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Backscattered Intensity Profiles from Horizontal Acoustic Doppler Current Profilers

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ABSTRACT: Horizontal Acoustic Doppler Current Profilers (HADCPs) are a relatively new instrument that can be used to measure cross-river profiles of streamwise velocity and may also provide a relative measure of particle concentration. A number of these instruments are currently installed along three French rivers at locations intermediate to power plants and gauging stations. Unfortunately, during the first year of operation it was found that during low flow conditions at some sites, the horizontal ADCPs often underestimated velocity relative to measurements from gauging with a portable, vertically-oriented ADCP. In an attempt to understand the velocity underestimation that has been observed, studies of velocity and echo intensity profiles have been carried out under a range of flow conditions at various sites. This paper presents an analysis of the echo intensity profiles measured by a 300 kHz horizontal ADCP at the Romans-sur-Isère study site over a ten-day period during November 2009. Time series of intensity data are compared to measurements from two other horizontal ADCPs operating at 600 kHz and 1200 kHz, as well as measurements of optical turbidity. The cross-river intensity profiles are compared to theoretical predictions and it is found that instead of decreasing with range as expected, the echo intensity often diverges from theory, ballooning with distance from the receiver. This increase in signal intensity with distance appears to be a result of acoustic reflection from either the river bottom or roughness at the water surface.

Keywords: Underwater acoustics, measuring river flow, ADCPs, hydrometry

1 INTRODUCTION

In recent years, the field of underwater acoustics has advanced greatly, such that a wide range of acoustic instruments are now commercially available for the measurement of water currents. Amongst them, the Acoustic Doppler Current Profiler (ADCP) is the most commonly used instrument for obtaining velocity measurements over a range of distances. This instrument is composed of one or more circular piezoelectric transducer which generally function as both emitter and receiver of acoustic waves. To begin with, an acoustic pulse or burst of pulses is transmitted. When these waves encounter particles suspended in the water column, they are scattered in a manner dictated by the shape, size, composition and concentration of the particles; a portion of this scattered energy is directed towards the ADCP. The intensity and frequency of these scattered waves are recorded by each transducer and the along-beam component of the relative scatterer velocity is calculated using the Doppler principle, which relates the observed frequency shift to the relative scatterer velocity. Alternatively, particle velocities can be obtained from the phase shift of the scattered waves from two successive pusles, as is the case with the RD Instruments Broadband ADCPs used in this study (RD Instruments, 1996). The signal is then divided into bins of a set width, and in this way we obtain a profile of velocities that have been spatially averaged over the dimensions of each acoustic bin.

Five study sites in east-central France are equipped with RD Instruments fixed side-looking Acoustic Doppler Current Profilers, however in this paper we shall focus on only one of these sites. These instruments, which operate at either 300, 600, or 1200 kHz, can be used to provide continuous measurements of river flow. Each instrument measures a horizontal profile of the along-stream velocity, with a maximum measurement range determined by its operating frequency. Using a calibration method such as the index velocity or the velocity profile method, discharge values can be calculated from the horizontal velocity profile (e.g. Hoitink *et al.*, 2009, Le Coz *et al.,* 2008, Nihei *et al.*, 2008).

In order to verify the HADCP velocity measurements, one can make simultaneous measurements using a downward-facing ADCP that is attached to a motor boat. With the ADCP transmitting and recording, the motor boat performs multiple crossings along the line-of-sight of the HADCP and after a series of vector projections, we obtain one average ADCP velocity measurement for each "cell" of HADCP data. A detailed description of this procedure can be found in Moore *et al.* (2009). ADCP-HADCP velocity comparisons at a variety of study sites revealed that although there is good agreement between the velocity measurements the majority of the time, under low-flow conditions the horizontal ADCP tended to underestimate velocity at some sites. The mean velocity at which this underestimation occurs depends on the study site.

At the Romans-sur-Isère study site, it was found that often times when the horizontal ADCP underestimates velocity, the intensity profile measured by the HADCP does not correspond to the profile predicted by theory. Instead, the intensity profiles have a range of unusual forms that cannot be the result of inhomogeneities in either particle size, composition or concentration. This implies that there must be acoustic scattering by something other than the suspended particles in the water column. Thus, in an attempt to understand the velocity underestimation that has been observed under certain hydraulic conditions, an investigation of the signal intensity profiles was initiated. This was done because the echo intensities should provide information on the objects from which the sound is being scattered. The hope is that in understanding the source of the deviations between the observed and expected theoretical HADCP intensity profiles, we will find the source of the discrepancies between the HADCP and ADCP velocity measurements. This paper shall focus on ten days of data from the most problematic site, that of Romans-sur-Isère.

