GROUND-PENETRATING RADAR METHODS USED IN SURFACE-WATER DISCHARGE MEASUREMENTS

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ABSTRACT

The U.S. Geological Survey (USGS) operates a network of about 7,000 streamflow-gaging stations that monitor open-channel water discharge at locations throughout the United States. The expense, technical difficulties, and concern for the safety of operational personnel under some field conditions have led to the search for alternate measurement methods. Ground-penetrating radar (GPR) has been used by the USGS in hydrologic, geologic, environmental, and bridge-scour studies by floating antennas on water or mounting antennas in boats. GPR methods were developed to measure and monitor remotely the cross-sectional area of rivers by suspending a 100-megahertz (MHz) radar antenna from a cableway car or bridge at four unstable streams that drained the slopes of Mount St. Helens in Washington.

Based on the success of these initial efforts, an experiment was conducted in 1999 to see if a combination of complementary radar methods could be used to calculate the discharge of a river without having any of the measuring equipment in the water. The cross-sectional area of the 183-meter (m) wide Skagit River in Washington State was measured using a GPR system with a single 100-MHz antenna suspended 0.5 to 3 m above the water surface from a cableway car. A van-mounted, side-looking pulsed-Doppler (10 gigahertz) radar system was used to collect water-surface velocity data across the same section of the river. The combined radar data sets were used to calculate the river discharge and the results compared closely to the discharge measurement made by using the standard in-water measurement techniques. The depth to the river bottom, which was determined from the GPR data by using a radar velocity of 0.04 meters per nanosecond in water, was about 3 m, which was within 0.25 m of the manually measured values.

Upon the successful completion of this experiment, the USGS designed two additional experiments to measure surface-water discharge remotely. One planned experiment will be conducted in the eastern United States using a multi-frequency mono-static radar system located on one bank of the river. The other planned experiment will be conducted in the western United States using a multi-frequency bi-static radar system with the transmitter on one riverbank and the receiver on the opposite bank.

Key words*:* GPR, geophysics, streamflow gaging, ground-penetrating radar, surface water, stream-discharge measurement

INTRODUCTION

The U. S. Geological Survey (USGS) conducts streamflow gaging at more then 7000 sites across the country. The steamflow data collected at these sites are used for multiple purposes, such as flood forecasting, water resources management, regional hydrologic analysis, and water-quality monitoring by local, state, and national entities. The current method of streamgaging was developed in the early 1900s and consists of physically measuring the channel geometry and the velocity of the water on a periodic basis. Because these data are needed over the entire range of flow conditions, personnel and equipment are often subjected to dangerous weather and river flow conditions. In addition, because many of the gaging locations are in remote locations, obtaining the data is expensive, and cannot be done frequently or continuously.

To improve the present system and take advantage of recent technological advances in geophysics and remote sensing, the USGS formed a committee to identify new technologies that could be used to improve streamflow gaging. After two years of identifying technologies in other fields that could be used for streamflow gaging, the committee concluded that the tasks presently performed in contact with the water needed to be performed remotely, i.e. without contacting the water. After reviewing acoustic, laser, and radar technologies and their applications in other related scientific fields, the committee decided that radar technologies held the most promise for measuring remotely the water depth, water-level elevation, and water-surface velocity. This decision was based in part on prior research and operational experience that the USGS had with ground-penetrating radar (GPR) and recent advances in oceanographic surface-velocity measurements.

The USGS has used GPR methods on electrically resistive water bodies in hydrologic (Beres and Haeni, 1991), geologic (Haeni and others, 1987), environmental (Wright and others, 1984; Haeni, 1996; Powers and others, 1999), and bridge scour studies (Gorin and Haeni, 1989; Crumrine, 1991; Placzek and Haeni 1995) for many years. These studies used GPR systems with antenna center frequencies ranging from 80- to 300-megahertz (MHz). The antennas were either floated directly on the water or were placed in the bottom of a rubber raft so that they were virtually in contact with the water. The object of the hydrologic, geologic, and environmental studies was to map the subsurface sediments beneath lakes, rivers, and streams. The object of the bridge-scour studies was to detect and determine the depth of infilled scour holes around bridge piers. Penetration of the water column and subsurface was dependent on the depth and specific conductance of the water, the electrical conductivity of the sediments, and the center frequency and output power of the radar transmitter and antenna. The results were site dependent, ranging from not detecting the bottom in less than one meter (m) of water to detecting the bottom and penetrating the subsurface sediments in about 20 m of water with a specific conductance of about 70 microsiemens per centimeter (μS/cm) (Powers and others, 1999).

