problems in signal return and interpretation at water depths from 2 to 5 m. Other limitations of GPR measurement of stream cross sections are its inability to image steep banks at the side of the river, interference of side reflections, and reflections from large metal objects like bridge supports or decks.

[13] In spite of the above limitations, a GPR (100 MHz center frequency) can be suspended above the river from a bridge or cableway, transmit a signal through the air, water, and sometimes channel bed material, and receive the return signals with sufficient clarity to define the channel cross section based on differences in dielectric constants [*Spicer et al.*, 1997]. In low-conductivity water, GPR can measure depths to within a few centimeters and cross-sectional area within 1–5 % [*Costa et al.*, 2000; *Cheng et al.*, 2004a] (Figure 2). The primary limitations on GPR measurements of channel geometry are the dampening effects of conductivity on signal strength, and the requirement to have the antennas out over the water surface scanning vertically. Depth penetration of a 100 MHz GPR signal is about 6 m with water conductivity less than 100 μS/cm, and about 1–2 m with water conductivity of about 400 μS/cm. These are

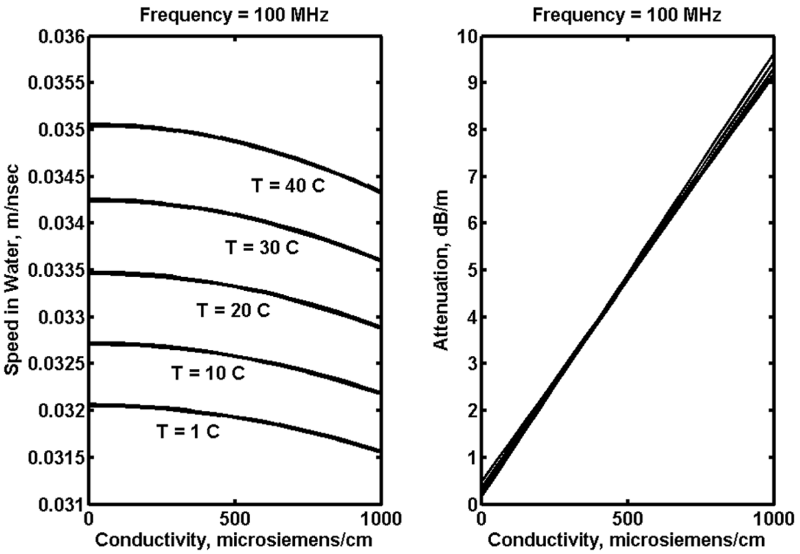

Figure 3. Effects of conductivity on 100 MHz GPR signals in impure freshwater.

minimum depths, limited by the channel depths being imaged. Fortunately, during most floods, even high-conductivity rivers are substantially diluted so that GPR could theoretically work [*Hem*, 1985, Figure 38]. This technology would not be usable in estuarine environments, and not during low flows in highly conductive river water that is undiluted.

2.2. Surface Velocity of Streams

2.2.1. Measurement With Water Contact Instruments

[14] Surface velocity of rivers is difficult to measure with water contacting instruments and therefore it is difficult to verify radar determined surface velocities. Conventional current meters are subject to surface wave effects and must be submerged below the water surface to allow uninterrupted spinning of cups. A Price AA meter must have its cups about 15 cm below the surface, and thus measures the point velocity substantially below the water's surface. An ADCP cannot measure velocity in a layer near the water surface or a layer near the bed [*Simpson and Oltman*, 1992]. When a 1200 KHz ADCP is used with a bin size of 25 cm, the first velocity point is measured at about 75 cm below the water surface. Near the bed, the velocity in the bottom 6% of the total depth cannot be measured due to acoustic signal sidelobe interference. An acoustic instrument called BoogieDopp (BD) has been developed for river discharge measurements in small and shallow rivers. The first valid velocity of the shallow-looking forward transducer beam is measured at about 11 cm below the water surface. This velocity has been used to verify radar-measured surface velocity [*Cheng and Gartner*, 2003].

[15] Another simple way to estimate surface velocity involves timing seeded or naturally occurring floating materials to establish surface velocity fields. This method, known as particle image velocimetry, or PIV, has produced generally good results [e.g., *Creutin et al.*, 2003], but requires the photography of floating materials across the entire river to define the surface velocity flow patterns. It was not used in our experiments.

2.2.2. Surface Velocity Measurement Using Electromagnetic Waves at UHF and Microwave Frequencies

[16] Three different radar systems designed to measure surface velocity of rivers were deployed and evaluated in the field tests described later. They were a continuous wave microwave systems (24 GHz) [e.g., *Yamaguchi and Niizato*, 1994], a monostatic UHF (350 MHz) Doppler radar [*Teague et al.*, 2003a] and an pulsed Doppler (9.36 GHz) microwave radar [*Plant et al.*, 2005a]. Both microwave and UHF Doppler radars receive scattered signals from random waves on the water surface because of Bragg scattering of electromagnetic waves by short surface waves that roughen the water surface. These short waves produce a Doppler shift both because they have an intrinsic phase speed and because they are advected by the current in the river [*Plant and Keller*, 1990]. Bragg scattering is a resonant phenomenon in which the lengths of those short waves that cause backscatter are well characterized by the Bragg condition:

$$\lambda_b = \lambda/(2\sin\theta)$$

where λ_b is the wavelength of the resonant water wave (the Bragg wave), λ is the wavelength, and θ is the incidence angle. For an X band radar of frequency 10 GHz, $\lambda \sim 3$ cm so λ_b is about 1.5 to 2 cm; at a UHF frequency of 350 MHz, $\lambda \sim 86$ cm so λ_b is about 50 cm. For surface velocities to be successfully measured by this technique, some water surface roughness must be present. This roughness can be generated by turbulent boils on the water surface, by wind, or by rain.

[17] As a result of diffraction effects, typical microwave antennas have beam widths on the order of a few degrees. This sets the size of the illuminated area in the azimuth direction. In the pointing direction of the antenna, the range direction, the footprint on the river surface can be limited by pulsing the transmitted signal. Sampling the return signal at a variety of time delays then yields signals from small "range bins" equally spaced over the water. In both range

and azimuth dimensions, the areas on the water surface illuminated by electromagnetic waves are decimeters to meters in size, and contain many cycles of the resonant water wave. The Bragg scattering process is highly selective in both wavelength and direction, and the only significant energy returned to the radar comes from water waves having approximately one half the radar wavelength that are traveling radially toward or away from the radar. Other water waves also scatter the radar signal, but not back to the antenna. The signal that is returned to the radar represents an average over the scattering patch. The same phenomena occur at UHF frequencies, the primary difference being that beam widths are much broader at this frequency for similar-sized antennas. The result is that Bragg waves traveling toward or away from the antenna occur over a wide range of azimuth angles. Neither system will work in the absence of short waves (here meant to be wavelengths less than about 0.5m) on the surface of the water.

