Long-Term UHF RiverSonde River Velocity Observations at Castle Rock, Washington and Threemile Slough, California

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Abstract— **Long-term, non-contact river velocity measurements have been made using a UHF RiverSonde system for several months at each of two locations having quite different flow characteristics. Observations were made on the Cowlitz River at Castle Rock, Washington from October 2003 to June 2004, where the unidirectional flow of the river ranged from about 1.0 to 3.5 m/s. The radar velocity was highly correlated with the stage height which was continually measured by the U. S. Geological Survey. The profile of the along-channel velocity across the water channel also compared favorably with in-situ measurements performed by the Survey.**

The RiverSonde was moved to Threemile Slough, in central California, in September 2004 and has been operating there for several months. At Threemile Slough, which connects the Sacramento and San Joaquin Rivers, the flow is dominated by tidal effects and reverses direction four times per day, with a maximum speed of about 0.8 m/s in each direction. Water level and water velocity are continually measured by the Survey at the Threemile Slough site, with velocity recorded every 15 minutes from measurements made by an ultrasonic velocity meter (UVM). Over a period of several months, the radar and UVM velocity measurements have been highly correlated, with a coefficient of determination R^2 of 0.976.

I. Introduction

The RiverSonde is a compact, low-power radar system which allows non-contact river velocity measurement [1]. It is based on the SeaSonde normally used at high frequencies (HF) to measure ocean surface currents, and operates in the ultrahigh frequency (UHF) range with a wavelength near 1 m with a radiated power of less than 1 W. The dominant scattering process is first-order Bragg scattering [2], with water waves of about 0.5-m wavelength providing the dominant scattered energy. Since the wavelength of the resonant water waves is known, and assuming that the waves are in deep water (more than 1/4 of their wavelength), the Doppler shift due to the phase velocity of the scattering waves also is known. The water velocity is deduced from the difference between the measured Doppler shift and that expected from the phase velocity of the resonant water waves.

A frequency-modulated chirp signal allows the range to a scattering patch to be determined with a range resolution of 5 or 15 m, depending on the bandwidth used. Direction of arrival of the echoes is determined by using MUSIC direction finding [3] applied to a three-yagi antenna array. Usually the radar is installed on one bank of a river, with the antennas looking broadly across the water flow as in Fig. 1. The center yagi is used for transmission and all three yagis are used for reception. The arrival direction of the echo is determined with a resolution of 1°.

Data processing is done in real time on a small laptop computer which usually is accessible via a dial-up modem or dedicated internet connection. Plots of radial velocity vectors, velocity profiles and time series of velocity are available either hourly (at Cowlitz) or every 15 minutes (at Threemile Slough). The RiverSonde equipment and laptop computer are shown in Fig. 2.

II. Cowlitz River

In October 2003 the RiverSonde was installed on the Cowlitz River at Castle Rock in central Washington, USA, about 28 km north of the confluence of the Cowlitz and Columbia Rivers. It remained there until June 2004. The river

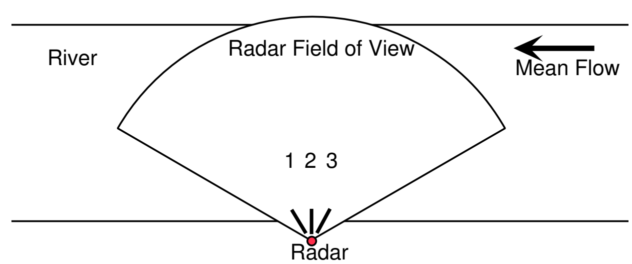

Fig. 1. Experiment geometry. The radar typically is installed on one bank of the river. The wide field of view of each antenna is across the river. The antennas are shown schematically; the 3 yagis are displaced along the river axis with a spacing of about 0.5 wavelength, and the two end yagis are rotated about 30° outward.

Fig. 2. RiverSonde equipment and laptop computer. The equipment is installed in a weather-resistant enclosure.

Fig. 3. RiverSonde antenna on the Cowlitz River at Castle Rock, Washington. Energy was transmitted on the center yagi and received on all 3 yagis.

