# Profiling River Surface Velocities and Volume Flow Estmation with Bistatic UHF RiverSonde Radar

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**ABSTRACT -- During the summer of 2000, a bistatic UHF radar -- the RiverSonde -- was designed, built, and tested on rivers and canals in the Central Valley of California. The transmitter and receiver were on opposite banks. They simultaneously transmit to and receive from elliptical time-delay cells that span the river, with the transmit and receive antennas as their focal points. With 30 MHz bandwidth, the cell span up/down-river is ~10 m. A three-element receive array employs the direction finding MUSIC algorithm to determine echo bearing. Velocity along the river channel is measured vs position across the river from the first-order Bragg-echo Doppler shifts. Radiating less than 1 w power, received surface-echo signal-to-noise ratios of 40 dB were received, both across narrow canals and across the American River that was 80 meters wide.**

**Our tests and analyses were sponsored by and conducted along with the U.S. Geological Survey in Menlo Park, CA. "Surface truth" velocity profiles were established by current meters suspended from a boat, from a bridge, and from timing the drifts of tennis balls between two transverse cuts. RMS velocity differences between 6% - 13% of the typical average flow velocity were observed. The rms differences between the three "surface truth" measurements themselves also fell within the same span.**

**From the velocity profiles across the river, estimates of total volume flow for the four methods were calculated based on a knowledge of the bottom depth vs position across the river. The flow comparisons for the American River were much closer, within 2% of each other among all of the methods. Sources of positional biases and anomlies in the RiverSonde measurement patterns along the river are identified and discussed.**

## I. THE BISTATIC UHF RIVERSONDE RADAR

The CODAR RiverSonde is based on a bistatic geometry. In contrast with the features of a bistatic with that of conventional backscatter (monostatic) radars, contours of constant echo time delay for the latter are circles (range rings), and velocity is measured via Doppler shift as arrows directed perpendicular to the circles along bearing spokes. For bistatic radars, constant time delay contours become ellipses confocal about the transmitter and receiver locations. The velocity component measured by Doppler is perpendicular to the ellipses, lying along hyperbolas confocal about the same transmitter and receiver points.

In the RiverSonde, the transmitter and receive straddle the river. An idealized sketch of this is shown below. Only the portions of the elliptical range cells transecting the river channel are shown. Echoes from the ellipse portions over land are not Doppler shifted by the moving water waves, and hence are filtered out of the processing. We highlight in pink one cell for a given time delay. Echoes from several such elliptical time delay cells on the river are processed. An advantage is the bistatic geometry equalizes the the signal strength scattered from portions of a cell from one side of the river to the other, whereas backscatter radars have a large echo variation as one moves away from the radar to the far side of the river.

Echoes come from water waves that Bragg scatter, i.e., waves whose lengths are greater than half the radar wavelength, tangent to the elliptical contours. In the absence of a flow, the speeds and Dopplers of these waves are well known based on the gravity-wave dispersion relation. The downriver flow adds a velocity/Doppler component to the known wave phase speed, and this is determined from spectral analysis of the echo-signal time series.

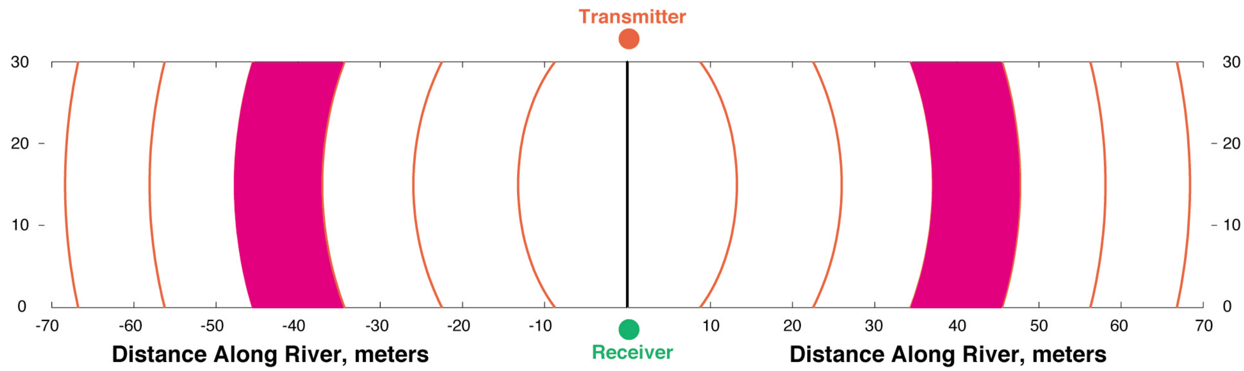


Figure 1. Sketch of bistatic transmitter & receiver straddling river; pink time-delay cell highlighted.