[18] For the narrow beams of microwave antennas, the Doppler spectrum typically shows two peaks, one for short waves advancing toward the antenna and one for those receding from the antenna. Since these peaks are close in frequency and their intensities may differ, and indeed, one may vanish, the problem at microwave frequencies is determining the mean frequency between these peaks. The shift of this frequency from zero is a measure of the surface current. For the broader beams of UHF antennas, the problem is different. Here peaks caused by advancing and receding waves in any given direction are well separated and can be used individually to determine surface currents by subtracting their known phase speed. The problem, however, is that signals are received from a wide range of azimuth angles simultaneously. Some of these angles are directed upstream and some downstream. Thus advancing and receding waves from different directions may overlap if the current is strong. This must be sorted out in data processing.

2.3. Wind Effects on Surface Velocity

[19] After proper processing, the surface current in the river can be determined from the Doppler shifts but this current includes the drift current caused at the surface by the wind. The effective depth at which the velocity is measured, both at UHF and microwave frequencies, is approximately 0.044 λ_b [*Stewart and Joy*, 1974; *Plant and Wright*, 1980]. For λ_b = 1.7 cm, relevant to microwave scattering, this depth is about 0.75 mm. At this depth, the wind drift layer has not completely decayed. The magnitude of the wind drift at the surface is well known from experiment to be about 2% of the wind speed measured 10 m above the surface and in the wind direction [*Plant and Wright*, 1980]. For a 10 m/s wind speed, this is 20 cm/s. Assuming a logarithmic decay to the effective depth of the microwave measurement following *Plant and Wright* [1980], the wind drift at the effective measurement depth is about 11 cm/s. This amount of error is incurred in the measurement of surface velocity only if the wind blows exactly along the direction in which the antenna is pointing. For other directions, the error will be less.

[20] At UHF, the wind drift has an even smaller effect. For λ_b = 50 cm, the effective measurement depth is about 2.2 cm where the wind drift created by a 10 m/s wind has decayed to about 4 cm/s. This is very difficult to detect even for wind blowing directly along the river.

2.4. Continuous Wave Microwave System

[21] Presently, the simplest and least expensive method for monitoring the surface velocity of a river is with a continuous wave microwave system. RiverScat was developed at the Applied Physics Laboratory, University of Washington. A transceiver operating at 24 GHz (K band) and producing 5 mW of power is attached to a vertically polarized, 30 cm diameter, parabolic antenna. This system digitizes the analog signals at a 1 kHz rate, computes Doppler spectra every half second, and stores the results in files for subsequent processing. Spectra are analyzed by fitting the noise level to an inverse frequency function, dividing the received signal by this noise level, and applying an algorithm to determine the Doppler frequency shift midway between the Bragg lines [*Plant et al.*, 2005a].

[22] In a low-turbulence river, continuous wave microwave sensors will not yield a measurement unless rain is falling or wind is blowing. The limitation is lack of surface roughness, not slow flow velocity. Thus gaps in the data record can occur if turbulence is too low. The number of gaps can be reduced by operating the system closer to the water. As stage increases or decreases, the illuminated spot on the river surface from RiverScat is simply displaced a small distance along streamlines. Since RiverScat is mounted in a fixed position or moved across the channel on a cableway, georeferencing is accomplished by noting location across the river.

2.5. Pulsed Doppler Microwave Radar

[23] A second method for measuring surface velocity is the pulsed Doppler microwave radar (RiverRad) developed by the Applied Physics Laboratory, University of Washington. The radar emits bursts of 9.36 GHz microwaves across the water surface from two antennae on the riverbank. The average transmitted power is 5 mW. Average surface velocities are measured in a series of bins across the river, whose locations are determined by time gating, and whose size varies with beam width in the azimuth direction. Azimuth widths vary from about 1 m near the antenna to about 4 m at a distance of 100 m. In the range direction, RiverRad can measure in bins of width 3.75, 7.5, 15, or 30 m. The maximum range at this resolution is 480 m and is proportional to resolution. Doppler spectra averaged over a 30 s interval were recorded for each measurement. The actual velocity vectors were determined from a pair of along-beam velocities pointing at 23° upstream and downstream of the river by assuming the velocity was steady between the two footprints [*Plant et al.*, 2005a]. The optimal location for radar measurements is a straight channel with steady, uniform flow and no significant variation of bed roughness, bottom slope, or channel geometry between radar footprints.

[24] Uncertainties caused by variations in stage on bankside radar systems are negligible. For RiverRad, changes in stage will change the grazing angle. A stage change of 3 meters causes a grazing angle change of 2°–3°, which leads to a change in velocity of no more than a fraction of a percent. RiverRad georeferencing is easy since the velocity drops to zero at both riverbanks in the absence of current.

2.6. UHF Radar

[25] A different kind of radar system for measuring surface velocity was developed by CODAR Ocean Sensors, Ltd. [*Teague et al.*, 2003a, 2003b]. A high-frequency system used to observe ocean currents (SeaSonde) was modified to a higher frequency (UHF) consistent with the shorter Bragg wavelengths in open channel flow of rivers. The radar makes three basic measurements: the Doppler frequency, the distance or range to the scattering patch, and the direction of arrival of the radar echoes. From these, the radial component of the flow velocity can be mapped as a function of position on the water surface. If, in addition, the flow is assumed to be predominantly in one direction, as is often the case for a river, the total flow velocity and the cross-channel flow profile can be estimated.

[26] The UHF radar, named RiverSonde, works by Fourier processing of the received signal to determine its Doppler shift and direction in each frequency bin producing the Doppler shift. RiverSonde uses a yagi antenna system and monostatic geometry (transmitting and receiving antennas located on the same side of the river) that broadcasts at 350 MHz. The radar antenna system consists of three multielement yagi antennas, separated by one half of the radar wavelength and oriented in different directions, with the outer yagi antenna rotated 30° from the direction of the center antenna. Processing signals separately from the three yagi antennas allows the direction of arrival of the radar echoes to be measured to a resolution of about 1° using a MUSIC direction finding algorithm [*Schmidt*, 1986]. The range resolution of the radar was set to 5 m, with a maximum range of 140 m, although the range resolution can be varied by software setting. Transmitted power is less than 1 W.

