UHF RiverSonde Observations of Cowlitz River Flow Velocity at Castle Rock, Washington

Calvin C. Teague, Donald E. Barrick, and Peter M. Lilleboe
CODAR Ocean Sensors, Ltd.
Los Altos, California 94024
(408) 773-8240, fax (408) 773-0514
cal@alpha.stanford.edu, COSDon@aol.com, pete@codaros.com

***Abstract*— A UHF RiverSonde system, operating at a frequency of approximately 350 MHz, has been in operation on the Cowlitz River at Castle Rock, Washington since October 2003. The system uses SeaSonde electronics developed over many years for measuring ocean surface currents in salt water at HF. A three-yagi antenna system designed using a genetic algorithm optimization procedure replaces the conventional crossed-loop HF array. The antennas, located on one bank of the river, are directed across the river at three different azimuths and are separated by approximately one-half wavelength, allowing both amplitude and phase differences to be used for MUSIC direction finding. Scattering from the fresh water surface is dominated by Bragg scattering as it is at HF, but the data processing algorithms are modified to accommodate flow velocities which can be several times the deep-water phase velocity of the Bragg waves. Data are processed in real time on a portable laptop computer and are available through a dial-up modem. The radar data provide hourly estimates of mean flow and cross-channel variations in the flow. Mean values of the radar flow profile track very closely continuous in-situ stage height measurements. River flow velocities of 0.8 – 3.5 m s^{-1} were observed in the first five months of the experiment, with a nearly linear relationship between radar-inferred flow velocity and stage height of 9 – 14 m. The radar velocity also appears to have a weak correlation with the local wind and several tidal frequencies. The strong correlation between surface velocity and stage height suggests that – with refinement – surface velocity could replace stage height in river gaging, as well as offering additional flow information.**

I. INTRODUCTION

A RiverSonde UHF radar system [1], operating near 350 MHz, recently has been developed to explore its capabilities to provide non-contact streamflow measurements in moderate-sized rivers. This system is built around a standard SeaSonde radar which normally operates at HF over salt water. The UHF system operates with low power over a short range ($\sim$ 150 m) over fresh water. A 30-MHz chirp bandwidth gives a range resolution of 5 m. As with the SeaSonde, predominant scattering is from the 0.5-m Bragg-resonant waves on the river, and radial flow velocity is determined from the difference between the observed Doppler shift and that predicted by the deep-water phase velocity [2]. However, the river flow velocity can be considerably greater than the Bragg phase velocity, and in some cases the energy from the approaching and receding waves overlap in the frequency spectrum, so the processing algorithms are modified from their HF counterparts.

Fig. 1. RiverSonde antenna array. The spacing between the yagis is about 0.5 m.

Direction of arrival of the radar echoes is determined using the MUSIC algorithm [3], but the SeaSonde crossed-loop antenna system is replaced by the 3-yagi antenna array shown in Fig 1. The center yagi is used by the transmitter, and all three are used by the receiver. The yagis were designed using a genetic algorithm which optimized both the azimuthal patterns and the feed-point impedance. The outer yagis are displaced from the center yagi by about 0.5 wavelength, and they are rotated outward by about 30°. This configuration produces both amplitude and phase differences as a function of arrival direction which are utilized by the MUSIC algorithm.

The RiverSonde hardware is derived from standard SeaSonde HF hardware, using mixers to translate the signal to UHF. System control and real-time data processing are done on a PowerBook G4 laptop computer. The integrated modem provides dial-in access and allows both program configuration and data retrieval. Both raw and processed data are stored on a small FireWire disk drive, allowing reprocessing of the raw data if desired. Flow velocity estimates are made hourly. Local environmental conditions from a weather station are also recorded, and a webcam provides visual monitoring.

II. COWLITZ RIVER EXPERIMENT

In order to evaluate the performance of the RiverSonde system, an experiment was started on 28 October 2003 and continued through May 2004. The site on the Cowlitz River at Castle Rock, Washington, is about 28 km north of the

0-7803-8743-0/04/$20.00 (C) 2004 IEEE

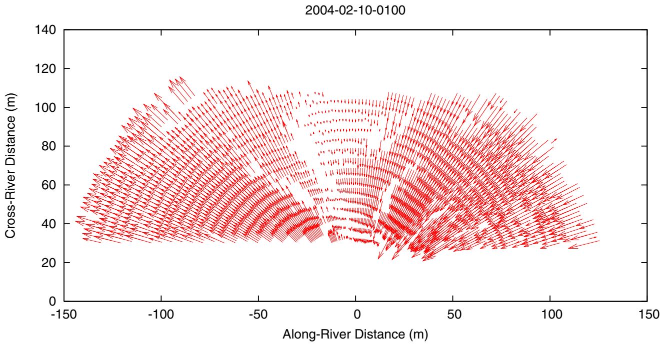

Fig. 2. Radial flow vectors averaged over one hour on 10 February 2004. Vectors are plotted between river banks with 1° resolution in angle and 5 m in range. A velocity of 1.0 $\mathrm{m\,s^{-1}}$ is plotted with an equivalent length of 10 m.

confluence of the Cowlitz and Columbia Rivers. The U. S. Geological Survey maintains a river gaging station at Castle Rock which provides stage height measurements every 15 minutes. In addition, the Geological Survey deployed in-situ instruments on several occasions during the experiment, using acoustic instruments to measure horizontal and vertical water flow velocity and ground-penetrating radar to measure water depth. The acoustic instruments were deployed from a small boat tethered to a cross-channel cable 18 m upstream from the radar and to a bridge across the river 93 m downstream from the radar. The weather station reports wind speed and direction, air temperature, barometric pressure, rainfall and humidity.