2 MOTIVATION FOR THE STUDY

2.1 *Study site*

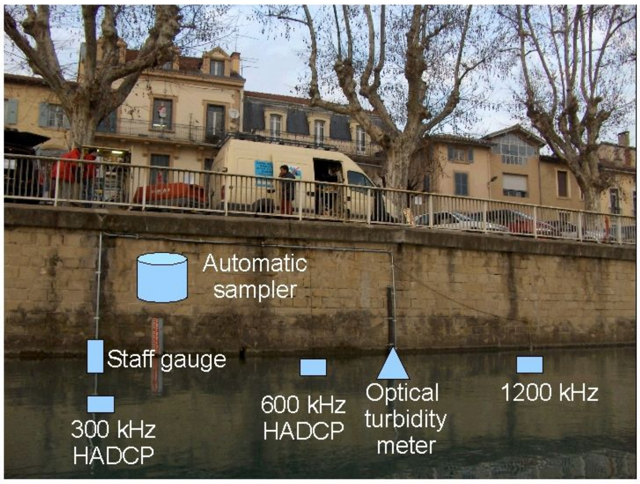

Figure 1. View of the right river bank at the Romans-sur-Isère study site.

The Romans-sur-Isère study site (see Figure 1) is located on the right bank of the Isère river, in the town of Romans-sur-Isère in east-central France. At this location, the river is 90 m wide and the maximum depth is ~4 m. A horizontal cross section of the bathymetry obtained with the bottom tracking function of a 600 kHz RD Instruments Workhorse Rio Grande ADCP during one river crossing is shown in Figure 2. Depth is given with respect to the zero of the staff gauge at this site. The water level that is indicated, 0.14 m, was the observed level at the time of installation of the 1200 kHz and 600 kHz HADCPs; it is plotted as a horizontal gray line in Figure 2. Since the site is located in the backwater of a hydropower dam, the water level changes minimally, ranging from 0.06 m to 0.21 m during our study period.

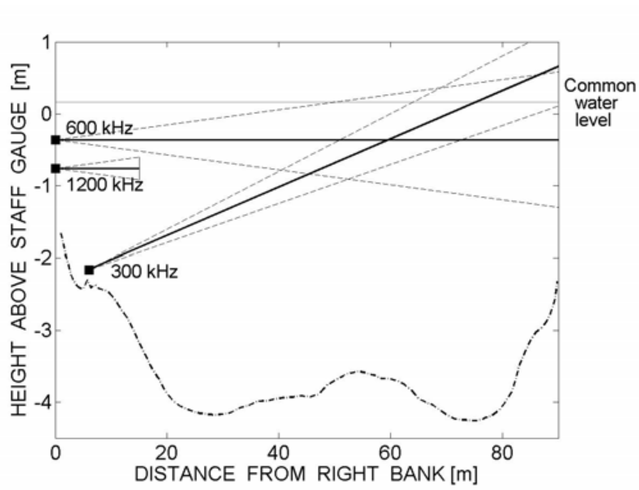

Figure 2. Side view of the instruments at Romans-sur-Isère. The horizontal ADCPs are represented by squares. The projection of the "central" beam of each instrument is shown as a solid line. Dashed lines represent the axes of the –3dB intensity levels, for a given instrument, this is the same for all transducers.

2.2 *Velocity measurements by the 300 kHz HADCP at Romans-sur-Isère: motivation for the acoustic intensity study*

According to the manufacturer's specifications, the cross-sectional aspect ratio limitation of a 300 kHz HADCP is 19/1. Thus, taking the mean depth at Romans-sur-Isère to be 4 m, it was expected that this instrument should provide reliable measures of velocity up to 76 meters from the right bank. However, it was found that when the mean velocity of the horizontal profile at Romans-sur-Isère was less than ~1 m/s, the velocity measurements were erroneous, particularly in the middle of the river. In order to illustrate this phenomenon, data collected on two different days are shown in Figure 3. The horizontal profiles of stream-wise velocity as measured by the vertical, mobile ADCP are plotted in black and the results from the fixed side-looking ADCP are plotted in grey. These profiles represent the average of 30 minutes of data.