2.7. Converting Surface Velocity to Mean Velocity

[27] All noncontact methods for measurement of stream velocity measure the velocity of the river current at or very close to the surface of the water. For discharge computations, the average velocity in the vertical water column must be known. Most open channel flow, especially during floods, has high Reynolds numbers and is turbulent. This is advantageous because while turbulent flow field velocities fluctuate widely, over time the constant flow mixing makes the river's mean velocity structure predictable.

[28] Numerous observations and measurements have shown that in natural channels, flow velocity increases vertically with the logarithm of the distance from the channel boundary. Velocity changes rapidly near the channel bed and banks, and more slowly in the interior of the flow, allowing larger eddies to develop in the middle of the flow. This predictable log layer (absent significant secondary flows) leads to the fundamental basis for measurement of streamflow by current meters: the mean velocity of a log law vertical flow profile occurs at about 0.6 the mean depth, or the average of 0.2 and 0.8 mean depth.

[29] The measurement of surface velocity by noncontact methods can serve as a surrogate for mean flow velocity if one assumes that open channel flows conform to the log law. To convert surface velocity to mean velocity in the water column, assuming the velocity profile follows the log law of the wall, the theoretical mean to surface velocity ratio is 0.85 [*Rantz*, 1982] for a wide range of depth to bottom roughness ratios. For steep rivers where relative roughness is large, a logarithmic velocity profile does not develop because of drag from coarse bed material and the high-velocity flow near the water surface [*Jarrett*, 1991]. These conditions did not exist in the two rivers used for these tests, but when computing flow in steeper channels, individual sites may need to be calibrated to their unique vertical velocity profiles.

Table 1. Instruments Used to Measure Surface Velocity

Standard Water Contact Instrument	Closest Distance to Surface
BoogieDopp	~11 cm
Price AA current meter	~15 cm
Rio Grande 1200 KHz ADCP	~75 cm

3. Field Tests of Noncontact River Discharge Measurements

3.1. San Joaquin River Near Vernalis, California

[30] In April–May 2002, a month-long experiment in the San Joaquin River at Vernalis, California, was conducted. The goal was to simulate a system of continuous noncontact direct measurements of surface velocity and periodic measurements of channel cross section to produce discharge by noncontact methods and without using a rating curve. The experiment involved continuous recording of surface velocity by microwave radar not counting periods of mechanical repairs or power interruptions, 23 separate measurements of channel cross section by GPR, and testing of a UHF radar system.

[31] The GPR system used to measure channel cross-section area is a Mala Geoscience Ramac X3M Corder GPR system using shielded antennas with a center frequency of 100 MHz and weighing about 25–30 kg. This frequency seems to give the best compromise of penetration and resolution in fresh water settings. The GPR unit is operated from a cableway that allows the antenna to be moved across the river while suspended 0.5–2 m above the water surface. For these experiments, the speed of electromagnetic waves in water was measured to be 0.033 m/ns (0.11 ft/ns), and this value was used to convert the timescale GPR data into a length scale to determine water depth.

[32] Water contact instruments used to estimate surface velocity during the experiments described here are listed in Table 1.

[33] The site of the experiment was the USGS stream gauging station 11303500 San Joaquin River near Vernalis, California. This is a daily record stream gauging station with data extending back to 1930. The rating curve for this station is frequently inaccurate due to the unstable nature of the channel bed during high flows. During high runoff periods, weekly and even daily direct current meter discharge measurements are necessary to make adjustments to the rating curve. Noncontact direct measurement of river velocity and channel cross sections hold the promise of avoiding the time and resources needed to maintain a rating curve at an unstable channel such as exists at this site.

[34] The pulsed Doppler microwave radar RiverRad (with a bin width of 3.75 m) was used to measure surface velocity, and the GPR system was suspended over the river using a bank-operated cableway (Figure 4). Numerous profiles of

Figure 4. GPR antenna suspended over the San Joaquin River, California, on a light cableway system.

the vertical velocity field were collected with hydroacoustic equipment, and proved that the vertical velocity could be represented by a smooth logarithmic velocity profile [*Cheng et al.*, 2004a]. Knowing this, mean velocities for each subsection were assumed to be 85% of the radar-measured surface velocity in the subsection. Comparison data were obtained by direct current meter, BoogieDopp and ADCP measurements during the period of the experiment [*Cheng and Gartner*, 2003]. High-conductivity water (up to 600 μS/cm) in the San Joaquin River from irrigation return flow absorbed much of the radar return signals and made interpretations of channel cross-section GPR data difficult.

[35] Figure 5 shows the continuous flow record for the San Joaquin River near Vernalis, California, based on the stream gauging station rating curve, and the individual direct discharge measurements by current meter, ADCP, and BoogieDopp [*Cheng et al.*, 2004b]. The discharge computed from the unshifted rating (lower curve) represents the discharge that would have been estimated from the stage record in the absence of any direct discharge measurements. The upper curve represents discharge using a rating curve