The frequency -- 300 to 400 MHz -- is selected as a tradeoff. The echo interpretation may be cleaner for longer waves (lower frequencies), but such waves may not be present on calm days. At much higher frequencies, the scattering process becomes more complicated, introducing errors due to small-scale effects unrelated to the surface flow velocity (like capillary and breaking waves). The frequency region selected in fact proved ideal, as strong echoes were seen at all times (even morning periods on the canal when calm conditions were expected).

Slightly less than one watt of transmit power produced echo signal-to-noise ratios between 20 and 50 dB. Time delay is measured by linearly modulating the frequency and demodulating in the receiver; frequency offset after demodulation is proportional to echo time delay, which defines the location of the scattering cell.

To minimize ambiguous upriver echoes, our YAGI transmit antenna pointed in the downriver direction. It was also designed to transmit minimum energy directly across the river toward the receiver. This is desirable to reduce the "direct" transmit signal seen bistatically to minimize dynamic range requirements. Our prototype done with screen mesh and copper-clad PVC pipe mounts on a simple tripod is shown in Fig. 2 as set up on the American River.

The receive antenna unit consists of a three-dipole array. Direction-finding (DF) was used instead of beamforming. We employ the MUSIC algorithm which is standard for SeaSonde surface-current mapping. The dipole array's broadside points down the river, so that its best coverage region matches the transmit antenna's field of view. We used the iMac® computer at the receiver for real-time acquisition and pre-processing of the echo data. It was located in an SUV and was powered (along with the receiver and transmitter) by a small Honda 1kW generator. Most of the techniques we used to produce the results in this report were developed and optimized offline after the tests. A photo of equipment and cabling to the receive antenna are shown in Fig. 3.

The RiverSonde signal processing algorithms estimate velocity profiles that completely span the river (from shore to shore). For the American River tests, two USGS velocity profiling methods were used as comparisons: (1) boat Pygmy flowmeter transects done downstream of the bridge; and (2) profiles constructed from drift rates of tennis balls lofted into the river by a pitching machine.

## II. RESULTS AND "TRUTH" COMPARISONS

The RiverSonde gathered data continuously over a four-hour period on June 7, 2000 on the American River at the California State University at Sacramento campus. It looked continuously at several swaths across the river, beginning about 250 feet downstream, with the last swath being 500 feet downstream. For the American River, six swaths were profiled. Data from all of these downriver swaths were averaged to produce one downriver RiverSonde profile for comparison with the USGS data. In all, ~20,000 points were averaged in the final three RiverSonde profiles prepared for comparisons here. Fig. 4 below shows the comparisons. (In keeping with USGS standard practice, all units are reported in the English rather than the metric system of units.)

From these three profiles, the following statistics listed in Table 1 were calculated for the mean differences, based on 20 equally spaced points on the interpolating curves of Fig. 4, and using the common overlapping regions between each pair of curves.

The percent differences among the RiverSonde and two "truth" comparisons above are: 5.0% and 14.6%. The percent difference between the two "truth" measurements themselves is: 18.7%.

Figure 2.  RiverSonde bistatic transmit YAGI antenna on American River in June 2002.

Figure 3.  RiverSonde receive antenna; receiver and Macintosh processor are in the van.

TABLE 1
Differences Among Various Velocity Profile Measurements

| | |
|---|---|
| • **[RiverSonde - Pygmy boat]:** | **RMS Difference = 0.075 ft/s** |
| • **[RiverSonde - Tennis balls]:** | **RMS Difference = 0.168 ft/s** |
| • **[Pygmy boat - Tennis balls]:** | **RMS Difference = 0.215 ft/s** |