It can be seen that on both 2009-01-09 and 2009-03-05, the HADCP underestimated velocity significantly between about 20 meters and 75 meters from the right bank. Observations of this sort spurred an in-depth study at this site. This has included the installation of both an optical turbidity meter and an automatic sampler, as well as a study of HADCP echo intensity profiles. In the remainder of this paper, we shall focus on an analysis of the intensity profiles recorded by the side-looking ADCPs, with specific emphasis on the 300 kHz instrument.

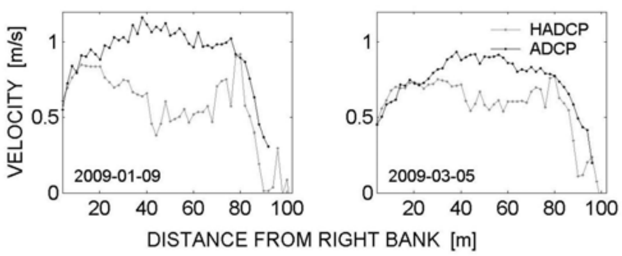

Figure 3. The horizontal profiles of streamwise velocity measured by a vertically-oriented, mobile 600 kHz ADCP (black) and the fixed 300 kHz HADCP (grey) at Romans-sur-Isère.

2.3 *Instrumentation*

The site is equipped with three side-looking ADCPs manufactured by RD Instruments, a limnimeter, an optical turbidity meter, and an automatic sampler. The main instrument is a 300 kHz Workhorse HADCP which is mounted on a 6-meter long arm protruding from the right bank. The 300 kHz instrument has three transducers, each separated by 20 degrees. It is directed towards the surface at a pitch angle of 1.8 deg as illustrated in Figure 2. This was done in order to avoid the beams encountering the central rise in the river bottom, which appeared to act as a strong reflector at the time of installation. Two further side-looking ADCPs, a 600 kHz Workhorse, and a 1200 kHz Channel Master are installed along the right channel wall, approximately 6 m and 13 m upstream of the 300 kHz instrument, respectively. The 600 kHz instrument has three transducers in the same horizontal plane, each separated by 25 degrees, while the 1200 kHz instrument has two transducers that are separated by 40 degrees. Both instruments have a pitch angle close to zero, and thus face directly across stream. Since the 1200 kHz instrument has two, not three transducers, the "central" beam traced in Figure 2 refers to the projection of either one of the two beams.

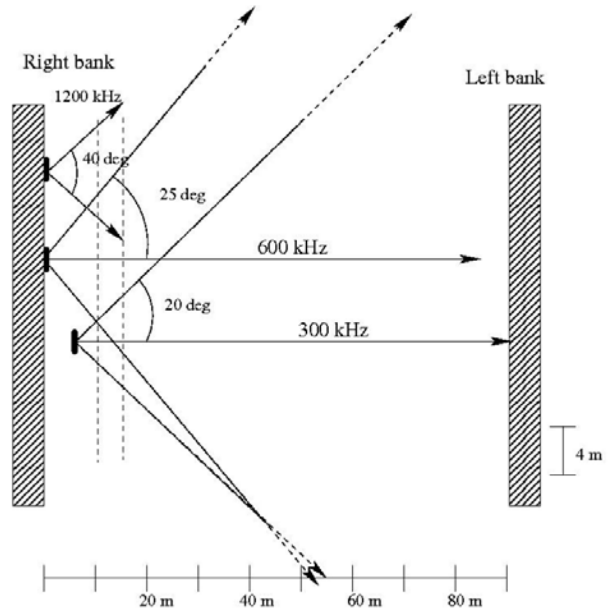

Figure 4. Top view of the horizontal ADCPs at Romans-sur-Isère. The acoustic axes of each transducer of each instrument are indicated with arrows. Dashed arrows are used when the maximum range of a transducer is larger than the extent of the figure. The dashed vertical lines between 10 and 15 m delineate the observed range that is common to all instruments.