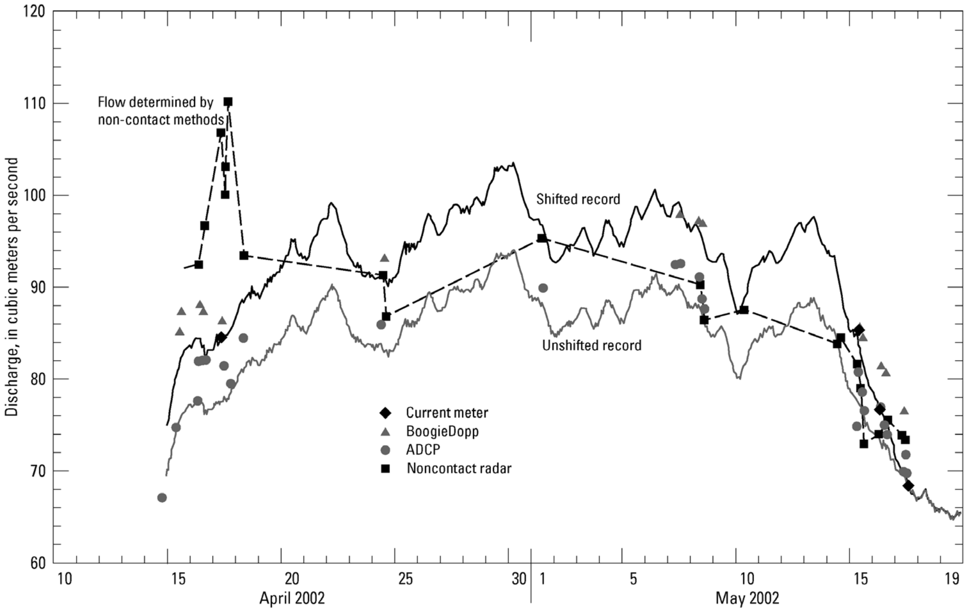

Figure 5. Discharge of the San Joaquin River near Vernalis River, California, from 15 April to 17 May 2002, showing unshifted (bottom line) and shifted (top line) discharge values. Independent determinations of discharge are represented by symbols: diamonds are current meter, triangles are BoogieDopp, circles are ADCP, and squares are noncontact radar measurements using GPR cross sections and microwave radar (RiverRad).

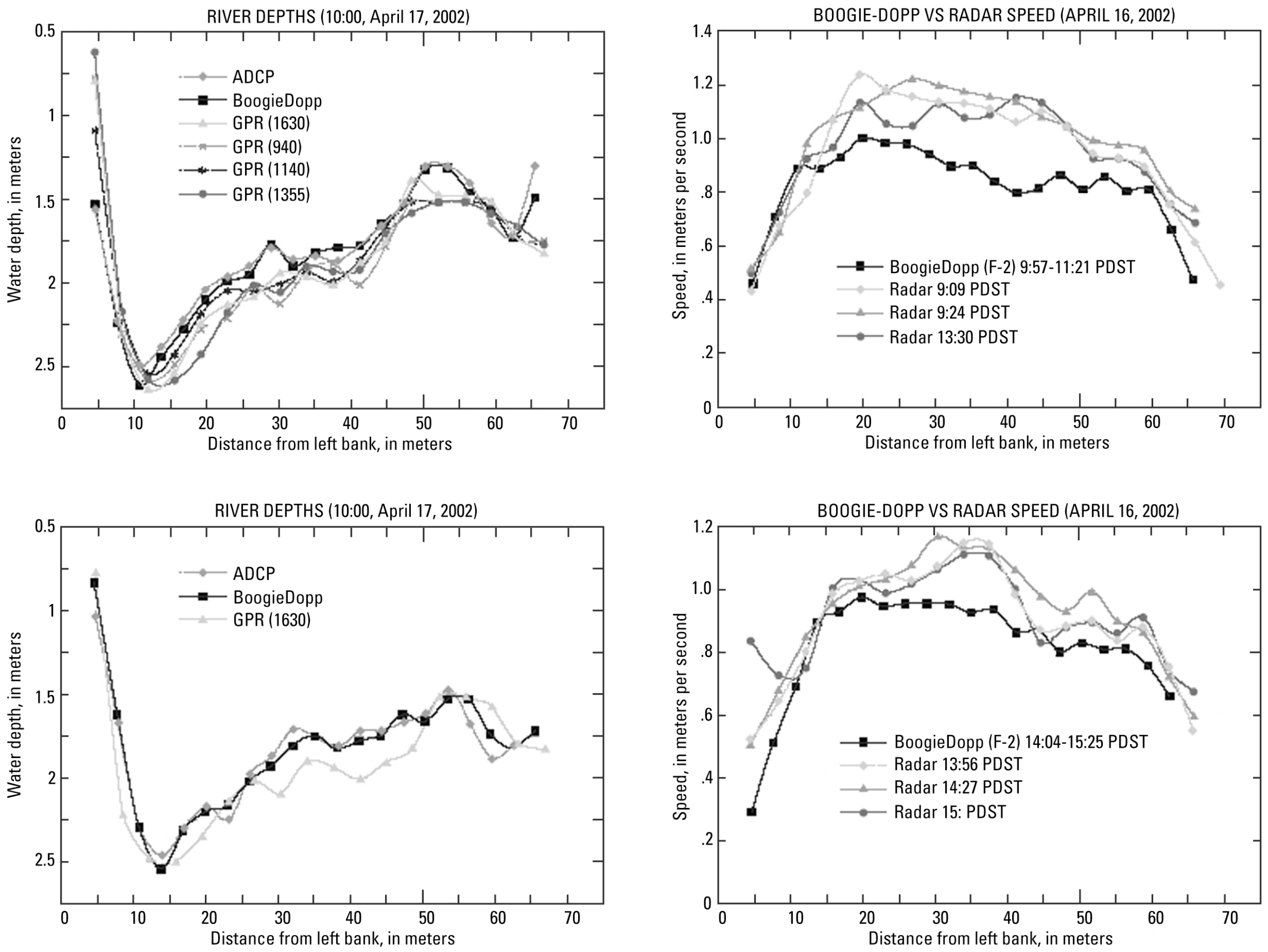

Figure 6. Comparisons of radar depth and surface velocity measurements with water contact measurements during the first days of the experiment on the San Joaquin River, California.

that has been corrected based on direct measurements. Noncontact (radar) discharges measured in April and May 2002 are plotted as squares. During the first 3 days of the experiment, water was being released from upstream reservoirs and discharge increased from 62 to 91 m^3/s. All the direct discharge measurements by current meter, BoogieDopp, and ADCP are in good agreement. The radar measurements produced discharges more than 20% higher than the other independent measurements in the early part of the experiment. The data show that the GPR depth measurements at this time were about 5–10% larger than the in situ measurements and that RiverRad's surface velocities were about 15–20% higher than the hydroacoustic comparison data (Figure 6). The depth differences could be related to the high-conductivity river water at the beginning of the experiment that may have led to greater error in interpretation of channel cross-section area. The reason for the higher RiverRad surface velocities compared with hydroacoustic data remains unclear. After the first three days, the noncontact radar discharge measurements are within 5% of the rating values, and agreement appears to be good (Figure 5).