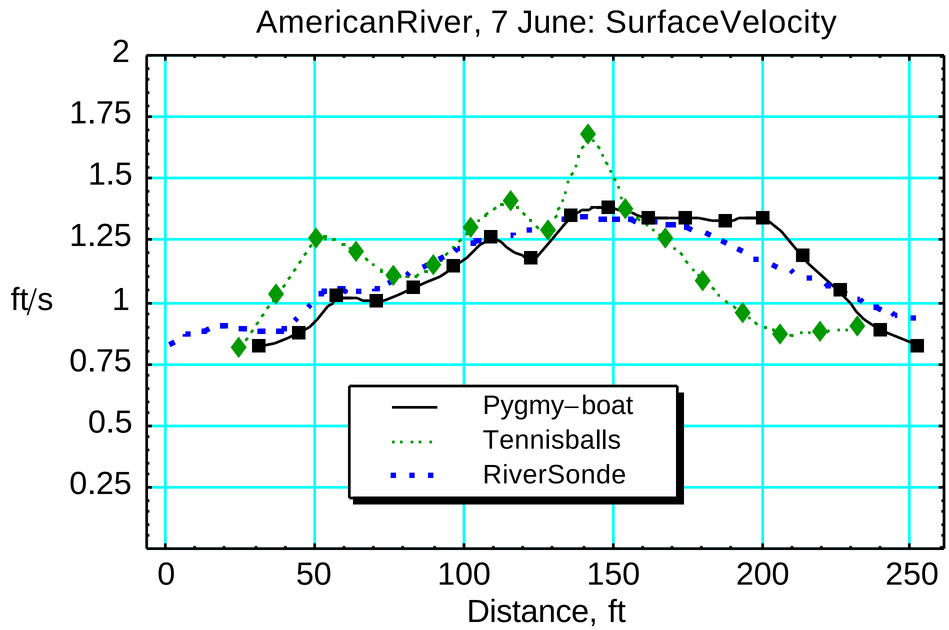


Figure 4. Cumulative American River Velocity Profile Comparisons for June 7, 2002.

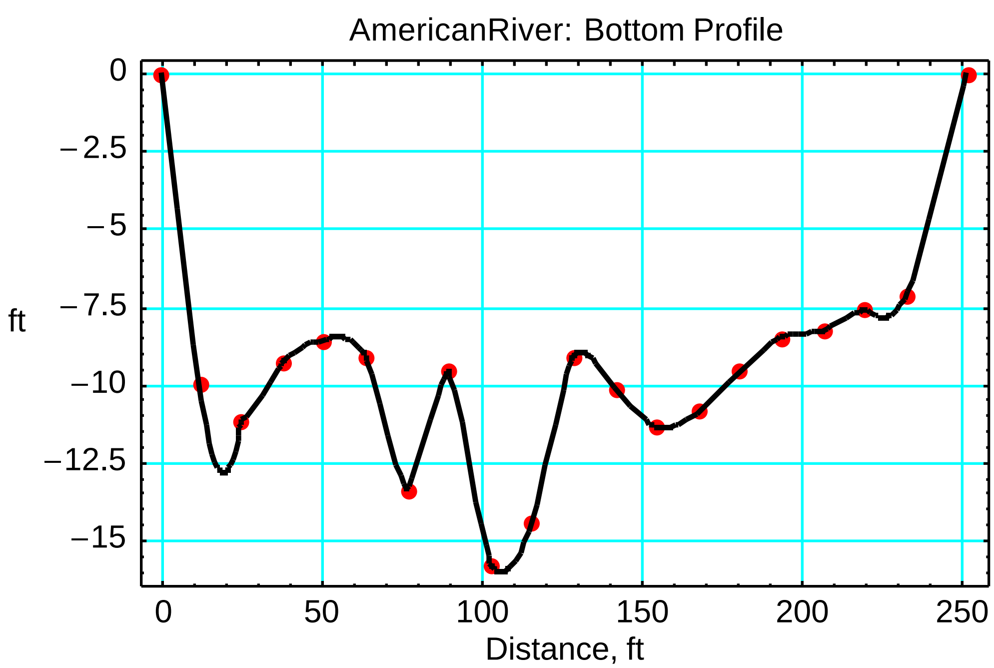


Figure 5. Bottom profile of American River in region of RiverSonde measurements.

A primary objective of USGS stream gaging is estimation of volume flow. To do this, one must know the bottom profile as well as mean velocity vs depth. A standard USGS rule calculates the mean velocity as 90% of its surface value. Fig. 5 shows the measured bottom profile of the American River at the time of the measurements.

Using this, estimates of volume flow in cubic feet per second (cf/s) are calculated from the three methods. Since the "truth" measurements did not reach the bank, only the common swath portions were used in our volume flow comparison calculations. Table 2 summarizes these results below.

As can be seen, volume-flow agreement is quite good due to the integrating effect of the calculations: 0.26% and 1.61% respectively.

TABLE 2
Differences Among Various Calculations of Volume Flow

| | |
|---|---|
| **Pygmy Boat Swath Flow: 2263 cf/s** | **Same-Swath RiverSonde Flow: 2269 cf/s** |
| **Tennis Ball Swath Flow: 2300 cf/s** | **Same-Swath RiverSonde Flow: 2263 cf/s** |

**Bank-to-Bank RiverSonde Flow: 2503 cf/s**