DISCHARGE OBSERVATION BY ADCP

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1.0 ABSTRACT

Advanced techniques of discharge observation deploying Acoustic Doppler Current Profiler and dilution technology have revolutionized the river flow gauging in rivers. These technologies are quite accurate and very cost effective. Further, these are very quick and save time as compared to conventional method. The equipment could be deployed from a manned boat or a cableway or any other floating device either from a bridge or across a river. In particular, the new ADCP user is advised to read first the "Practical Primer" published by RD Instruments, for an introduction to the principles and terminology of Doppler profiling. This lecture aims at the techniques by providing an insight into the observation techniques even with high sediment concentrations and with DGPS mount.

1.1 THE ADCP EQUIPMENT

The Acoustic Doppler Current Profiler (ADCP) is a device for measuring current velocity and direction, throughout the water column, in an efficient and non-intrusive manner. It can produce an instantaneous velocity profile down through the water column while only disturbing the top few decimeters. The instrument is based on the Doppler effect of sound waves scattered on particles suspended in the water. The instrument was originally developed for use in the study of ocean currents- tracking them and producing velocity profiles - and other oceanographic work. It has since been developed for use in estuaries and rivers. It can also be used to measure flows in tidal rivers and, to some extent, monitor sediment flux. An ADCP can be mounted on a boat or a flotation collar or a raft and propelled across a river. The route taken does not need to be straight or perpendicular to the bank. The instrument collects measurements of velocity, depth, signal intensity and boat movement as it goes. Physically, an ADCP is a cylinder with a transducer head on the end. The transducer head on the most widely used systems contains three or four acoustic transducers with their faces angled at 20º (RDI) or 25° (SonTek) from the vertical and 90° or 120° to each other. The cylinder houses a compass, tilt sensors, a data processing and storage unit and optionally, a battery pack. The battery pack is not necessary if a suitable external power source can be provided. Smaller instruments are currently under development. Recent developments resulted in specialized instruments, several for horizontal use and another with small cell size (centimeter) for application in very shallow (< 1m depth) water.

The reflection of sound waves from a particle, which is moving within a fluid, causes a change in frequency to the reflected sound wave. The difference in frequency between the transmitted and reflected sound wave is known as the *Doppler shift*. The ultrasonic Doppler flow measurement technology is based on this phenomenon. Sound consists of pressure waves in air, water or solids. Sound wave crests and troughs consist of bands of high and low pressure. The *wavelength* is the distance between successive waves i.e. between two successive crests or troughs. The speed-of-sound is the speed at which waves propagate, or move by. The *frequency* is the number of waves that pass by per unit of time. The highlighted quantities are related by: speed-of-sound = frequency x wavelength.

1.1.1 The Doppler effect

The Doppler effect is a change in the observed sound pitch that results from relative motion i.e. a change in frequency by the motion of the source relative to a fixed point. A good example of this is the sound made by a train as it passes by a stationary person. The train's whistle has a higher pitch as the train approaches and a lower pitch as it moves away from the observer. This change in pitch (frequency) is directly proportional to how fast the train is moving. Therefore, if the pitch and by how much it changes is measured it is possible to estimate the speed of the train.

Another example of the Doppler-effect refers to an observer who is standing next to water and is watching waves passing him. While standing still he sees ten waves pass by him in a given interval of time. If he starts walking towards the waves, more than ten waves will pass by him in the same interval. Thus the wave frequency appears to be higher. Conversely, if he walks in the opposite direction, fewer than ten waves will pass him in the same time interval and the frequency appears to be lower. In terms of sound the Doppler shift is the difference between the frequency the observer hears when standing still and what he hears when he moves. The equation for the Doppler shift in such a situation is:

$$f_d = f_s \frac{v}{c}$$

where: f_d = the Doppler frequency shift

f_s = the frequency of sound when everything is still

v = the relative velocity between the sound source and the sound receiver (the speed at which you are walking towards the sound in m/s)

c = the speed of sound in m/s

If the observer walks faster, the Doppler shift increases;

- If the observer walks away from the sound, the Doppler shift is negative;
- If the frequency of sound increases the Doppler shift increases;
- If the speed-of-sound increases, the Doppler shift decreases.

1.1.2 Doppler velocity meters

The Doppler flow meter uses the Doppler shift principle to measure velocity in flowing water. The sensor transmits a high frequency (hundreds of kHz) ultra-sound wave into the water. This sound wave is reflected back towards the sensor by suspended particles, plankton or air bubbles. Very clean water can prove to be a difficult medium in which to use the Doppler technique. However, most, but not all, open channels should have sufficient suspended particles to obtain satisfactory reflected signals. The velocity sensor then measures the difference in frequency and this is converted into velocity by means of a processor built into the system.