The RiverSonde system is installed on one bank of the river, which was about 88 m wide and 10 m deep during most of the experiment. The antenna is about 30 m from the near shore and 13 m above the water surface, with the antenna looking directly across the river. Maximum radar range is about 140 m with less than 1 W of transmitted power.

III. RESULTS

The radar data are processed to provide hourly estimates of radial flow velocity at points separated by 1° in angle and 5 m in range over the field of view. An example of a radial vector map, during a time of relatively calm conditions, is shown in Fig. 2. Generally the radial vector maps are quite smooth, with some gaps which often appear at the same location. It is believed that these gaps are due to signal attenuation caused by trees between the antenna and the water. The trees were bare during the winter, and as the foliage returned during the spring, the attenuation increased. The coverage area also varies, probably due to changes in the wave spectrum in response to the wind, but usually there were sufficient returns during an hour to yield good velocity estimates.

Cross-channel flow is estimated from the radial vectors by assuming that the flow is essentially parallel to the mean channel direction, with some variation in magnitude across the channel. The mean flow direction is estimated by noting the direction for which the radial velocity is zero, about 8° counterclockwise from the antenna broadside direction in Fig. 2. The radial vectors are collected into 5-m wide strips parallel to the mean flow direction, and the flow in this strip is estimated as a least-squares fit to all the available radial vectors in the strip, assuming a $v\cos\theta$ projection of the river flow v on the radar look direction θ. An example of the estimated cross-channel profile is shown in Fig. 3, obtained near the time of maximum flow. Agreement between the radar and in-situ measurements is good in the region 40–100 m from the antenna, but the radar measurements do not show the decrease in velocity near the banks which is recorded by the acoustic instruments.

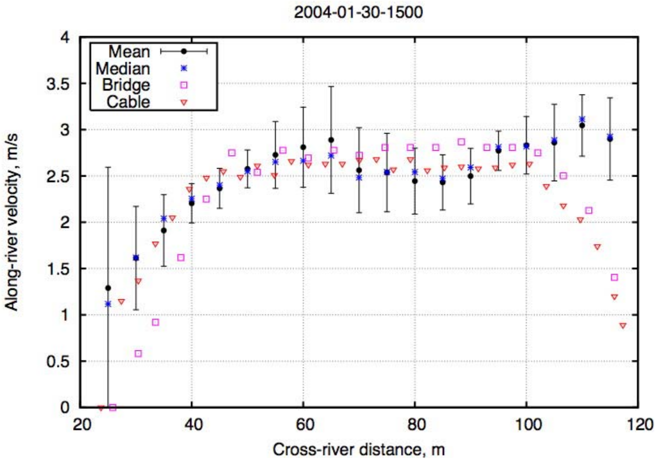

Fig. 3. Cross-channel velocity profile on 30 January 2004, during a period of high flow. Velocity is estimated at 5-m intervals across the channel. The mean estimate from all radial vectors within each 5-m strip is indicated by the dots, the standard deviation is indicated by the error bars, and the median estimate is indicated by the asterisks. In-situ acoustic measurements taken at a cross-channel cable and at a nearby bridge are indicated by squares and triangles, respectively.

Finally, a single mean velocity estimate for each hour is made by calculating the mean of the cross-channel median velocity estimates over the strips from 40 to 80 m from the radar antenna. Generally the flow is stable in this region and the signals are strong. A two-week time series of the mean velocity estimate is shown in Fig. 4, along with the river stage height and hourly wind vectors. This period included the highest velocity and stage height observed during the experiment. The relative scales of the radar velocity (left) and stage height (right) have been adjusted based on a least-squares fit between radar velocity and stage height. The close tracking between radar-inferred velocity and stage height is apparent. The Regress function of Mathematica was used to compute formal regressions of radar velocity on several variables. A regression of radar velocity on height alone yields a coefficient of determination R^2 of 0.926. Including the wind and allowing for a height-squared term increases R^2 to 0.933.

There appears to be an additional velocity signal in Fig. 4, on the order of 10 $\mathrm{cm\,s^{-1}}$, which is roughly periodic and which is not reflected in the stage height data. (The stage height curve does include rapid jumps in value which indicate that the periodic signal is not simply filtered out of the height data.)