3.2. Cowlitz River at Castle Rock, Washington

[36] From October 2003 to March, 2004, another experiment was conducted to demonstrate continuous noncontact monitoring of river discharge. The bank-operated cableway and the GPR unit used in the San Joaquin River experiments were relocated to the Cowlitz River at Castle Rock, Washington, just upstream of a USGS stream gauging station (14243000). This site was selected because buildings to

Table 2. Characteristics and Features of Different Radar Systems Used in Experiments

Responsible Organization	Radar	Radar System	Frequency	Purpose	Accuracy	Light Wind Operation	Range Resolution
USGS	*Mala* X3M Corder	GPR	100 MHz	cross section	15–20 cm	OK	
UW	RiverScat	Microwave/CW	24 GHz	surface velocity	15 cm/s	difficult	~5 m
UW	RiverRad	Microwave/pulsed Doppler	9.36 GHz	surface velocity	10 cm/s	OK	~5 m
CODAR	RiverSonde	UHF/monostatic	350 MHz	surface velocity	15 cm/s	OK	~5 m

Figure 7. View under Cowlitz River bridge with four of eight RiverScat antennas visible and pointing upstream.

house instrumentation and provide power and telemetry were located next to the field site, the stream gauge was located between Portland, OR, and Seattle, Washington, where field personnel were located, and the flow history of the river indicated a high probability of floods during the time of the experiment. The Cowlitz River at Castle Rock drains about 5,800 km^2 in the Cascade Mountains in central Washington. The river is about 92 m wide and between 2–7 m deep at the measurement site.

[37] Three organizations interested in noncontact measurement of streamflow participated in the Cowlitz River stream gauging station experiment: the USGS, the Applied Physics Laboratory of the University of Washington (UW), and CODAR Ocean Sensors, Ltd. Table 2 describes the radar systems deployed by each organization. All systems were installed and operational for the period 28 October 2003 to 4 March 2004.

[38] The RiverRad system was deployed with two dish antennas, one pointing up river and one pointing down river, separated by an angle of about 23°. A RiverScat array of eight microwave antennas was mounted under the highway bridge over the Cowlitz River at the stream gauging station about 100 m downstream from the bank-operated cableway (Figure 7) [*Plant et al.*, 2005b].

Figure 8. Continuous wave RiverScat system (antenna and control box) mounted atop a GPR antenna suspended from a cableway approximately 3–4 m above the water, across the Cowlitz River, Washington.

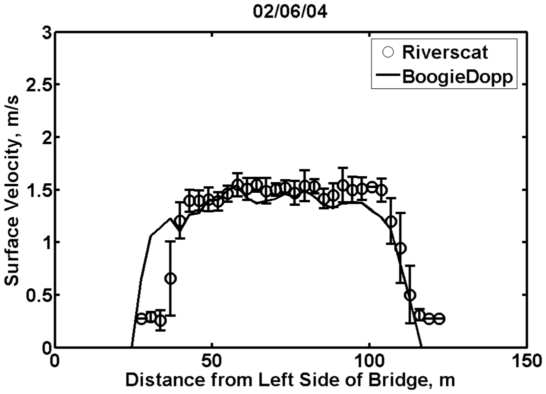

Figure 9. Comparison of surface velocities measured by RiverScat with those from the acoustic system, BoogieDopp, from the Cowlitz River, Washington.

[39] To make complete discharge measurements from a light cableway, a single RiverScat antenna was mounted on top of a GPR antenna. This arrangement is shown in Figure 8. The package was sufficiently light that it could be towed across the river by an electric motor on the bank. No personnel were required to be on the cableway. A short video of equipment used to make this discharge measurement is attached to the electronic version of this paper (Animation 1).

[40] Surface velocities measured by RiverScat were compared with those measured by an acoustic system (BoogieDopp) that had to be placed in the water and towed across the river in a boat or from a bridge to collect data. The results are shown in Figure 9. Velocity data are not identical, possibly indicating a small bias in the RiverScat measurement. This bias was not consistently present. Outputs of both RiverRad and RiverScat were sent over phone lines to the University of Washington twice a day.

[41] Agreement between directly measured (hydroacoustic) and noncontact surface velocity (RiverRad) has been good (Figure 10), except near the banks of the river where bank interference can disrupt or block return signals [*Costa et al.*, 2000; *Cheng et al.*, 2004b, Figure 8]. In these experiments, we never observed a situation where the signal to RiverRad was absent, which is attributed to the much lower noise levels in RiverRad.

[42] Both RiverRad and the bridge-mounted RiverScat units collected a near-continuous record of surface velocity over the 4-month period of the experiment. The USGS stream gauging station measured a continuous record of river stage (and, with use of a rating curve, discharge) over the same period, while cross-section profiles were measured periodically with a fathometer or ADCP/BoogieDopp, and GPR.

[43] The RiverSonde system was installed and began collecting data on 28 October 2003. A weather station that recorded wind speed and direction, air temperature, barometric pressure, rainfall and humidity, was later added to the installation. The antennas were erected on the left bank of the river on the artificial levee. Electronics were housed in an adjoining building that had AC power and allowed for a telephone line and modem for direct, remote interrogation of data, and a live video camera.

[44] Figure 11 is a photo of the four radar systems used to measure surface velocity on the Cowlitz River. Results from the four radar systems were compared with the rating curve of stage versus discharge maintained by the USGS, and direct discharge measurements by current meter and hydroacoustic methods.

3.3. Continuous Noncontact Measurements of Surface Velocity and Discharge

[45] Truly continuous noncontact discharge measurements could not be obtained for the Cowlitz River because the GPR was operated only intermittently from the cableway. The bed of the river, however, is stable and this stability can be used to estimate continuous discharges from the radar measurements of surface velocity. All GPR measurements of the height of the bottom of the river above a datum (mean sea level for this site) were averaged and this average value was subtracted from the continuous record of stage measurements. This yielded a time series of cross sections to compliment surface-velocity measurements, both of which are then used to compute discharge. The product of cross section and surface velocity multiplied by 0.85 (to obtain mean velocity) yielded the record of continuous radar discharge measurements shown in Figure 12. Figure 12 also shows the discharge obtained from the rating curve and from in situ conventional measurements made by hydroacoustic or mechanical meters during the experiment.