High-frequency Doppler radar systems have been developed to measure ocean currents from shore-based stations (Paduan and Graber, 1997). Microwave Doppler radar systems have recently been developed to measure the water-surface velocities in rivers, based on experience in ocean scattering (Plant and Keller, 1990). These systems measure the Doppler shift of Bragg's scatter from waves on the water surface.

INITIAL NON-WATER-CONTACTING GROUND-PENETRATING RADAR FIELD EXPERIMENTS

The first non-contacting river-based GPR experiments conducted by the USGS were carried out in the late 1980s to support research on the use of geophysics to delineate refilled scour holes at bridge piers. In these early experiments, the antennas were suspended from boats or bridges to map the bottom and subsurface sediments around the bridge piers. The unprocessed radar data contained multiple air-water reflections and side echoes from the bridge structure. By using the simple filtering methods available at that time, some bottom and almost no subbottom reflections were obtained using the suspended antenna methods. Therefore, this method of obtaining radar data was abandoned in favor of placing the antennas directly in the water by using modified commercial 80- and 100-MHz antennas in waterproof housings.

Improvements in antenna design and signal processing ability permitted the USGS to reconsider the acquisition of radar data with the use of suspended antennas. In 1993, non-contacting river GPR experiments were conducted on the Connecticut River near Haddam, Conn. These experiments were conducted as a first step towards determining whether GPR could monitor the streambed of a river under extremely turbulent, high-flow conditions, when the streambed elevation changed in response to flow. A GSSI SIR-10[1] radar unit was used to collect radar data from a boat using 80-, 100-, and 120- MHz antennas suspended up to 1 m above the water surface. Profiles were conducted across the river where the maximum water depth was about 10 m, and the water conductivity was 126 µS/cm on November 9, 1993. The reflection of the radar energy from the sloping water bottom was extracted from the strong air-water multiple reflections with digital signal-processing methods. The ability to obtain clear radar images of the river bottom by use of suspended antennas provided the basis for subsequent experiments on streams with unstable beds.

In 1996, GPR was used to determine the cross-sectional area of four streams with unstable beds that drained the slopes of Mount St. Helens in southwestern Washington State (Spicer and others, 1997). At these sites, a GSSI SIR-10 with a single 100-MHz antenna was suspended from either a bridge or a cableway above the water surface. The specific conductance of water at these sites ranged from 32 to 262 µS/cm, and the water depths ranged from 0 to 4.8 m. The geometry of each river bottom was determined from both GPR measurements and sounding-weight measurements, and the discharge of each river was computed with the use of manual measurements of the surface velocity of the river. The cross-sectional areas of the stream channels computed from the GPR measurements were within 10 to 20 percent of the areas computed by the sounding-weight method. Two advantages of the GPR data were noted in these experiments: (1) the rapid collection of the data documented rapid changes in the geometry of the river channel and (2) a continuous profile of the river bottom was obtained without any equipment touching the water.