When the sound reflectors (particles) move towards the sensor due to the velocity of flow, the sound heard by the reflectors is Doppler shifted to a higher frequency. The amount of this shift is proportional to the relative velocity between the sensor and the reflector. Part of this Doppler shifted sound reflects backwards or is "backscattered" to the sensor. The backscattered sound appears to the sensor as if the reflectors in the water were the sound source. Therefore the sensor hears the sound Doppler shifted a second time. Since the Doppler flow meter sensor both transmits and receives sound, the Doppler shift is doubled and the relationship becomes

$$f_d = 2f_s \frac{v}{c}$$

The Doppler shift only exists when sound sources and receivers move closer to or further from one another. If both move relative to a known datum but stay at a fixed distance relative to each other then there is no Doppler shift, i.e. the Doppler shift is 0. Also, if the receiver moves perpendicular to the sound source there will be no Doppler shift. Mathematically this means that the Doppler shift results from the velocity component in the direction of the line between the sensor and the reflector. Therefore the equation becomes

$$f_d = 2f_s \frac{v}{c} \cos\theta$$

where: θ = angle between the particle (reflector) line of motion i.e. flow path and the direction of the acoustic (sound) beam.

1.2 ADCP FUNCTIONING AND COMPONENTS

Figure 1- ADCP beams action

An ADCP uses the Doppler effect to measure the relative velocities between itself and suspended particles in the water column. The ADCP applies the same method to measure its velocity relative to the bottom or riverbed. This measurement is known as bottom tracking. The bottom tracking acquires the velocity of the boat with respect to the bottom (river bed) in x and y direction. The x and y direction are ADCP referenced. If a compass is used, the velocity of the boat can be converted to east and north referenced boat velocities. Each of the ADCP transducers emits a pulse of sound (a ping) into the water column. Suspended particles in the column reflect some of the sound back. The ADCP measures the Doppler shift of the reflected sound and uses this to calculate the relative velocity of the particles to it. *The velocity of the particles is assumed to be equal to the velocity of the water current.*

The ADCP divides the water column into horizontal layers (cells). The thickness of the layers is adjustable, the maximum and minimum thickness are brand and model dependent. Typical ranges are 0.1 and 8 m (600 kHz RDI Workhorse) and 0.25 to 5 m (1000 kHz SonTek ADP). It is possible for the ADCP to estimate the x, y and z direction velocity components from the data obtained from 3 beams. The fourth beam, which is implemented on some models, is redundant. In case one of the four beams fails, still the velocities in x, y and z direction can be calculated. If all four beams deliver good data, the data of the fourth beam can be used to calculate an error velocity. The error velocity is a useful quality indicator for the delivered x, y, and z velocities. When ADCP measurements are executed close to a feature like a steep bank, vertical rock, sluice wall or similar, the data of the fourth beam - the one that radiates the feature - could be discarded. The remaining three undisturbed beams could be used to calculate the water velocity in each cell and the boat velocity with respect to bottom. Under such conditions, the three-beam ADCP is likely to produce distorted data.

The average velocity of each cell is calculated to produce a velocity profile (of the stack of cells or layers) of the water column. Velocity profiles, which were collected while traversing the channel, are subsequently processed by supporting software to estimate the total discharge of that channel. The operator can adjust a multitude of parameters when setting up the ADCP for a deployment. Details of these parameters can be found in the manuals pertaining to the specific model of instrument. These manuals should be thoroughly understood by the ADCP operators and the data processing staff. Below some of the set-up parameters (cell size, ping rate, averaging interval) are discussed in general terms. The smaller the cell size, the finer the spatial detail in the profile, i.e. the more layers can be sampled. Further, when the cells are small, the ADCP can sample in shallower water. This can be easily understood when one imagines what would happen if the cell size were set to 5 m in 4 meters of water depth. In case of 0.25 m cells still many cells could be sampled in the very same water depth. However, the smaller a cell is the larger the single ping standard deviation will be.

The manufacturers specify the systematic velocity error, as introduced by the sensor, as less than 1 cm/s. However, the single ping velocity error can be in the order of 1 m/s. In normal operation the ADCP is programmed to execute a number of pings and report the averaged results thereof. In this context a ping is a measurement with a single sound burst from which a set of velocity data (Vx, Vy, Vup) can be derived. In rivers, the execution and processing of a single ping is a matter of milliseconds, in deep ocean water a single ping may take a few seconds. The standard deviation of the single ping velocity results is a fundamental instrument property, which is, roughly speaking, primarily dependent upon the noise threshold of the acoustic transducers with associated electronics and the number of sound waves that is available for the measurement. The higher the transmitted frequency and the larger the cell the smaller the single ping standard deviation becomes. The single ping velocity errors have a Gaussian distribution and as a result, the averaged velocity values will have a reduced standard deviation.