A top view of the installation is shown in Figure 4. Note that although the axes of the different transducers appear to interfere, the instruments are synchronized so that each one transmits and receives in turn, avoiding any acoustical interference. The depth, pitch, and maximum range of the horizontal ADCPs are summarized in Table 1

Table 1. Table of HADCP characteristics

HADCP	beams [#]	depth [m]	pitch [deg]	max range [m]
300 kHz	3	-2.16	1.8	250
600 kHz	3	-0.36	0.1	85
1200 kHz	2	-0.76	0.1	15

* Note: a positive pitch corresponds to an upwards tilt, and depths are given with respect to the zero of the staff gauge.

The maximum range at which each instrument provides a reliable measure of velocity is highly frequency dependent. The waves emitted by the 1200 kHz instrument are very quickly attenuated, and its maximum range is roughly 15 meters. As a result, the measured range common to all three instruments is limited to the area between 10 and 15 m from the right bank; this range is delineated with dashed lines in Figure 4.

An optical turbidity meter was also installed on the right bank of the river, 8 m upstream of the 300 kHz HADCP at a depth of 0.5 m. This instrument was used to provide an indirect measure of the evolution of suspended particle concentration. The turbidity meter is a ts-line Solitax sc, manufactured by Hach Lange.

3 RESULTS

3.1 *Times series of echo intensity*

For this study we have chosen to analyze the data collected between 2009-11-20 and 2009-11-30 inclusive, a period during which we had simultaneous measurements from both the turbidity meter and the three HADCPs. A time series of the average intensity recorded by each HADCP in the cell located at 10 m from the right bank is provided in Figure 5(a), and a zoom on the last two days of 300 kHz data is provided in Figure 5(b). The data have been smoothed using a 30 minute running average. These beam-averaged intensities are expressed in units of counts, as output by each instrument. Counts can be related to the relative echo intensity in decibels, where the reference value is a pressure of one micropascal at a distance of one meter. Since the intensities recorded by the 1200 kHz instrument are much smaller than those of the other two instruments, they have been multiplied by two in Figure 5(a) in order to facilitate a visual comparison of the temporal evolution of all signals.

From Figure 5(a), we see that the signals recorded by all three instruments evolve in essentially the same manner in terms of trends and relative changes in amplitude. This is true for all but the last day of measurements when the 300 and 600 kHz instruments appear to be saturated, whereas the 1200 kHz signal increases two-fold. Looking at the zoom on the 300 kHz data in Figure 5(b), it can be seen that this high signal amplitude event began at around 23:00 November 29, and lasted nearly twelve hours.

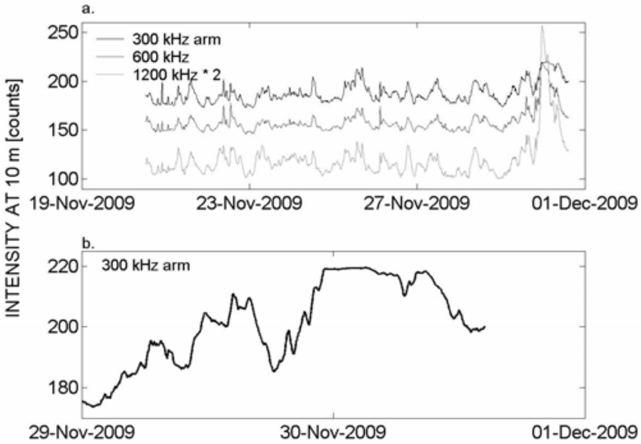

Figure 5. (a) Time series of the beam-averaged intensity recorded by each side-looking ADCP at the measurement cell nearest to 10 m from the right bank. Data are smoothed over 30 min using a running mean average and the 1200 kHz signal is doubled for ease of viewing. (b) zoomed portion of the 300 kHz HADCP data showing saturation event.

Optical turbidity was measured using the Solitax sc turbidity meter throughout the duration of this study. Although the turbidity meter was not calibrated prior to installation, samples of surface water collected near the instrument enable a rough calibration of the instrument. The calibration curve of recorded turbidity (arbitrary units) versus particle concentration (mg/L) is shown in Figure 6. As can be seen, all the water samples were collected when the turbidity was either ~100 or ~300, which makes a linear regression based on this data precarious. However, at sites where the size range of particles is roughly constant, it is safe to assume a linear relationship between turbidity and particle concentration (Hicks and Gomez, 2003). This is the case at Romans-sur-Isère, especially for this period of observation during which there was neither snow melt, dam flushing, nor floods. The R^2 value of the linear fit is 0.84.