NON-WATER-CONTACTING STREAM-DISCHARGE MEASUREMENT

In cooperation with the Applied Physics Laboratory of the University of Washington, the USGS conducted an experiment in April 1999 on the Skagit River, Mt.Vernon, Washington (Costa and others, 2000). At this site, the Skagit River is 183-m wide, 3-m deep, has a specific conductance of 70 µS/cm, and is confined between two flood-control levees with steep banks. A Malå Geoscience GPR system was used to produce a continuous river-bottom profile near the USGS streamflow-gaging station 12000500. The GPR system is a portable, battery-powered, modular system. The control electronics and laptop computer used for data acquisition were placed in the cableway car. The antennas were suspended from the cableway car about 0.5 to 3 m above the water surface (fig. 1). The antennas were suspended using nylon rope and were connected to the system control electronics with fiber optic cables to minimize reverberations of the radar signal from the rope, cableway car, and cables. Broadband transmitter and receiver antennas with a nominal center frequency in air of about 100 MHz were used for the study. Analysis of the radar reflections from the river bottom yielded a signal center frequency of about 150 MHz after the signal had propagated through the water column.

Figure 1. Ground-penetrating radar system mounted inside cableway car with 100 mega-hertz antennas suspended 0.5 to 3 m above the water surface.

GPR data were collected continuously as the cableway car was moved across the river channel. Radar traces were collected and stacked 64 times every 20 centimeters. Timed trace-by-trace collection of the GPR data was not possible because cableway sag and car momentum prevented moving the car at a constant speed. A complete profile measurement across the river required about 8 minutes. The two-way travel-time of the GPR signal was recorded using a 500-nanosecond (ns) time window to ensure detection of all river-bottom reflections. The reflected signal was sampled 512 times at a sampling frequency of 999.5 MHz to reproduce accurately the digital signal, and to record the water-bottom reflection and distinguish it from other non-water-bottom reflections. The unprocessed data are shown in figure 2A. In this figure the river bottom is clearly delineated,

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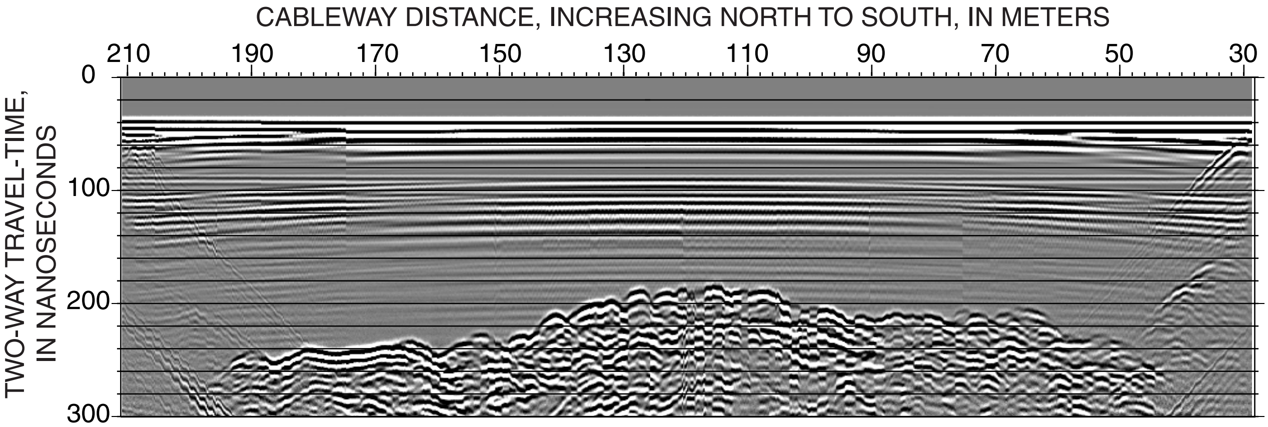
[1] The use of trade, product, or firm names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

although some reverberations are present in the upper part of the record.

The GPR data were processed by using a commercially available software package, Gradix (Interprex, Ltd.), to remove unwanted noise and clutter, while preserving the water-bottom and subsurface-sediment reflections. Processing included application of a low-cut, residual-mean-frequency filter with a cut-off at 50 MHz to remove low frequency noise. Continuous horizontal bands of background noise caused by reverberations of the radar signal from the metal cableway and car, the nearby highway bridge, and the water surface were removed by using a background horizontal filter. The background filter was composed of a moving average of 31 traces with the result subtracted from the center trace. The effect of the background filter was damped near the top early-time portion of the trace to preserve the direct arrival pulse. The direct arrival pulse was used as the time-zero point for subsequent depth interpretations.