[46] Between 1 November 2003 and 1 March 2004, the USGS stream gauging station recorded 10,358 individual stage readings, or about 9% less than the expected number because of lost record when bankside construction destroyed the orifice line of the stream gauging station. During this time, the total number of RiverScat measurements was 5,931; RiverRad measurements totaled 4,807; and RiverSonde measurements were 1,155. The radar systems measured river velocity less frequently than stage was measured to keep telephone-transmitted data files to reasonable size. Correlation coefficients between the discharge computed from the stream gauging station rating curve, and each of the three radars are:

Rating curve/RiverScat = 0.883
Rating curve/RiverRad = 0.969
Rating curve/RiverSonde = 0.992

[47] On average, noncontact instantaneous discharges were within 1–3% of conventional method discharges, and there are no significant differences between conven-

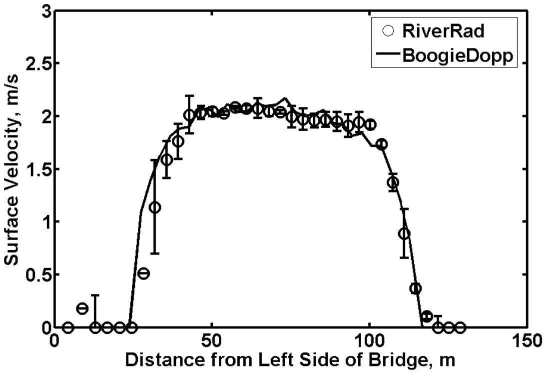

Figure 10. Comparison of RiverRad-derived surface velocity and BoogieDopp for the Cowlitz River, Washington.

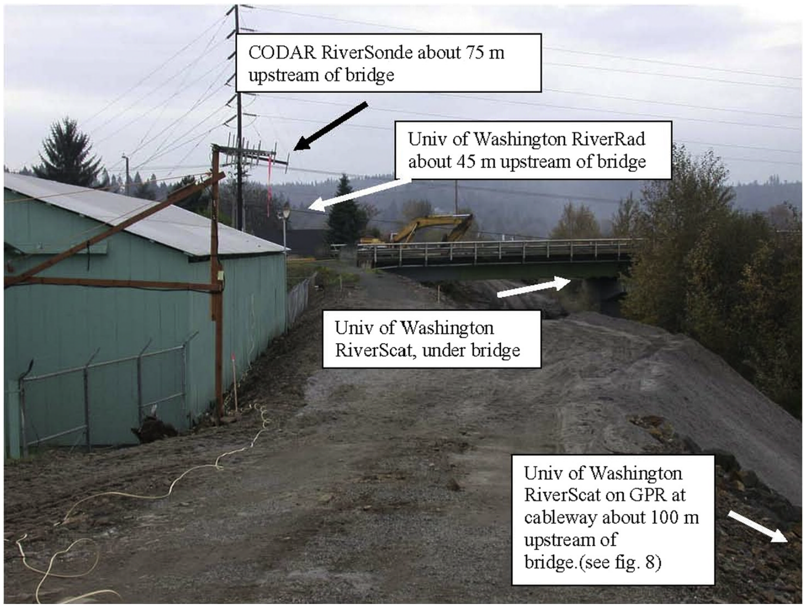

Figure 11. Four radar systems were used to collect surface velocity data for use with GPR-derived cross-section data to continuously compute river flow of the Cowlitz River, Washington. View is on the left bank looking downstream.

tional and noncontact records such as occurred in the early part of the San Joaquin River experiment. Noncontact discharge values are well within the expected range of uncertainty of a stream gauging station record.

[48] This experiment also generated insight about flow in the Cowlitz River that is not possible to ascertain from conventional-stage-only stream gauging station data and imply that surface velocity may be a more sensitive measure of river flux than stage alone. A periodic signal was seen in the Cowlitz River surface velocity data throughout most of the experiment. Careful examination of stage data shows no evidence or very weak evidence of this signal that was never noticed before. This signal shows little or no correlation with wind intensity or direction. The radar velocity signal shows an unusual low-frequency cycle of about 7 cm/s that is not reflected in the stage record [*Teague et al.*, 2004]. Later this low-frequency signal was also discovered in the output of

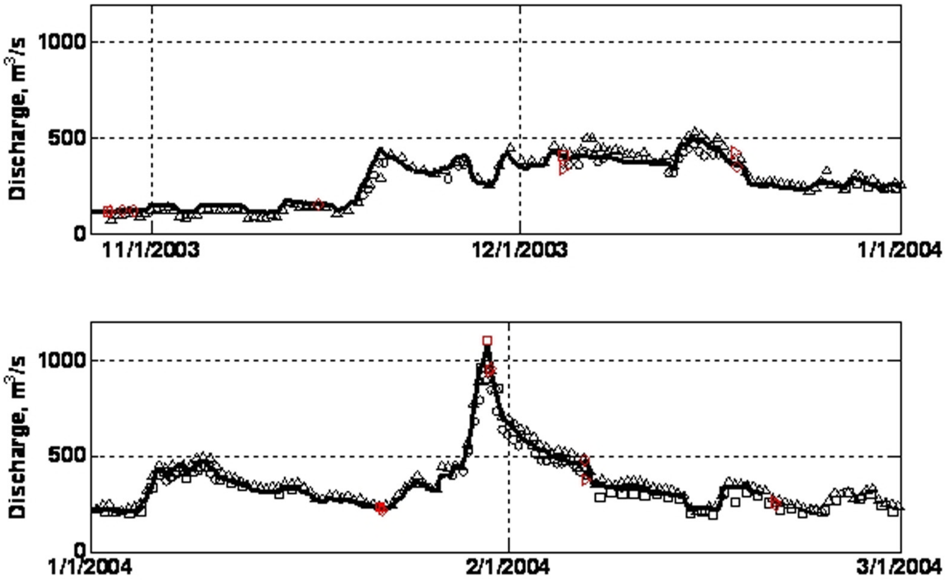

Figure 12. Measurements of the discharge of the Cowlitz River at Castle Rock, Washington, for the time period 1 November 2003 to 1 March 2004. Symbols indicate the following: black line, rating curve; black triangles, RiverRad; black squares, RiverSonde; black circles, bridge RiverScat; red diamonds, BoogieDopp; red squares, current meter; red triangles, cableway RiverScat.