The data of Figure 5(a) are reproduced with the signal recorded by the turbidity meter overlayed as a thick red line in Figure 7. It can be seen that although an intense and short-lasting optical event is observed at the start of the HADCP saturation, a much longer-lasting turbidity event occurred one day prior during which the turbidity increased from ~100 arbitrary units (equivalent to ~ 4 mg/L) to ~220 arbitrary units (equivalent to ~7 mg/L). It is not alarming that the optical turbidity event went unnoticed by the acoustic transducers, since optical and acoustical instruments can respond differently to the same particles. What is more, the optical event corresponded to a relatively insignificant change in concentration for this site, where concentrations can reach 1 g/L during the spring melt. Thus, in the following analysis, turbidity values shall be used to determine particle concentration when no water samples are available.

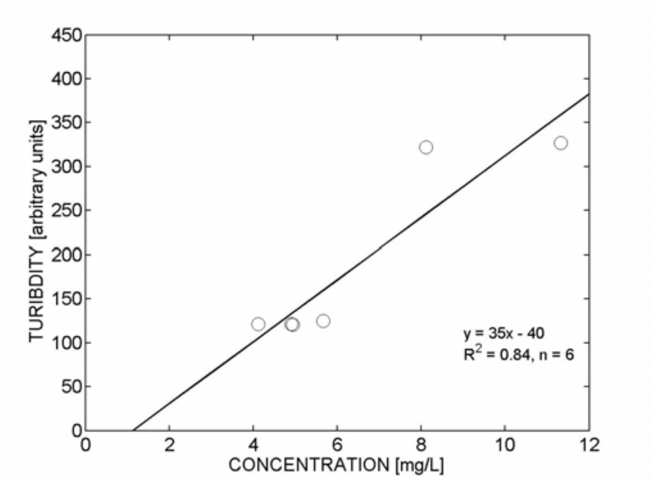

Figure 6. Linear regression between the optical turbidity at 0.5 m depth and the concentration of suspended sediment measured in surface water samples collected along the right river bank. The best-fit line to the six data points is traced and the correlation coefficient, R^2, is displayed.

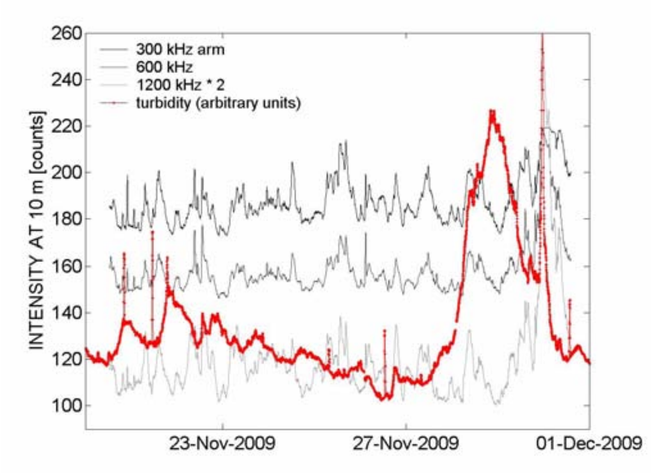

Figure 7. Time series of the beam-averaged intensity recorded by each side-looking ADCP at the measurement cell corresponding to 10 m from the right bank, as in Figure 5, plus optical turbidity measured at 0.5 m depth, 8 m upstream of the 300 kHz HADCP. Data are smoothed using a 30-min running average.

3.2 *Measured intensity profiles*

An examination of the time-averaged intensity profiles measured by the 300 kHz HADCP throughout this ten-day experiment unexpectedly revealed profiles with a wide range of forms. A selection of the across-river profiles that were encountered are plotted in Figure 8. In both this figure and the subsequent analysis, the intensities in question are those recorded by the instrument's central transducer that is the transducer that faces directly across the river. The choice to present only the central beam data was purely arbitrary as the measurements by the other two transducers reveal the same results in terms of trends and relative signal amplitude. The strong peak in echo intensity seen at ~90 m in each profile is the acoustic reflection from the left river bank.

In Figure 8, the concentration of suspended particles is denoted beside each profile; these values are calculated from the turbidity data previously presented in Figure 7, using the calibration relation of Figure 6. These profiles are assigned letters by which they shall be referred from now on. During this ten-day experiment, the measured intensity profiles most often resembled profiles B and D of Figure 8.