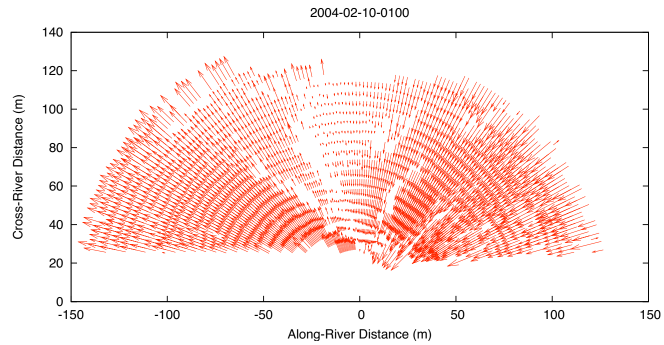

Fig. 4. Radial flow vectors averaged over one hour on 10 February 2004. Vectors are plotted between the river banks with 1° resolution in angle and 5 m in range. A velocity of 1.0 m/s is plotted with an equivalent length of 10 m.

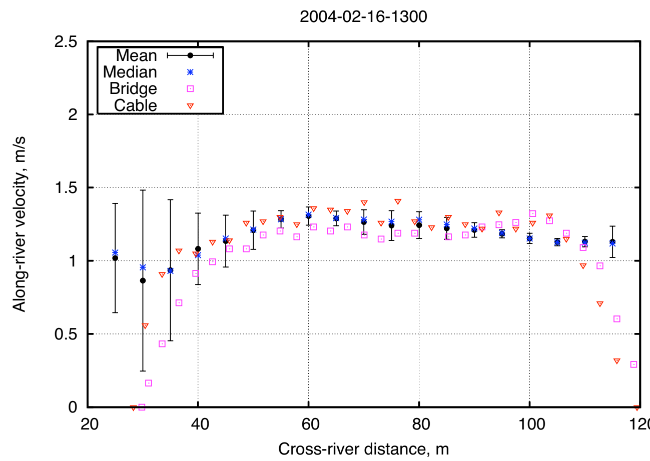

Fig. 5. Profiles of along-channel velocity *vs* distance across the channel from USGS measurements on 22 January 2004 and RiverSonde measurements on 16 February 2004 for very similar river stages. USGS measurements were taken at a bridge downstream of the radar and at a cable slightly upstream of the radar.

was about 3 m deep at the start of the experiment, and it was about 88 m wide. The antenna was about 30 m from the near bank. The antenna array is shown in Fig. 3. Stage height data are routinely recorded every 15 minutes by the U. S. Geological Survey. Several times during the course of the experiment, the Survey also measured the bottom profile using a ground-penetrating radar (GPR) and the water velocity as a function of distance across the channel and depth using *in-situ* acoustic instruments. Wind speed and direction and other weather data were recorded every 10 minutes. Finally, several microwave radars (not discussed here) were in operation during the experiment.

Radar data were processed in 2.5-minute blocks and averaged over an hour. Radial velocity vectors were computed at intervals of 5 m in range and 1° in angle. An example of a radial velocity vector map averaged over one hour is shown in Fig. 4. From the radial vectors, estimates of the variation in the along-channel velocity as a function of distance across the channel were made by two methods. One method was to combine vectors symmetrically displaced in angle about the perpendicular to the mean flow direction; the other was to compute a least-squares fit to all of the radial vectors falling in strips 5-m wide and parallel to the mean flow direction. Fig. 5 shows the result of the latter method, along with *in-situ* acoustic velocity measurements at two locations in the radar antenna footprint.

Finally, a single mean velocity estimate for each hour was made by calculating the median of the individual median velocity profile estimates over the strips from 40 to 80 m from the radar angenna (10 to 50 m from the near bank), for which the flow generally was stable and the radar signals were strong. A time series of the mean velocity estimates for a two-week period is shown in Fig. 6, along with the river stage height data and hourly wind vectors. The relative scales of the radar velocity and water height have been adjusted based on a least-squares fit between radar velocity and water height, and it is

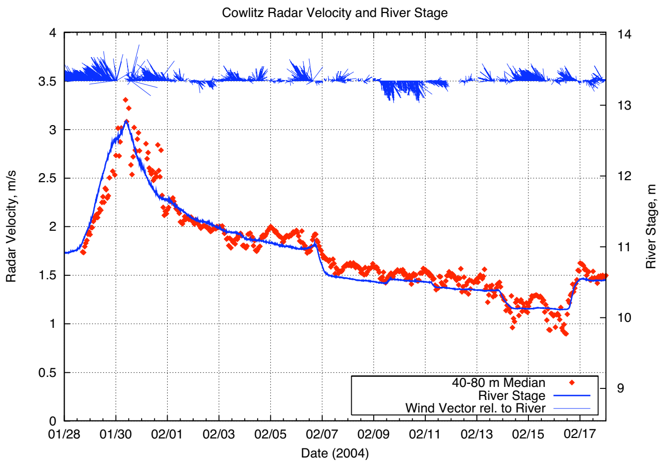

Fig. 6. Time series of radar velocity (points), river stage height (solid line), and wind vectors for 28 January to 18 February 2004. Wind vectors vertically upward indicate flow upstream (opposing the water flow).