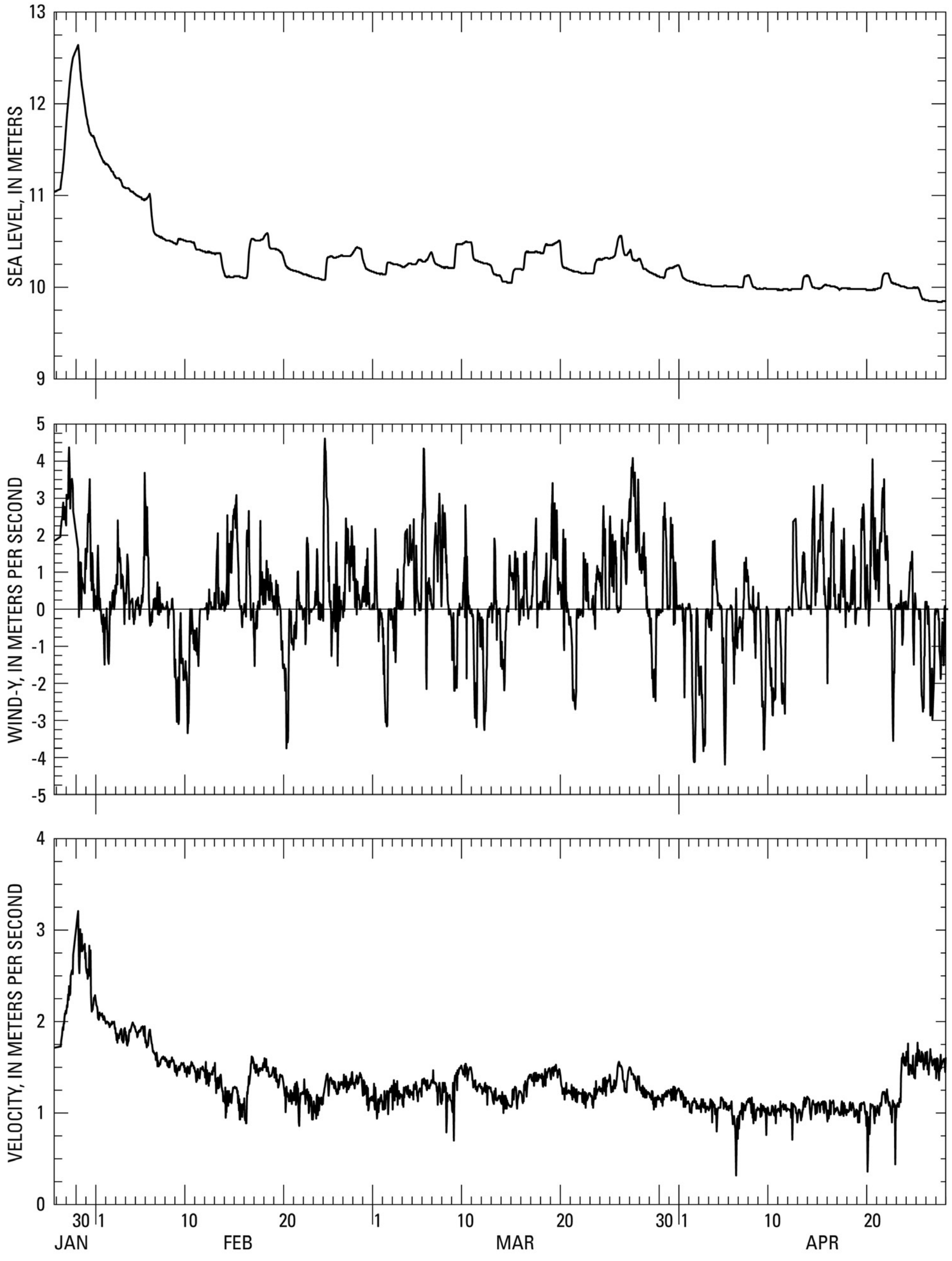

Figure 13. Time series of water level (reference to mean sea level), along-channel wind speed (m/s), and water surface velocity measured by RiverSonde (m/s) for the Cowlitz River at Castle Rock, Washington.

RiverRad. Upon discovery of this signal, the time series record was carefully analyzed. The time series record includes hourly measurements of water level (stage), along-channel wind speed, and the surface velocity measured by RiverSonde. The original measurements were taken at finer time intervals, but averaged over an hour to construct an hourly time series that covers the period from 29 January 2004 to 15 April 2004 (Figure 13).

[49] The standard tidal harmonic analysis procedure was applied to the time series [*Foreman*, 2004]. The time series was analyzed in three ways: (1) the entire record between 15 February and 15 April 2004, (2) the record covering from 15 February to 17 March 2004 (30 days), and (3) 15 March to 15 April 2004. Because of the high-flow event that took place at the end of January (see section 3.4), the record in the first two weeks in February was not used. The major astronomical tidal components of velocity and water level have values higher than the minor components. Only the amplitudes and phases of the four major tidal components (two diurnal, O_1

Table 3a. Results of Harmonic Analysis: Water Surface Velocity[a]

	Amplitude, m/s			Phase, deg		
	A	B	C	A	B	C
O_1	0.0298	0.0232	0.0321	55.64	52.61	61.08
K_1	0.0243	0.0164	0.0231	129.78	124.57	136.83
M_2	0.0127	0.0151	0.0106	339.74	43.20	343.35
S_2	0.0205	0.0225	0.0169	73.58	78.10	67.71

[a] In Tables 3a and 3b, A refers to the entire record between 15 February and 15 April 2004, B refers to the record covering 15 February to 17 March 2004, and C refers to the record covering 15 March to 15 April 2004.

Table 3b. Results of Harmonic Analysis: Water Level (Stage)

	Amplitude, m			Phase, deg		
	A	B	C	A	B	C
O_1	0.0030	0.0100	0.0221	190.29	83.8	237.88
K_1	0.0137	0.0030	0.0269	197.20	329.42	119.47
M_2	0.0155	0.0138	0.0102	49.14	36.58	14.87
S_2	0.0101	0.0085	0.0100	60.71	60.39	357.52

and K_1 and two semidiurnal, M_2 and S_2) are compiled and given in Tables 3a and 3b. Of the three independently analyzed time series, the amplitudes of these major components consistently show higher values when compared with the minor components (not shown). The phase angles of these independent analyses show stationarity, i.e., the maximum difference of the phase angles from different analysis is less than 7°. Thus the time variations of velocity are definitely associated with astronomical forcings no matter how small the amplitudes of the velocity components may be. In contrast, with water level the amplitudes of the major components are also higher than minor components (not shown), but there is no sign of stationarity in the phase angles between these independent analyses. There is not a clear explanation why the astronomical properties are reflected in surface velocity but not in the water level measurements. Keeping in mind that the velocity fluctuations are only on the order of 5–7 cm/s, the respective water level fluctuations might be too small to be detected by stage recorders.