The table below shows the single ping standard deviation as reported by the M/s SonTek and M/s RDI. The RDI Workhorse Rio Grande can be operated in several modes. Mode 1 is very robust and can be used in most of the applications; it has the largest operational depth range. Modes 5 and 8 are intended for shallow water. M/s RDI reports that the maximum range should be less than 7 m. For that depth the maximum velocity should be less than 1 m/s. For operation in 4 m depth, the maximum velocity should be less than 2 m/s. In mode 5 the velocity shears and turbulence should be very low, in mode 8 there is no limitation in this respect.

manufacturer	frequency	mode	single ping st dev in cm/s
SonTek 3D ADP	1000 kHz	n/a	94
RDI Rio Grande	600 kHz	1	27
RDI Rio Grande	600 kHz	5	0.3
RDI Rio Grande	600 kHz	8	3.3

Table 6.1: Single ping velocity standard deviation for cell size of 0.25 m.

$v_{sp} = 235 / (f\ z)$

where: v_{sp} = the single ping velocity standard deviation in m/s

f = the acoustic frequency in kHz and

z = the size of the depth cell in m.

The value of v_{sp} halves when the cell size is doubled, however, when the readings of two adjacent cells are combined to a new value (also doubling the cell size) the standard deviation of the result decreases with the square root of 2 (1.4) only. From this it can be concluded that measuring with double cell size results in a smaller velocity standard deviation than is obtained by combining the data of two adjacent cells to get the same effective cell size. It should be noted that for other ADCP models the velocity standard deviation could show a different function of the cell size.

The standard deviation pertaining to averaged velocity values is estimated by:

vasd = vsp / N (6.20)

where, N is the number of pings available to calculate the average velocity.

The ping rate should be set at the highest value to acquire as many pings as possible for the averaging. The maximum ping rate for the SonTek ADP is 12 pings per second.

1.3 Bottom-Tracking

The primary function of bottom-track is to measure the ADCP's speed-over-bottom and detected range-to-bottom. In the discharge calculation, these two pieces of information are used to

i) Calculate the absolute water velocity by subtracting the boat's velocity from the relative water velocity measured by the ADCP,

ii) Estimate the cross-sectional area of the transect. During high flow or high sediment concentration conditions, the environment may result in biased bottom track measurements. When the bottom track data is biased, it is necessary to have an external means for estimating the boat's velocity.

1.4 VELOCITY RELATIVE TO A REFERENCE LAYER

Whenever an ADCP is available, it should be used as the speed log; it will almost certainly be the best available if it has been installed and calibrated properly. The reference layer should be chosen so that it is expected to be as smoothly varying as possible along the cruise track. Hence one wants the thickest layer that usually contains good data, and that perhaps omits the _rst few depth bins near the surface.

1.5 COMPONENTS OF THE ADCP

A typical ADCP set-up comprises 3 main units:

1. ADCP with a laptop PC with the ADCP data processing software installed for control of the ADCP

2. a car battery and power adapter for the laptop PC

The ADCP can be used in two ways:

i) The ADCP can be set to record in stand-alone (Self Contained) mode, sent off to record the data and the collected data is downloaded to the PC later.

ii) The second way is in real-time. The ADCP stays connected throughout the gauging process and the data is processed and displayed on the computer screen as it is recorded. This is the normal way for river discharge profiling from a moving boat.

The 2nd way is preferred since the 1st way does not provide any immediate feedback while the measurements are being taken. An external power supply is required on the boat in the 2nd case.

1.6 PRACTICAL USE OF THE ADCP

In this sub-section following practicalities about the ADCP will be discussed:

- Deployment methods
- Practical considerations for use of the ADCP
- Overall performance of the ADCP

1.7 DEPLOYMENT METHODS

To produce a discharge estimate the ADCP has to be taken across (traversing) a river once with its transducers submerged to a known constant depth. Usually it is more convenient to cross the river from the one bank to the other and back again to end on the same bank as it started effectively executing two traverses. This should be executed at least trice. An average of the (3 x 2) results can then be taken. The discharge figures of these individual traverses should be compared with each other. Traverses showing large deviations should be neglected (not deleted). The measurements should continue till at least four discharge figures deviate by less than 5% from the average value. It is recommended that a number of traverses is made to see if, in steady flow conditions, repeatability occurs. In unsteady flow conditions executing multiple traverses provides an opportunity to monitor changes in discharge.

The most common way of using the ADCP is to fix it to a boat so that it can be vertically adjusted. The boat fixings should be such as to allow the transducers to be fixed at different depths relative to the water surface. Also, they should allow the easy installation and fixing of the ADCP to the boat i.e. the ADCP should not be permanently fixed in the boat. Another way is to mount it in a flotation collar, which ensures that the transducers remain submerged to a constant depth. The flotation collar containing the instrument can then be towed across the river on a cableway or the end of a rope, pushed by a boat or even driven by a remote control motor. For the larger rivers the boat mounting method is recommended.