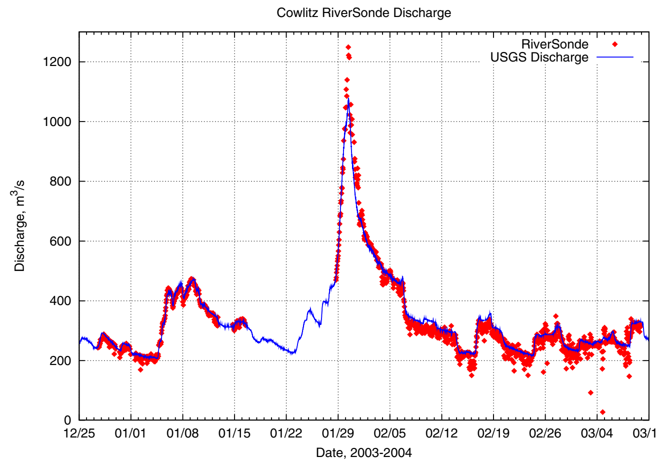

Fig. 7. Time series of discharge estimated from radar velocity, *in-situ* stage height, and GPR profile (red points), and USGS discharge estimates (blue curve) for 25 December 2003 to 11 March 2004.

clear that the radar-inferred water velocity and stage height are highly correlated. A linear regression of radar velocity on water height alone yielded a model coefficient of determination R^2 of 0.926. Including the square of the water height and the along- and cross-channel wind raised the model R^2 to 0.933.

Also obvious is a roughly periodic variation in the radar velocity, on the order of 10 cm/s, which is not reflected in the height data, and which does not appear to be related to the wind. A Fourier analysis of the radar time series indicates peaks near 1 and 2 cycles/day. Including the major tidal components in the linear regression analysis above results in a model R^2 of 0.936, with significant diurnal and semi-diurnal terms. Although there is very little tidal signature in the stage height data at Castle Rock, there is a strong tidal height signal at the confluence of the Cowlitz and Columbia rivers some 26 km away, and apparently that generates a small but detectable tidal signature in the water velocity upstream.

For comparison with the USGS estimates of total water volume discharge, the discharge was estimated using the radar velocity estimates and *in-situ* stage height data. Estimation of discharge volume involves both the velocity and the cross-sectional area. The radar surface velocity profile across the channel was multiplied by 0.85 to give an estimate of the depth-averaged velocity. The factor of 0.85 has been observed in many experiments using acoustic instruments to relate the depth-averaged velocity to the surface velocity [4]. The cross-sectional area was estimated from the GPR bottom profile obtained on 30 October 2003 with a stage height of 9.68 m, plus an area estimated from the difference between the *in-situ* stage height observation and the reference height, times the width of the water surface (88 m) at the time of the GPR measurement. The velocity profile and depth profile were both interpolated to 1-m intervals and the product of velocity and depth was integrated across the channel to obtain a total volume discharge each hour. Fig. 7 compares the radar estimates with the USGS estimates derived from the stage height measurements. The two estimates agree quite well. A regression analysis gives $Q_r = -36.0 + 1.08 Q_u$ m^3/s, with a coefficient of determination R^2 of 0.977, where Q_r is the discharge estimated from the RiverSonde measurements and Q_u is the discharge estimated by the USGS. The RMS difference between the two estimates is 22.9 m^3/s