3.4. Peak Flow of January 2004

[50] On 30 January 2004, the Cowlitz River crested at the highest flow during the 4 month experiment. Heavy rainfall in the headwaters of the Cowlitz basin resulted in a peak discharge of 1,079 m^3/s at a stage of 12.77 m (41.89 ft). Peak stage occurred at 0930. We were able to make a direct current meter measurement at the peak of this flood, although the measurement took two hours to complete and conditions conducive to making an accurate measurement continued to deteriorate. The current meter discharge measurement (made at a mean time of 0930) was 1,102 m^3/s (mean gauge height 12.77 m (41.89 ft)), 2.1% greater than the rating curve value of 1,079 m^3/s. Large volumes of floating logs and debris made this measurement difficult as well as dangerous. One method to deal with large volumes of floating debris is to leave the current meter in the water for only half the prescribed time for a velocity measurement with a Price AA meter. While this allows a measurement to be made, the uncertainty of point velocities obtained by using this "half count" method increases. The time (2 hours), effort, uncertainty, and safety considerations of making this discharge measurement reinforced the reasons for continued pursuit of a noncontact flow measuring system.

[51] The three surface velocity measuring radars were operational during this flood. The channel cross section was measured with GPR from the bank-operated cableway about two hours following the peak. The water surface had only declined about 0.1 m and flow had dropped by less than 4%. GPR profiles for cross-section measurements took about 10 min to acquire following a 30 min antenna setup. Interpreted water surface and channel bed reflections made every 3 m were marked on the profile. Radar signals were converted from timescale to length scale, assuming the velocity of radar waves in water was 0.033 m/ns. These values were entered into a spreadsheet with the area computed for each subsection and summed to obtain total area. GPR-derived depths were compared with depth measurements from hydroacoustics (BoogieDopp) and agreed to within about 3%.

[52] Surface velocity data collected from the different radars during the time GPR measurements were being made were converted to mean velocity (assuming a logarithmic velocity profile). These data were then combined with the GPR-derived channel depths and subsection discharges computed, then summed to obtain a total noncontact discharge flow value. Results are tabulated in Table 4.

[53] Noncontact discharge measurements made following the peak on 30 January 2004 agreed with the rated discharge to within 5%. Best results (+1.4%) were obtained using RiverScat mounted on the GPR antenna, as pictured in Figure 8 and Animation 1.

4. Conclusions

[54] The desire to improve the safety, speed, and cost effectiveness of the stream gauging program in the USGS sparked new interest in investigating new or different technologies for streamflow measurements. Partnerships with university colleagues and a private company were essential for the successful completion of several experiments to measure the flow of rivers without having instruments in the water. The two experiments described herein provide some direction and guidance on what can be accomplished. Water surface velocity has been measured successfully (when compared to data collected with acoustic instruments or mechanical current meters) with a microwave Doppler radar at 9.36 GHz, continuous wave microwave systems using 24 GHz, and a UHF radar system using 350 MHz center frequencies. All radars use the principle of Bragg scatter from roughness elements on the water's surface. Channel cross sections were measured successfully (when compared to fathometer, sounding weight, and ADCP data) with a GPR unit suspended above the water surface. Conductivity is the most significant problem faced during the experiments. On the San Joaquin River near Vernalis, California, conductivity values ranged from 300 to 600 μS/cm, making GPR interpretations of cross-sectional area difficult.

[55] The most important contribution of these experiments may be the demonstration of the ability to measure directly all of the properties of river flow needed to compute discharge, velocity and cross-sectional area, by noncontact

Table 4. Comparison of Discharge Measurements With Conventional Methods (BoogieDopp, Rating Curve, and Current Meter) and With Radars for High Flow on Cowlitz River, Washington, Measured During the Period 0930–1530 LT, 30 January 2004

Time	Source	Discharge, m^3/s
0930	rating curve	1,079
0930	current meter	1,102
1200	rating curve	1,039
1200	GPR/RiverRad	991
1200	GPR/RiverSonde	997
1200	GPR/RiverScat (cableway)	1,054
1530	rating curve	974
1530	BoogieDopp	954

methods and thereby, in the future, potentially eliminate the need for a rating curve. There are some aspects of these methods that are not completely resolved and may be site dependent. One is the need to convert from surface velocity to mean velocity in a subsection of the river. We concluded that an assumption of the lognormal velocity profile was appropriate for the two river sites used in these experiments. This assumption will not apply to all rivers. The periodic velocity pulses observed in all radar-derived surface velocities in the Cowlitz River, Washington, are interpreted to result from tidal influences, but their lack of signal in the stage record is an unresolved dilemma.

[56] Another technical problem is how to measure the cross section of a river from a single point on the bank of the river. We have not yet solved this, and for now a bridge, cableway, or helicopter [*Melcher et al.*, 2002] is required to move the GPR antenna out over the river. Additional experiments are planned in the future to test a bankside channel–cross section radar system.

[57] These experiments have demonstrated that technology exists for making continuous noncontact measurements of streamflow that could supersede present methods that rely on a rating curve adjusted with periodic direct flow measurements by mechanical meter or hydroacoustic instruments. The primary constraint identified is high-conductivity water. In time, these methods may lead to new processes and practices for stream gauging, ones that are safer, faster, less expensive, and more accurate than present methods.

[58] **Acknowledgments.** This work was supported by the National Streamflow Information Program (NSIP), U.S. Geological Survey. We wish to thank Mark Landers and Scott Morlock for helpful reviews, Robert Hirsch and Stephen Blanchard for their vision and leadership, and William Keller and Chris Siani for technical support. The Editors and reviewers for the journal were equally thoughtful and supportive. W. J. Plant and K. Hayes would like to acknowledge partial support for this project from the National Science Foundation through grant EAR-0106391.

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D. Barrick and C. Teague, CODAR Ocean Sensors, 1914 Plymouth Street, Mountain View, CA 94043, USA.

R. T. Cheng, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025, USA.

J. E. Costa and K. R. Spicer, U.S. Geological Survey, Office of Surface Water, 1300 Cardinal Court, Building 10, Suite 100, Vancouver, WA 98683, USA. (jecosta@usgs.gov)

F. P. Haeni, U.S. Geological Survey, 11 Sherman Place U-5015, Storrs, CN 06269-5015, USA.

E. Hayes, U.S. Geological Survey, Building 2101, Stennis Space Center, MS 39529, USA.

K. Hayes and W. Plant, Applied Physics Laboratory, University of Washington, 1013 NE 40th Street,Box 355640, Seattle, WA 98105-6698, USA.

N. Melcher, U.S. Geological Survey, 520 North Park Avenue, Suite 221, Tucson, AZ 85719, USA.