In theory, if the sound speed of the medium is constant, then the root mean square pressure, P, at a distance R within the far field of the transducer can be expressed in terms of a reference pressure, P_0, at distance R_0 in the following manner (Clay and Medwin, 1977):

$$P = \frac{P_0 R_0}{R} \exp[-\alpha(R - R_0)], \qquad (1)$$

where α is the attenuation in the medium in m^{-1}. According to the American National Standards Institute (Clay and Medwin, 1977), the far field begins at the critical range of $\pi a^2/\lambda$ for a circular piston transducer, where a is the radius of the active element of the transducer and λ is the wavelength of the transmitted signal. For a 300 kHz transducer, this corresponds to 14 m. Therefore, since the echo intensity is proportional to the square of the pressure amplitude in the far field, it should be a continuously decreasing function of range beyond 14 m, barring any contamination due to scattering from obstacles. Looking at Figure 8, this is only the case for profile B, and even then we see some roughness half-way across the river.

The results of Figure 8 are puzzling due to the wide range of forms we see for very similar concentrations. What is more, although the profile with the highest intensity values corresponds to the highest scatterer concentration (5.8 mg/L), there appears to be no direct link between concentration and either profile form or mean amplitude. We also observed that the profiles can have very different forms from one hour to the next, even though the optical turbidity may change very little.

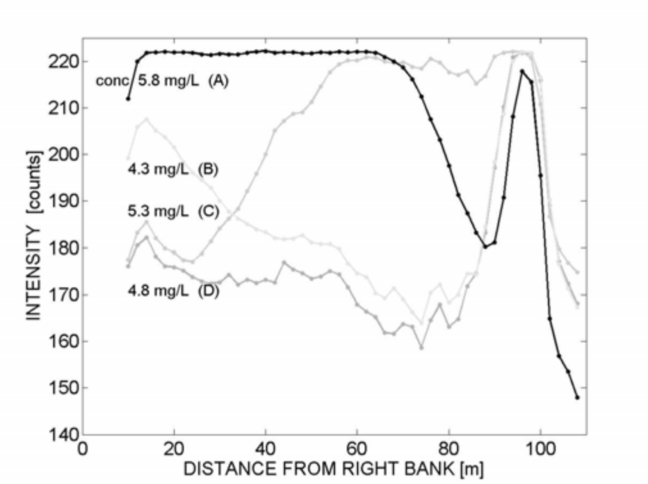

Figure 8. Typical examples of the intensity profiles measured by the central transducer of the 300 kHz side-looking ADCP at Romans-sur-Isère. The profiles represent the average of 15 min of data. The mean values of suspended particle concentration as calculated from the turbidity measurements are indicated. They were calculated using the turbidity-concentration relationship of Figure 6.

The form of profile A can be explained as the result of signal saturation. This has been concluded because the intensity recorded for ranges up to 70 m, ~222 counts, is the same as the intensity of the echo from the left bank. From previous grain size analysis at this study site, the median particle diameter from laser diffraction analysis was found to be roughly 20 microns. For an incident acoustic frequency of 300 kHz, this corresponds to ka = 0.013, which yields a backscatter far-field form factor of 1.7×10^{-4} for quartz particles, based on Eq. (10) of Thorne and Hanes (2002). The form factor is a function which describes the scattering properties of the particles, and the backscatter echo intensity is proportional to the square of this term. In addition, the echo intensity also depends on scatterer concentration. However, the gain of the HADCP would have to be set alarmingly high in order for signal saturation to occur when particle concentrations are less than 10 mg/L. Nonetheless, this appears to be the case.

The ballooning form of profile C is more difficult to explain. Even a theoretical change in local concentration and/or grain size on the order of 100 could not cause the echo intensity to increase with range in the manner with which it does beyond 25 m from the right bank. What is more, it is highly unlikely that the particle composition across the river would be heterogeneous.