Some models of ADCP support autonomous (self-recording) operation. A useful advantage of the autonomous operation is that no communication with a controlling PC is required during traversing which implies, that after proper set-up the instrument can be towed from one bank to the other without the need for a communication cable. Also during heavy rain, when the use of a PC is risky, the autonomous mode is very practical. After execution of one or more traverses, the data can be retrieved for processing. The start and stop times should be duly annotated to allow connection of the discharge figures to actual events. The annotated times should be derived from the same clock as used for setting the clock of the ADCP. To support the autonomous mode, the ADCP has to be fitted with a PC-card for storage of the data.

1.8 PRACTICAL CONSIDERATIONS

1. The ADCP unit makes large demands on power while operational. A car battery and adapter for the laptop PC are necessary to run the laptop and the ADCP in real-time. Some ADCP models allow the use of internal battery packs. Although this avoids the need for external power, it increases operational cost and the risk of water ingress due to sloppy closing of the ADCP housing after installation of the battery pack. 2. The boat velocity is measured by the bottom tracking function, which makes use of the bottom (Doppler) reflection of the sound beams to obtain the boat velocity relative to the bottom. This is an accurate measurement provided that the bottom is stationary. However, at high flow velocities, thick blankets of bottom sediment may be mobilised resulting in

bias on the bottom track measurement. Under such condition a (D)GPS system is required to obtain the velocity of the boat. This adds to the cost and increases complexity considerably. The DGPS provides the boat track relative to a north referenced coordinate system. The ADCP obtains water velocity with respect to the boat and referenced to magnetic north using the compass. The water velocity with respect to the ground is calculated subtracting the boat velocity form the measured water velocity (relative to the boat). This subtraction of two large values can only result in accurate flow data when the ADCP's compass is accurately calibrated and precisely lined up with true north. The importance of this can be appreciated when one considers the measurement of velocity in stagnant water e.g. of a reservoir. If the compass is not precisely lined up, the displayed water velocity will be proportional to the sine of the direction error multiplied by the boat's speed. At a boat speed of 1 m/s and a direction error of 5°, the velocity error would 9 cm/s. When using DGPS to obtain boat velocity and position data, it is essential that the ADCP compass is calibrated thoroughly prior to its use. Further a non-magnetic boat should be used. If magnetic anomalies exist, e.g. due to metal structures or ship nearby, the magnetic compass method will fail. An accurate gyrocompass should be used then. This again increases cost and power demand. For normal ADCP measurements when bottom tracking is performing well a normal compass calibration would suffice.

3. The minimum depth of deployment is recommended not to be less than 1.0m for more than 5% of the cross-section. The depth of operation is not the actual depth but the distance from the ADCP transducers which should be mounted whenever conditions allow, at least 0.3 m below the surface or below the hull of the boat (whichever is the greater). However, if a moon pool / well is used it should be possible to mount the faces of the transducers just below the hull of the boat provided aeration does not occur underneath the hull. (Aeration blocks the passage of sound waves.) Mechanical vibrations may adversely affect the performance of the ADCP. A special case is the coupling of sound waves into the hull and back to the ADCP again. In that case the transmitted sound penetrates the boat's hull, rings around in the boat and is transmitted into the water again. The ADCP in receiving mode captures the sound which effectively corrupts the proper measurement of the upper cell(s). If this occurs, the not-measurable layer just below the ADCP increases beyond the standard blanking distance.

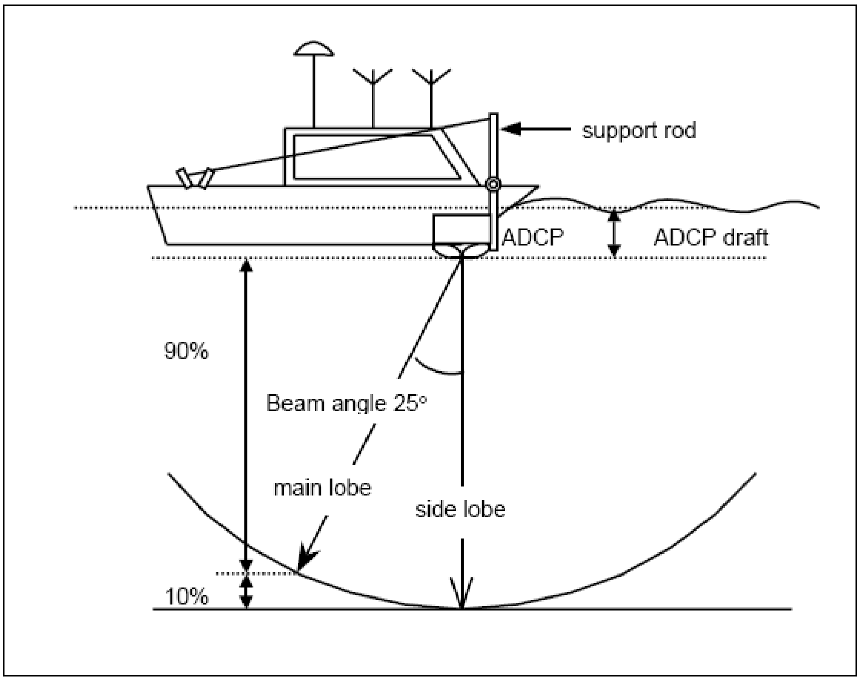
4. From a safety perspective, the average velocity in the measuring cross-section should not exceed 4 m/s. However, this will be governed to a certain extent by the boat engine size and the skill of the boat operator.