The starting time of the traces for each radar profile was adjusted to correct for the varying height of the cableway across the river by using a radar propagation velocity in air of 0.3 meters per nanosecond (m/ns). The first horizontal reflection at the top of the record is interpreted as the water-surface reflection. The reflection from the water surface and the direct wave signal traveling through the air between the transmitter and receiver antennas are indistinguishable on the radar record except at the river edges where the offset between the antennas and the water surface was about 3 m.

A. Unprocessed Data



B. Processed Data

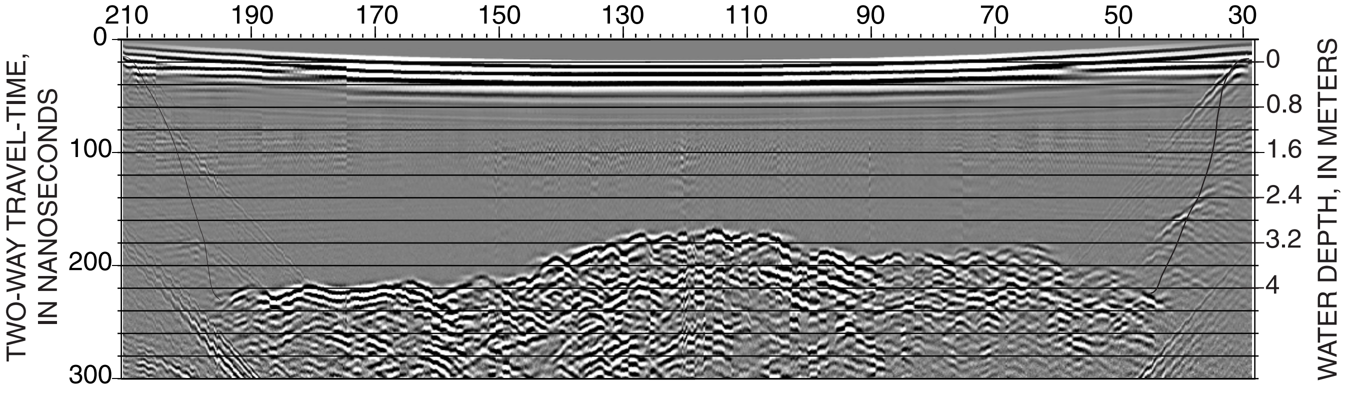


Figure 2. Ground-penetrating radar river-bottom reflection record collected across the Skagit River, Mount Vernon, Wash. (U.S. Geological Survey stream gaging station 12000500) A. The raw unprocessed field data. B. The processed data after filtering and static trace shifting. The depth scale was calculated assuming a 0.04 meters per nanosecond radar propagation velocity in water.

After processing, the radar data were displayed as a river cross-section (fig. 2B). The profile is from the north, facing downstream. The continuous high-amplitude reflector at about 200 ns two-way travel-time is interpreted as the water-bottom reflection. On the GPR data display, the horizontal cableway distance increases from north to south. The vertical axis represents the two-way travel-time of the radar signal (left side) and the water-column depth calculated by using the experimentally determined radar propagation velocity in water at the Skagit River (right side). The experimental radar propagation velocity was obtained by comparing the weight-sounded depth at multiple points along the river bottom profile to the radar reflection two-way travel-times at those points. An average experimental radar propagation velocity of 0.04 m/ns was obtained by using this method.

The reflection from the riverbank is difficult to identify because the dip of the bank is too steep to image given the offset of the antennas and the distance of the antennas from the surface geometry. Therefore, the general location of the riverbank is interpreted as the envelope of diffraction hyperbolas in the vicinity of the riverbank.