3.3 *Intensity profile analysis*

As a more quantitative analysis, we can compare theoretical intensity profiles to the measured values. If we assume that the size, concentration, and composition of the particles suspended in the water column are homogeneous throughout the measured cross-section (we believe this to be a fair assumption), then the far field equation relating echo intensity in the instrument units of counts, I_c, to the distance from the source, R, is the following,

$$10\log(10^{k_c I_c/10} - 10^{k_c I_c^{noise}/10}) = A - 20\log R - 2\alpha R \quad (2)$$

where α is now the attenuation in decibels. This equation is based on Gostiaux and van Haren's (2010) modified version of the commonly used sonar equation of Deines (1999). The parameter A is a constant that includes all range-independent parameters such as the system sensitivity and the transmitted power. Since the scatterer concentration and characteristics are assumed constant throughout the river cross-section, the backscattering strength of the particles is also included in this term. Based on water samples collected at this study site throughout the year, the assumption of homogeneity of scatterer concentration appears to be valid. The constant k_c is an instrument-specific conversion factor relating counts to dB, where the reference values are one micropascal at one meter. For the instrument in question, k_c is 0.43 (RD Instruments 2009, personal communication). The parameter I_c^{noise} is the noise level in counts, which can be obtained if the profiling range is sufficiently large and free of obstacles. This parameter will only have a significant impact on the theoretical profile if the signal amplitudes are close to the noise level (~60 counts for an RD Instruments 300 kHz ADCP, (Tessier et al, 2006)). This is not the case in the present study, as the echo intensities always exceeded 150 counts.

Theoretical intensity profiles are fit to the data by assuming I_c^{noise} = 60 counts and finding the value of A that minimizes the root mean square error between the theoretical curve and the selected data points. In order to illustrate a situation in which Eq. (2) provides a good fit to the data, a typical profile obtained at the Montélimar study site on September 14, 2007 is presented in Figure 9. The Montélimar study site is located on the Rhône river in France. The geometrical cross-section is trapezoidal, with a total width of 170 m and a maximum depth of 13 m. A 300 kHz HADCP is installed at a depth of 5 m, inclined towards the bottom at an angle of 0.4 deg. The profile is the average of 15 minutes of data, and the points used for the fit are circled. Unlike at Romans-sur-Isère, we do not see the echo from the opposing river bank because the HADCP was only programmed to record values within a range of 122 m of the instrument. As can be seen from Figure 9, the measured intensity profile is quite well modeled by Equation (2). This is often the case at Montélimar. However, when we apply the theoretical equation to the Romans-sur-Isère results, i.e. the data previously presented in Figure 8, we see that of the four different profiles, the theory only qualitatively represents intensity profile B. The best-fit theoretical curves to all but profile A are shown in Figure 10, since it is clear that the saturated profile cannot be fit by a decreasing curve. For all profiles, the theoretical curve was fit to the six circled points.

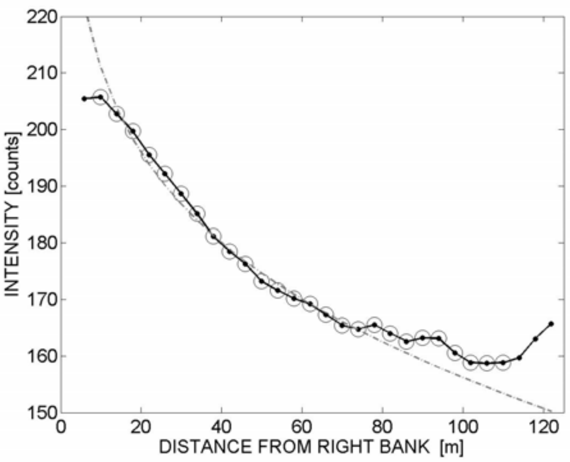

Figure 9. Experimental (solid line with points) and theoretical (dashed line) intensity profiles recorded by a 300 kHz side-looking ADCP at the Montélimar study site on the Rhône river. The theoretical profile is obtained by least squares fitting Eq. (2) to the circled data points. Experimental data are the 15-min average of the intensity recorded by the central transducer.

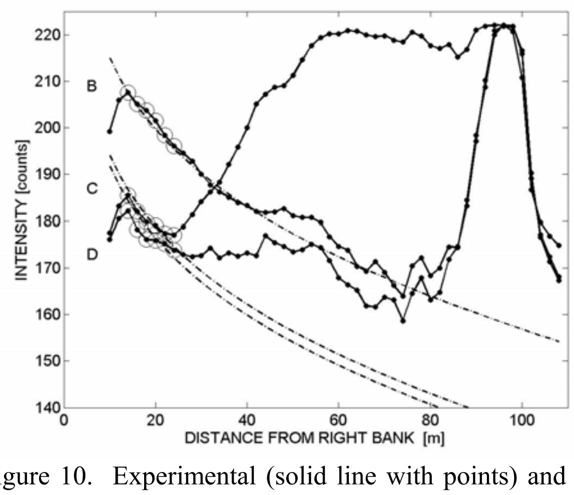

Figure 10. Experimental (solid line with points) and theoretical (dashed line) intensity profiles recorded by the 300 kHz side-looking ADCP at Romans-sur-Isère. The theoretical profile is obtained by least squares fitting Eq. (2) to the circled data points. Experimental data are the 15-min average of the intensities recorded by the central transducer.