5. The instrument is supported by a rod. While taking measurements, the rod is in vertical position to submerse the transducers whereas the rod is brought to horizontal position to enable sailing at high velocity, e.g. from one measuring

station to the other. The vertical position of the rod is maintained by a guy wire. Care should be taken that the rod can swivel away in case the instrument hits an obstruction; the guy wire may be allowed to slip free then. The ADCP can only function properly when it is in the water; therefore the instrument should be kept submersed. To cover as much of the water column as feasible, the ADCP should be fixed at a minimum submersion depth close to the water surface while avoiding trapping of bubbles or an air gap below the transducers.

6. The acoustic transducers were designed to have narrow beams; however, unavoidably the transducers also have side lobes, which transmit energy in unwanted directions. Most of the side lobes are entirely harmless; however, the side lobes that are directed at the bottom have a major impact on the capabilities of the ADCP. This can be understood as follows. Although the side lobes have much less acoustic efficiency as the main lobe, they receive a strong signal from the bottom; after all, the bottom is a very good reflector in comparison to the tiny suspended scatterers. As a result, the bottom reflection overwhelms the signals reflected of normal scatterers effectively corrupting the velocity measurement. The **distance** along the slanted beams to which the ADCP can measure velocity equals the water depth below the sensor. The **depth** to which the ADCP can measure water velocity depends upon the beam angle of the main lobe. For the SonTek ADP this angle is 25°, the related maximum measurement depth is at Cos(25°) x depth below the transducer, which is about 90% of the distance from the ADCP to the bottom. The blind zone is about 10% of the depth below the transducer. RDI ADCPs have an angle of 30° or 20°, which results in blind zones of 14% and 6% respectively.

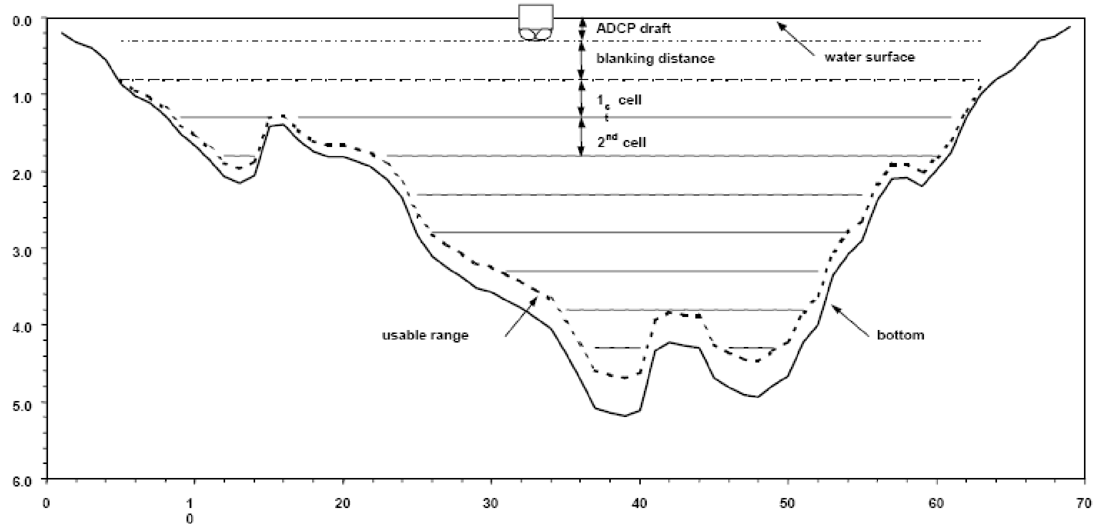
The valid range is calculated from 0.9 x (depth below sensor - depth below surface) – blanking distance. Only entire cells should be used, bottom cells that are (partly) contaminated by side lobe - bottom reflection should be discarded.