III. Threemile Slough

The RiverSonde was moved to Threemile Slough, in central California, in September 2004 and has been operating there for several months. At Threemile Slough, which connects the Sacramento and San Joaquin Rivers, the flow is dominated by tidal effects and reverses direction four times per day, with a maximum speed of about 0.8 m/s in each direction. Water level and water velocity are continually measured by the Survey at the Threemile Slough site, with velocity recorded every 15 minutes from measurements made by an ultrasonic velocity meter (UVM). The UVM determines the water velocity from two-way acoustic travel time-difference measurements made across the channel at approximately 45° from the mean flow direction. The installation is shown in Fig. 8. The radar antenna has an unobstructed view of the water with no intervening trees. The UVM installation is immediately to the left of Fig. 8. The water depth typically is 7 m, and the UVM transducers are about 2.4 m from the bottom of the channel. The UVM measurement is an index velocity and is indicative of the velocity a few meters below the surface, although not necessarily at the exact height of the acoustic sensors. The radar measurement, on the other hand, represents the velocity within the top 3 or 4 cm of the surface, at an effective depth of about 8% of the water wavelength [5], [6]. The channel is about 200 m wide at the measurement site.

Data processing at Threemile Slough is similar to that at Cowlitz, except that 15-m range cells are used instead of 5-m cells because of the wider channel, and flow estimates were

Fig. 8. RiverSonde installation at Threemile Slough. The RiverSonde antenna is mounted on the left side of the walkway and is over the water about 4 m from the bank. The weather station sensors are above the antenna. The smaller antenna is for USGS data telemetry. The USGS and RiverSonde equipment are inside the shelter.

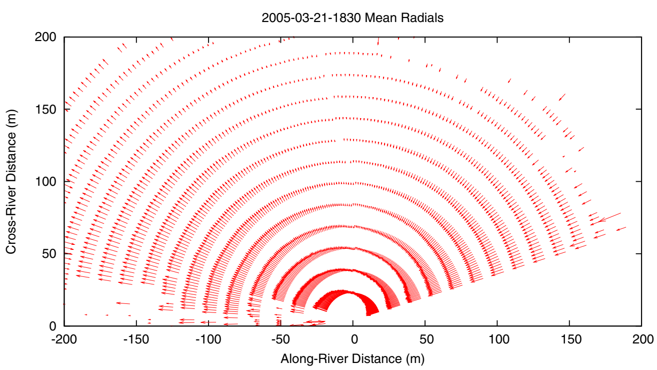

Fig. 9. Radial flow vectors averaged over 15 minutes on 21 March 2005 at 18:30 PST at Threemile Slough. Vectors are plotted between the river banks with 1° resolution in angle and 15 m in range. A velocity of 1.0 m/s is plotted with an equivalent length of 10 m. The mean direction of flow is aligned with the horizontal axis. The sharp angular cutoff at the right side of the plot is due to data processing limitations.

made every 15 minutes instead of hourly because of the variability of the flow. An example of radial vectors obtained on 21 March 2005 is shown in Fig. 9. The antenna was oriented about 13° counterclockwise with respect to the perpendicular to the channel direction, and signals were processed within ±86° from its broadside direction, so vectors are not plotted beyond that direction on the right. The radar coverage varied depending on the wind and flow conditions, but usually there were sufficient waves to produce good backscattered signals. However, if the wind was very low so that the water surface was very smooth, with no Bragg-resonant waves present, it was difficult to get a good measurement.

Fig. 10 shows the variation in the along-channel velocity as a function of distance across the channel for the data set corresponding to the radial vectors of Fig. 9. The profile was generated by fitting an along-channel velocity to all of the

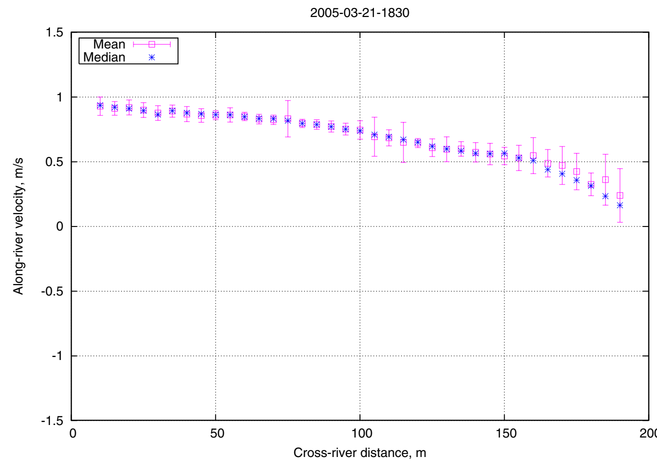

Fig. 10. Along-channel RiverSonde velocity *vs* distance across the channel for 21 March 2005 at 18:30 at Threemile Slough. The distance origin is at the radar antenna, and positive velocity represents flow toward the north. The blue asterisks show the median of 9 measurements taken over a 15-minute interval, and the red symbols show the sample means and standard deviations of the same measurements. Velocity estimates are made every 5 m across the 200-m wide channel.

radial vectors within 5-m-wide strips parallel to the mean flow direction. At the time of this measurement, the flow was changing rapidly, and the profile shows that the change was not uniform across the channel. At other times, the change was nearly uniform across the channel. As at Cowlitz, the median velocity estimates tended to be more stable than mean estimates, and the medians were used for subsequent data processing.