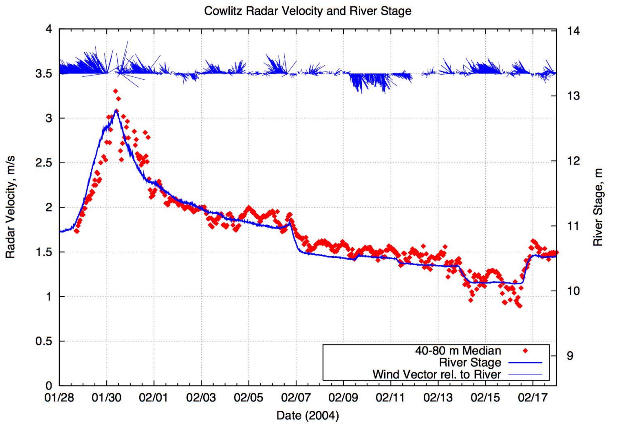

Fig. 4. Time series of radar velocity (points), river stage height (solid line), and wind vectors for 28 January to 18 February 2004. Wind vectors vertically upward indicate wind flow upstream, opposing the water flow.

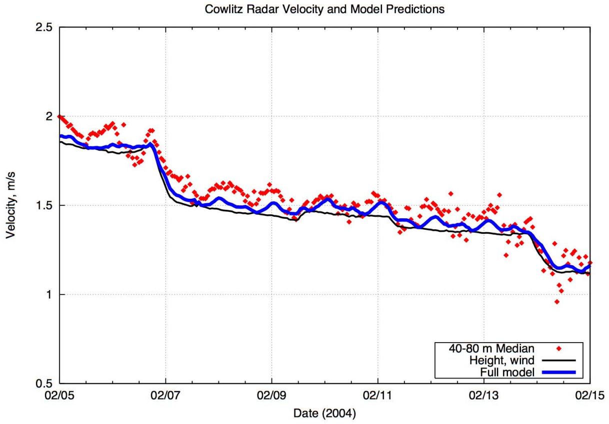

Fig. 5. Comparison of a 10-day sequence of radar velocity data (red points), a model which includes only height and wind terms (black line), and a model which includes height, wind and tidal terms (thick blue line).

At first it was suspected that there might be a periodic variation in the wind, but there is no obvious periodic signal in the wind vectors of Fig. 4. A Fourier analysis of the radar velocity time series shows peaks near one, two and four cycles per day, suggesting an ocean tidal connection. Consequently, a tidal fit using the $M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_4, MS_4, MF$ and MM terms [4] was added to the model. Including these tidal terms raised the R^2 of the regression to 0.936, with the diurnal and semi-diurnal terms dominating. Although their contribution to the overall fit is small, about 0.0025, compared to 0.926 for the linear height term, their inclusion results in a fit which more closely follows the radar velocity, as shown in Fig 5.

IV. DISCUSSION

The RiverSonde system at Castle Rock has been in nearly continuous operation for about six months since its installation on 28 October 2003, except for about two weeks during January 2004. It was still in operation in June 2004, although increased foliage on the trees between the antenna and the water has resulted in decreased signal strength. During the course of the experiment, the stage height varied from about 9 to 14 m, and the flow velocity varied from about 0.8 to nearly 3.5 m s^{-1}. Over that range, there is a very high correlation between radar-inferred flow velocity and measured river stage height, with an R^2 of at least 0.93. The cross-channel flow profile agrees well with the in-situ acoustic measurements across the center of the channel, but the acoustic instruments show a decrease of velocity near the banks which is missed by the radar. The bank may mask the water on the shore near the radar, and at the far shore the signal level may be too low for reliable measurements. The influence of the wind has been small, on the order of 1 cm s^{-1} or less, but periodic variations on the order of 10 cm s^{-1} with frequencies similar to the diurnal and semi-diurnal oceanic tidal frequencies have been seen. Although those signals are very small in the river stage height at Castle Rock, they are very strong at the confluence of the Cowlitz and Columbia Rivers near Longview, Washington, with a daily water height variation there of over 2 m. Apparently their influence is felt in the water velocity 28 km upstream.

After some initial adjustments, the data processing has been completely automatic, and data have been available within an hour of their collection via a dial-up modem connection. All data, including the raw measurements, are archived to disks in case additional processing is desired. The strong correlation between radar-inferred surface velocity and river stage height suggests that the RiverSonde may be attractive for routine monitoring of medium-sized rivers. We hope to repeat the experiment at different locations to explore environmental influences.

ACKNOWLEDGMENT

The authors acknowledge the support of the Hydro-21 Committee of the U. S. Geological Survey for the planning and execution of the experiment and for providing in-situ data, and the city of Castle Rock, Washington for providing shelter for the equipment.

REFERENCES

[1] Calvin C. Teague, Donald E. Barrick, Peter M. Lilleboe, and Ralph T. Cheng, "Initial river test of a monostatic riversonde streamflow measurement system," in *Proc. of the IEEE/OES Seventh Working Conference on Current Measurement Technology*, Judith A. Rizoli, Ed., New York, March 2003, IEEE, pp. 46–50.

[2] R. H. Stewart and J. W. Joy, "HF radio measurement of surface currents," *Deep-Sea Research*, vol. 21, pp. 1039–1049, 1974.

[3] R. O. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Trans. on Antennas and Propagation*, vol. AP-34, pp. 276–280, 1986.

[4] S. Pond and G. L. Pickard, *Introductory Dynamical Oceanography*, Permagon Press, second edition, 1989.