7. It is not possible for the ADCP to sample the full vertical velocity profile. There is also an unmeasured band close to the surface. This unmeasured portion at the surface consists of the distance between the surface and the faces of the acoustic transducers (the draft of the ADCP) and a dead band which is the blanking distance of the acoustic transducer, e.g. 0.5m. The blanking distance is related to the length of the transmitted acoustic pulse and the switch-over from transmission mode to receive mode of the transducers. Therefore, if the transducers are fixed at e.g. 0.3 m below the surface no measurement of velocity will be obtained in the upper 0.8m of the water column, i.e. in this example the top of the first cell is at 0.8 m below the surface. The unmeasured upper and lower portions of the verticals are defined automatically by extrapolation by the ADCP's software. This extrapolation is undertaken using assumptions based on the classical form of the velocity profile, either using a power law or a straight-line method. Alternatively, an electromagnetic current meter can measure the velocity in the upper portion. The values in the example above depend upon the type of ADCP. The diagram below gives an impression of the measured and unmeasured sections of the cross section. For rivers where shoals have to be crossed in measuring mode, it is recommended to set the minimum cell size such that over the shoals of at least two cells valid data is obtained. Very close to the banks the velocity data may also be corrupted, depending upon the type of ADCP, the beam configuration and the slope of the banks.

8. The instrument does not perform well in aerated water. Therefore, the transducers have to be immersed at sufficient depth to avoid air entrapment caused by turbulence on the water surface and/or the movement of the boat. Conversely, particularly in shallower rivers the transducers should not be

immersed at too great a depth otherwise a significant portion of the vertical profile may not be sampled. Care should be taken to ensure that the transducers are at some distance from the boat's hull to avoid interference by sound reflected from the hull.



Effects of depth, draft and blanking on profile

9. It is recommended that a special lightweight (alloy) frame be built for the ADCP. This frame should serve three purposes:

- make carrying easier
- protect the ADCP
- provide a means of fixing the ADCP to any/most boats

The frame should be supported by a guy wire (as shown in the sketch above showing the ADCP mounted on a small boat) to prevent the ADCP leaning back while sailing at some speed. For high speed sailing it is recommended to swivel the frame so as to bring the ADCP above the water surface.

It is recommended that a cover is fabricated to fix over the bottom of the frame to protect the transducer faces when the ADCP is not being deployed. During traversing while collecting data the movements of the boat should be smooth to avoid errors in the bottom tracking function. Preferably the boat should maintain a constant speed during the entire traverse. Sudden changes of course and accelerations / decelerations should be avoided. The reason for this is the performance of the ADP bottom tracking, which is also affected by the faulty readings of the tilt sensors when the boat changes speed or heading. The tilt sensors are referenced to the direction of the local vector of acceleration, which is the acceleration of gravity under stationary conditions. However, the reference vector tilts in case of horizontal acceleration e.g. when the boat changes speed and / or coarse.

10. The ADP bottom tracking is having difficulty with sloping bottom. If in a cross section such failure is observed, a slightly more up stream or down stream cross section may be tried for better data.

1.9 OVERALL PERFORMANCE OF THE ADCP

Acoustic Doppler Current Profilers are relatively new hydrometric instruments. However, they have already been used successfully in small and large rivers such as the Great Lake system (on the Canada US border). River depths here vary between 4m and 20m and the average discharge is 5,000 m^3/s. Extensive use of the ADCP has been made on Ganges and Brahmaputra rivers in Bangladesh, measuring discharges up to 100,000 m^3/s (Delft Hydraulics et al. 1996). Successful projects have also been completed on rivers such as the Mississippi and the Danube. The equipment has been found to be very good at spotting areas of recirculation and other anomalies in the flow regimes.

ADCPs are established instruments for hydrometry. The equipment is costly and requires a relatively high level of technical ability. Therefore, it is only recommended for use at larger, more important sites e.g. inter-State borders where more conventional methods are not viable, for research and for verification measurements at gauging sites.

1.10 COLLECTING DISCHARGE DATA WITH A SONTEK ADP

The first step is to identify a proper cross section, which should be in a straight river section. The cross section should have uniform flow; heavy turbulence and boils are to be avoided. Actually the same selection criteria as applied for traditional discharge measurements should be applied. Some aspects need special attention to make best use of the ADCP's capabilities. The cross section should have as smooth a bottom profile as possible without steep slopes and shoals. Steep slopes hamper the performance of the bottom tracking because at the slope each of the beams obtains entirely different depth readings, further the averaged depth value may not be representative. The water depth should be sufficient to cover at least a few depth layers (cells) but should stay well within the depth capabilities of the ADCP. The unmeasurable section on each of the banks should be as small as possible. The flow rate at the banks and in particular in the unmeasurable sections should be as low as possible. The survey boat should traverse along the cross section in a smooth manner i.e. the speed and coarse should be kept steady during the data collection. Significant changes in speed (acceleration or deceleration), or sudden coarse changes jeopardize the bottom tracking, which renders velocity readings of the affected profiles virtually useless. The ADP, being an acoustic instrument, needs information about the actual speed of sound. To estimate the speed of sound, the instrument is fitted with a temperature sensor. The salinity is to be entered manually, however, for use in non-tidal river sections and reservoirs the salinity would be 0. The use of the in-built temperature sensor should be enabled.