The median velocity profile values for positions from 40 to 120 m from the near bank were averaged to give a single mean flow value for each 15-minute interval. Fig. 11 shows the radar surface velocity estimates (red points) and the UVM index velocity estimates at depth (blue curve) along with wind vectors for a one-week period starting on 20 March 2005. No corrections to relate velocity at the surface to a depth-averaged mean have been applied to either data set. The agreement between the two instruments is striking. A formal regression analysis, relating radar velocity to UVM and wind velocity gives $v_r = -0.009 + 0.937 v_a - 0.002 w_e + 0.015 w_n$ where v_r is the RiverSonde velocity, v_a is the UVM acoustic velocity, w_e is the eastward wind at the anemometer (about 8 m above the water surface) and w_n is the northward wind, with a coefficient of determination R^2 of 0.976 and an RMS difference of 0.093 m/s. The channel runs almost directly north-south at the site, and the northward wind is in the direction of the channel. The regression was applied to 7985 data points covering 83 days.

Usually the effect of the wind on the velocity was very small. However, its effect could be seen on a few occasions, such as the beginning of 22 March 2005 when the wind was over 20 m/s. In Fig. 11 the radar data points are clearly displaced upward (higher velocity to the north) during the time of strong winds to the north. Such conditions have been seen

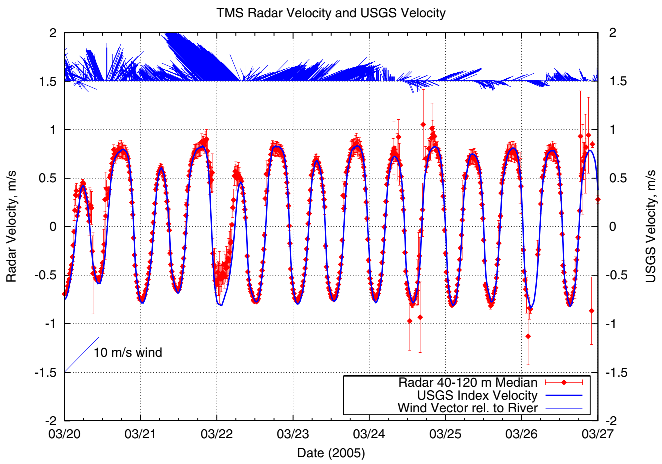

Fig. 11. Time series of mean water velocity inferred from the RiverSonde measurements (red) and from in-situ ultrasonic velocity meter measurements (blue curve) for the period 20 March 2005 to 27 March 2005. Wind vectors are shown at the top, with a vector vertically upward representing wind blowing toward the north (in the positive water velocity direction). The radar error bars indicate one standard deviation of 9 individual measurements for each 15-minute interval.

on only a few occasions so far, but they do provide evidence of a wind-related vertical velocity shear. The UHF radar is sensitive to water velocity at the topmost 3 or 4 cm of the water column [5] which is strongly coupled to the wind. The UVM measurement is made several meters below the surface, where the effect of wind-induced vertical shear is expected to be quite small.

IV. Summary

The RiverSonde system was in nearly continuous operation at Castle Rock for eight months from its installation on 28 October 2003 to its removal on 30 June 2004, and for a similar period at Threemile Slough from 16 September 2004 through mid-2005. Data processing is done in near real time on a laptop computer, and data are available either via a dedicated high-speed or dial-up telephone connection. Raw data are archived to small portable disks in case reprocessing is desired. At the Cowlitz site at Castle Rock, there was a high correlation between flow velocity and stage height, with a very small tidal signal visible in the radar data that was not seen in the stage height data. At Threemile Slough, the velocity is dominated by the tidal effects, and the velocity and stage height were nearly in phase quadrature. The radar velocity data were highly correlated with *in-situ* acoustic UVM measurements with $R^2 = 0.976$.

Acknowledgment

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