Based on the data calculated for this site and on previous work (Spicer and others, 1997), a radar propagation velocity in water of 0.04 m/ns was used with the two-way travel time of the radar in the water column to estimate the river cross section. The radar-derived cross-section along with the two direct sounding-weight measurements that were collected the same day are shown in figure 3. One set of sounding-weight measurements was taken before (0930 hours) the radar profile and one after (1630 hours) the radar profile was completed. The cross-sectional area of the river estimated from the radar data at 1345 hours is 598 square meters (m^2), whereas the two sounding-weight-determined areas are 572 and 547 m^2.

The velocity of water at the surface was measured by using a side-looking, van-mounted pulsed-Doppler radar system located about 9 m above the river (fig. 4). This radar operates at a frequency of 10 gigahertz (GHz) and measures the Doppler shift of the radar signal backscattered from short waves generated by the turbulence associated with the open-channel flow of water. The radar system measures the Doppler shift of the backscattered energy in cells about 7.5-m long and 10-m wide. These data were collected with the antenna pointed 15 degrees upstream and downstream of the measurement cross section. These measurements give the along- and cross-stream components of the surface velocity. The time required to obtain the field measurements and process the data averaged about 15 minutes, and the resulting plot of one of these measurements is shown in figure 5.

The GPR-generated cross section and the three pulsed-Doppler surface-velocity distributions, converted to mean velocity, were used to estimate stream discharge values. The mean velocity was calculated from the surface-velocity measurements by assuming a normal depth-velocity distribution and multiplying the radar-determined surface velocity by 0.85 (Rantz and others, 1982). The calculated stream-discharge values were compared to seven acoustic-Doppler current-profiler (ADCP) discharge measurements made from a boat and to a conventional current-meter discharge measurement. The mean of three non-contact

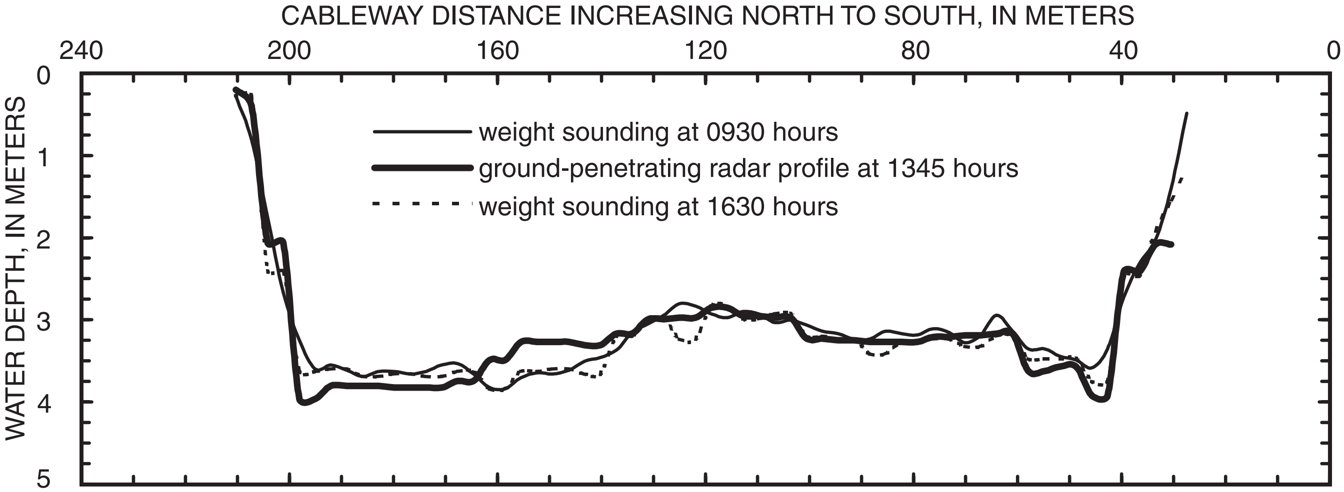


Figure 3. Ground-penetrating radar-derived cross section, compared to two sounding-weight cross-sections, Skagit River, Mount Vernon, Wash. (after Costa and others, 2000).

radar discharge measurements was 518 cubic meters per second (m^3/s) as compared to the mean value of the seven ADCP discharge measurements of 520 m^3/s and the current-meter measurement of 527 m^3/s.