After transport and at the beginning and end of each measuring day, the compass should be calibrated using the software supported calibration procedure. The results should be annotated in the instrument's logbook. If deviations with previous calibrations are substantial, i.e. exceeding several degrees, whereas the boat, installation and other significant aspects were not changed, the cause should be investigated. The choice of cell size (thickness of the measured layers) affects the measured section in the profile and the standard deviation of the velocity data. The smaller the cells, the larger the part of the vertical profile that can be measured and the shallower the water may be. However, the smaller the cells the larger the standard deviation becomes. For each cross section depth profile the optimum cell size should be assessed. The cell size should be chosen small enough to cover at least two valid cells over shoals (if they exist). Preferably, although difficult, a cross section with uniform depth is selected for discharge measurements.

Especially during periods of high discharge, the performance of the bottom tracking should be verified in particular to check if the bottom tracking performance is affected by moving bed. This is done by monitoring the apparent position of the boat as obtained from the bottom tracking while the boat remains anchored at some spots on the cross section where moving bed conditions are likely. The anchoring should be safe (high flow velocity) and stable, i.e. the anchor should hold properly. The anchor line should be at least 1.5 times the water depth preferably with some ends of chain between the anchor and the anchor line. The dragging of the anchor can be monitored visually with respect to points on the bank. An apparent upstream movement of the boat on the bottom tracking display is an indication of a moving bed condition. Moving bed can be very local, moving to another cross section may avoid the problem. The ADCP data file as collected during the bottom tracking test(s) should be retained and its name, time and other particulars duly annotated in the station logbook. At the start of each transect the distance to the bank is to be estimated to define the unmeasured section of the stream. Further, some qualitative information about the observed flow pattern at the surface would further enhance the flow estimate in the unmeasured sections. It would be interesting to know if the section between boat and bank is covered by plants, rock; if reverse flow is observed or large eddies and similar. The same observations are to be made and annotated at the end of the transect. The boat velocity with respect to the bottom should be slow in order to take as munch data as possible. Averaging a large number of pings would reduce the standard deviation of the velocity results and further it would reduce the effect of turbulence. As a rule of thumb, traversing the cross section should take at least a few minutes. On very small streams this may be difficult to achieve. On large rivers the velocity, relative to the bottom, should be chosen equal to the average water velocity or smaller, given the width of such rivers, traversing would take much longer than a few minutes. All the observations and actions should be duly annotated in the cross section logbook. The same applies to the observations while traversing the cross section. These may have to do with the measurements (bottom tracking failure due to steep slopes (too deep, jerks) large signal intensities (sediment?), the boat (jerk, deviation of track to avoid collision with floating debris) but also with the river proper.

Provided that the traverses are started and ended at a conspicuous point on each of the banks, an upstream drift in displayed end position could be an indication of a moving bed condition. However, many other reasons can result in similar drift. In any case, if consistent upstream drift is detected, in both left-to-right and reverse traverses, the data should be carefully assessed for possible moving bed conditions. Another indicator of possible moving bed is the measurement of high signal intensities (due to high sediment concentrations), in particular close to the bottom.

1.11 PROCESSING OF SONTEK ADP DATA

The top and bottom layers were extrapolated by the River Surveyor default method (power fit distribution with an exponent of 0.167 using the entire profile data). The distances-to-bank at begin and end of the cross section as entered during the measurements were used to extrapolate to the banks. Cell size was 0.25 m, transducer depth 0.15 m and blanking distance 0.5 m. The applied averaging interval was 5 seconds. It is of great importance to observe good validation practices. One of the key aspects is that the entire processing is traceable, i.e. starting with the raw data and using the annotations / remarks pertaining to a previous processing run on the same data, it should be possible to redo the processing and arrive at the same results.

Both RDI and SonTek include a software tool for processing of the ADCP data. Although these tools save some of the settings during processing, they do not keep track of the entire processing session. One of the causes is that part of the processing may be done with other tools like Excel or MatLab. Below the use of RiverSurveyor is addressed. The details about RiverSurveyor have to be learned from the accompanying manual. As discussed above, the ADCP cannot measure the entire complete cross section; mainly the edges (top, bottom, banks) are beyond reach. Hence, the contribution of the edges has to be estimated as good as possible. Next the RiverSurveyor settings to estimate the discharge of the unmeasured sections are discussed.