In Figure 10, it can be seen that beyond about 25 meters from the right bank (~40 m for profile B), the observed profiles diverge from theory. This divergence could be explained by reflection from either the river bottom or the free surface. We currently suspect that the free-surface is the more likely candidate, since we are searching for something with time-varying characteristics. If the interference we are seeing is scattering from surface roughness, this could explain the variable nature of it's impact on the intensity profiles.

4 DISCUSSION

Since the majority of the profiles measured at Romans-sur-Isère resemble profiles B and D of Figure 8, it is important to understand the physical phenomenon behind the divergence from theory that is observed with increasing distance from the right bank. Although the possibility remains that we have neglected a term in Equation (2), we do not believe this to be the case. Thus, as previously mentioned, we suspect that there are other physical processes at play besides simple propagation and scattering from the suspended particles.

Romans-sur-Isère is the most problematic of the study sites at which we have operating side-looking ADCPs. It is also the shallowest and most irregular in terms of river geometry. Since it was anticipated that strong bottom reflections by the acoustic side-lobes of the transducers might interfere with backscattering of the main beam, the 300 kHz HADCP was positioned at an angle towards the surface, as previously mentioned (see Figure 2). However, based on our observations, we suspect that these efforts may have worsened the situation. One interpretation is that the observed intensity profiles often begin to diverge from theory at the distance at which the angle of the river bottom changes, ~25 m from the right bank, and then regain the expected form beyond 60 m, where the bottom is once again sloped downwards. A second possibility is that we may be seeing scatter from the surface. This may be more likely, as the 300 kHz instrument is inclined upwards and fluctuations in surface roughness could lead to the time-varying response that has been observed in the intensity profiles.

In order to investigate the possible effects of surface and bottom reflections on the intensity profiles, we propose to carry out some basic acoustic modeling using the BELLHOP ray tracing program (Porter and Bucker, 1987, Rodriguez, 2008). This program is designed as a tool to perform two dimensional acoustic ray tracing in an environment where both the sound speed profile as well as the geometry and properties of the boundaries can change. Although the former option is not of interest in a riverine setting, the ability to model the acoustic pressure or transmission loss in an environment with irregular geometry is. The hope is to successfully model the acoustic pressure field created by a given transducer when installed in theoretical rivers with a range of simplified and real geometries. In this way, we hope to identify any features of the observed intensity profiles which may result from surface or bottom reflections of either the main beam or side lobes of the transducers.

In addition, we intend to investigate the link between the form of the intensity profiles and surface roughness. To do this, we intend to use wind data as a proxy for surface roughness.

5 CONCLUSIONS

In this paper we have presented velocity and echo intensity measurements from side-looking acoustic Doppler current profilers. The project began with the objective of measuring river discharge and sediment load in real time, but was redirected towards an analysis of the echo intensities recorded by the HADCPs when it was found that at the Romans-sur-Isère study site in east-central France, for relatively high mean velocities (>1m/s), the velocities were underestimated. In this paper we focused on echo intensity measurements during a ten-day period in November 2009.

Data were available from three HADCPs and one optical turbidity meter. It was found that, a large part of the time, the intensity profiles measured by the 300 kHz HADCP diverged significantly from theoretical predictions. Four typical intensity profiles observed at Romans-sur-Isère were presented and discussed. The forms of these profiles were difficult to explain based on the simultaneous measurements of optical turbidity which showed that concentrations changed very little throughout the experiment. There also appeared to be no direct link between the temporal evolution of the intensity profiles and the optical turbidity measurements. It was concluded that there must be scattering from other sources, such as the bottom or the free surface.

As a continuation of this study, we propose the use of a ray tracing program in order to investigate the possible effects of side-lobe reflections from both the river bottom and the air-water interface. As well, an investigation of the effect of surface roughness on the intensity profiles could prove interesting.

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