Figure 4. Van-mounted side-looking back-scattering microwave (gigahertz) radar system for acquiring surface-velocity data (after Costa and others, 2000).

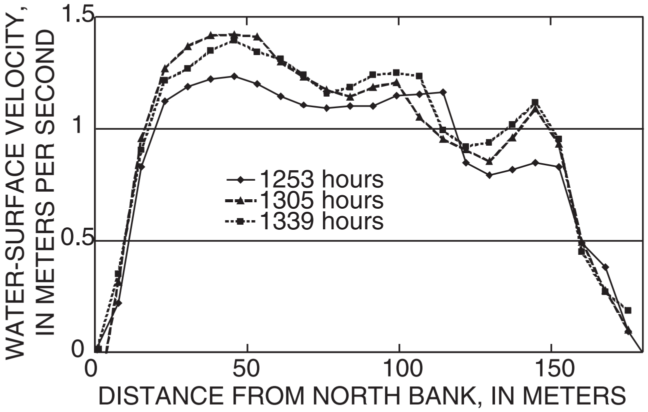


Figure 5. Surface-velocity profiles measured by the 10 giga-hertz van-mounted microwave-radar used in the computation of stream discharge (after Costa and others, 2000).

The apparent success of the initial non-contact river discharge experiments led to the award of additional demonstration contracts using (1) mono-static (backscattering) and (2) bi-static (forward-scattering) radars for direct measurements of channel cross-section and water-surface velocities. The planned mono-static experiment will be conducted in the eastern United States and the planned bi-static experiment will be conducted in the western United States.

MONO-STATIC ANTENNA NON-CONTACT STREAM-DISCHARGE MEASUREMENT

Upon the successful completion of the proof-of-concept experiment, the USGS funded additional research aimed at evaluating the feasibility of measuring the river surface elevation, river bottom depth, and water surface velocity from a fixed radar antenna installation on one bank of the river. This planned experiment will be conducted on the South Fork of the Shenandoah River at Front Royal, Virginia. A pulsed radar system with a selectable range of frequencies and a unique horn antenna will be used at this site.

CONCLUSIONS

GPR methods have been used by the USGS to determine the water-bottom geometry and the subsurface sediments of rivers, lakes, and streams for environmental, hydrologic, and engineering studies. Historically, this work was conducted with the antennas floating on the water or placed in the bottom of rafts or boats. Recent experiments in several rivers have shown that if the antennas are suspended above the water surface, the water-bottom geometry can be determined provided the specific conductance and depth of the water column are measurable by radar methods. Combination of water-bottom data with surface-velocity measurements of the river obtained with other non-contacting methods provides a means to measure stream discharge remotely. The surface velocity must be corrected to obtain mean velocity, and the radar travel time must be converted to depth before the discharge calculation is made.

River-bottom profiling done by using a 100-MHz GPR system that is suspended from a cableway car and surface-water velocity measurements made by using a side-looking, van-mounted 10-GHz radar system on the Skagit River in Washington State were used to estimate stream discharge remotely. When data from these two non-water-contacting methods were combined, the resulting discharge measurement was comparable to conventional in-water measurements. However, in this experiment, the GPR equipment and operating personnel were in a potentially dangerous position suspended above the river in a cableway car.

The next two planned experiments are designed to be conducted completely from the banks of the rivers. The first planned test is on the South Fork of the Shenandoah River in Virginia with variable frequency radar with a mono-static antenna installation on one bank of the river. The second planned test is on the American River in California with bi-static radar antennas where the transmitter and the receiver will be on opposite banks. The results of these two experiments will be used by the USGS to determine whether or not GPR, when combined with other non-contacting surface-water-velocity measurements, can be used to calculate stream discharge.

The non-contacting, stream-discharge experiments conducted to date by using GPR and other non-contacting surface velocity methods are quite promising. It may be possible to measure the discharge of many steams from the banks and to do so more efficiently and safely than using the present methods.

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