1.11.1 Bottom layer

RiverSurveyor supports two methods to estimate the velocity in the lower 10% (cannot be measured due to side lobe interference) of the profile. One method attributes the velocity of the lowest valid cell(s) to the unmeasured bottom layer. The second method applies a power-fit through the collected profile data and extrapolates this fit to the bottom. For calculation of river discharge, the power-fit method is to be preferred. The default exponent for the fit is 0.1667; the exponent may be changed but always with great care and only after checking the performance. Normally the entire profile should be used.

1.11.2 Top layer

The average velocity of the top layer may be estimated with the same methods as described under Bottom layer. Also in this case the power-fit method is to be preferred as it uses data of multiple cells which would reduce random error. However, under certain conditions, like stratified flow, the power-fit method might perform badly.

1.11.3 Banks

The discharges at the start-bank and the end-bank can be individually estimated. Two methods are available, viz.:

1. Entry of a user estimated discharge, e.g. measured by current meter

The quality of the estimate is determined by the measurement and the extent to which the manual and ADCP measured areas are complimentary without overlap or gap.

2. Calculated estimate based on distance to bank and velocity profile(s) measured next to the bank. Several fields have to be entered for a proper calculation.

• In a canal the bank shape may be chosen as Vertical, in a river it is normally Slope.

• The distance to the bank should be entered according to the distance where proper data collection started should be entered.

• The profile to start / end the calculation should be chosen with some care; it should not be contaminated by bad bottom tracking or similar and it should have one or more valid depth cells.

• If needed, the results of several profiles in a row can be used to calculate average values for depth and velocities which are to be used to calculate the estimate of the unmeasured discharge of the start / end section.

It should be noted that the described estimation methodologies rely on the assumption that the flow velocity distribution over the profile (vertical) is not stratified. In river bends (it is not recommended to collect discharge data there), and over shoals this may not be the case, special attention is required then. The speed-of-sound at the transducer faces should be known for the data processing. It is recommended to let the ADCP measure the water temperature at its sensor and use that value for automatic estimation of the speed-of-sound. The actually applied value should be checked.

Near shore velocity is estimated using the following relation:

$$\frac{V_e}{\sqrt{d_e}} = \frac{V_m}{\sqrt{d_m}}$$

Where, V_e, d_e= estimated mean velocity and depth at location e

V_m, d_m= measured velocity and depth at the first or last ADCP subsection

1.12 MEASURING RIVER DISCHARGE IN HIGH FLOW (FLOOD) OR HIGH SEDIMENT CONCENTRATION CONDITIONS

a) Bottom detection sound wave does not fully penetrate to the real bed material causing **moving bed conditions** to be detected,

b) Velocity detection sound wave does not penetrate deep enough into the water column or the return signal is attenuated to the point that **water velocities cannot be measured at depth**,

c) Bottom detection sound wave is attenuated to the point where the bottom position cannot be determined causing problems with **determination of the position**,

d) Bottom detection sound wave is attenuated so that the **depth of flow** cannot be accurately determined.

Conditions Characterized by:

i) Unstable (Moving) Bottom

ii) High Suspended Sediment Near River Bed

iii) Biased Bottom Track Data

iv) High Water Velocities

Not Characterized by:

i) Stable Bottom

ii) Unbiased Bottom Track

iii) Valid Bottom Track Depths

1.13 BOTTOM DETECTION IN HIGH SUSPENDED SEDIMENT CONCENTRATIONS

In order for the ADCP to correctly detect the bottom, the signal reflected from the bottom must be significantly higher than the signal reflected from the suspended scatterers in the water column. If there is a high sediment concentration near the bottom, there may not be enough contrast between the water and bottom returns, and the ADCP will not detect the true range to the bottom. Some users have gotten around this problem by using a lower frequency ADCP. The lower frequency allows the acoustic signal to "punch through" the suspended sediment and better detect the bottom. The reason for this is that the acoustic wavelength longer for lower frequency systems, and these longer wavelengths are not as effectively backscattered by the water. This allows for more contrast between the reflected energy of the suspended particles and the highly reflective bottom.

1.14 SYMPTOMS OF BIASED BOTTOM TRACK MEASUREMENTS

If one or more of the following occurs, it is an indication of bias in the bottom tracking data:

i) The *course made good* is longer than expected.

ii) The ship track plot shows an upstream offset compared to the actual track taken by the boat.

iii) If you hold station at a position in the channel, the ship track indicates that you are moving upstream.

iv) Discharge is lower than expected and not reproducible to better than 5%

Solution for sediment concentration

i) Employing a **lower frequency instrument**. [lower frequencies mean more power in the water and more penetration through sediment]

ii) Resorting **GPS** to determine platform position "**loop method**" to correct for the moving bed

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