Developing guidelines for using the Acoustic Scintillation Flow Meter to measure turbine discharges in short intakes

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ABSTRACT

By overcoming many of the practical difficulties associated with traditional methods, the Acoustic Scintillation Flow Meter (ASFM) offers an innovative, accurate and cost-effective means for flow measurement in short intakes of low head plants.

Over the past ten years, the ASFM has been used in more than a dozen intakes of plants with Kaplan, bulb, propeller and other low-head types of turbines. From the experience gained in these applications, guidelines are being developed for successful installation and operation of the ASFM under these hydraulically difficult conditions. This paper outlines the progress made to date, and covers the placement of sampling paths and sensor mounting considerations, instrument operating and sampling procedures, transducer spacing and boundary layer considerations.

Introduction

Short-intakes of low-head hydroelectric plants (sometimes referred to as close-coupled intakes) converge quickly over very short distances to the turbine itself, and frequently have spatially and/or temporally varying or unstable velocity distributions, making accurate turbine discharge measurements extremely difficult. Yet the increasing market competitiveness and constraints imposed by environmental and social requirements are making the operational improvements that can be achieved from optimizing unit and plant efficiencies a matter of vital interest for many utilities whose portfolios include low-head plants. The utilities on the Columbia River are a particularly good example.

Traditional discharge measurement methods such as current meters and time-of-flight acoustic flow meters have been and continue to be used for this purpose, although no codified standard exists for any of them. In addition, practical difficulties, such as the introduction of instruments into the flow, intensive labour requirements and/or the necessity to dewater the intake for installation exist for all of them.

Thus the need 'to simplify measurements of large quantities of water in the short conduits of low-head plants' (Brown, Haldane & Blackstone, 1970), recognized several decades ago, still exists today. An innovative flow measurement tool is needed, at least as accurate as those available today, but faster, easier and cheaper to use. In addressing this need, over the last 10 years ASL Environmental Sciences, and more recently a subsidiary company, ASL AQFlow Inc., both of Sidney, British Columbia, Canada, have developed the Acoustic Scintillation Flow Meter (ASFM).

ASFM Operation

The ASFM uses a technique called acoustic scintillation drift to measure the velocity by utilizing the natural turbulence embedded in the flow.

Fig. 1 shows a schematic representation of an ASFM in use. Two transmitters are placed at one side of the intake, two receivers at the other. The signal amplitude at the receivers varies randomly in time as the distribution of turbulence along the propagation paths changes with time and the flow. If the paths are sufficiently closely-spaced, the turbulence may be regarded as being embedded in the mean flow, and then the pattern of these variations (known as scintillations) at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, *Dt*. If these scintillations are examined over a suitable time period, this time delay, *Dt,* can be determined. The mean flow velocity perpendicular to the acoustic paths is *Dx/Dt*, where *Dx* is the separation between the paths.

With the use of three transmitters and three receivers at each end, the average magnitude and the average inclination of the velocity are measured at several preselected measurement levels. Total discharge is calculated by integrating the average horizontal component of the velocity at each level over the total cross-sectional area of the intake.

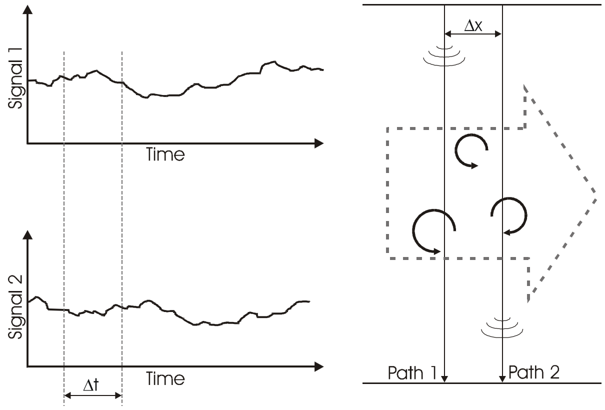

Fig. 1: Schematic representation of ASFM operation

ASFM Typical Arrangement

ASFM employs pairs of arrays of acoustic transducers mounted on opposite sides of fixed or movable support frames lowered into the intake stoplog or gate slots. This permits its use in very short intakes, with virtually no space between the intake and the turbine. It also minimizes the required plant down time during installation and removal, does not require dewatering and, in multiple unit plants, permits repeated use without removal/reinstallation of the equipment from/to the frame. No instruments are required in the measurement zone, which minimizes interference with the flow, and there are no moving parts requiring maintenance and frequent calibration.

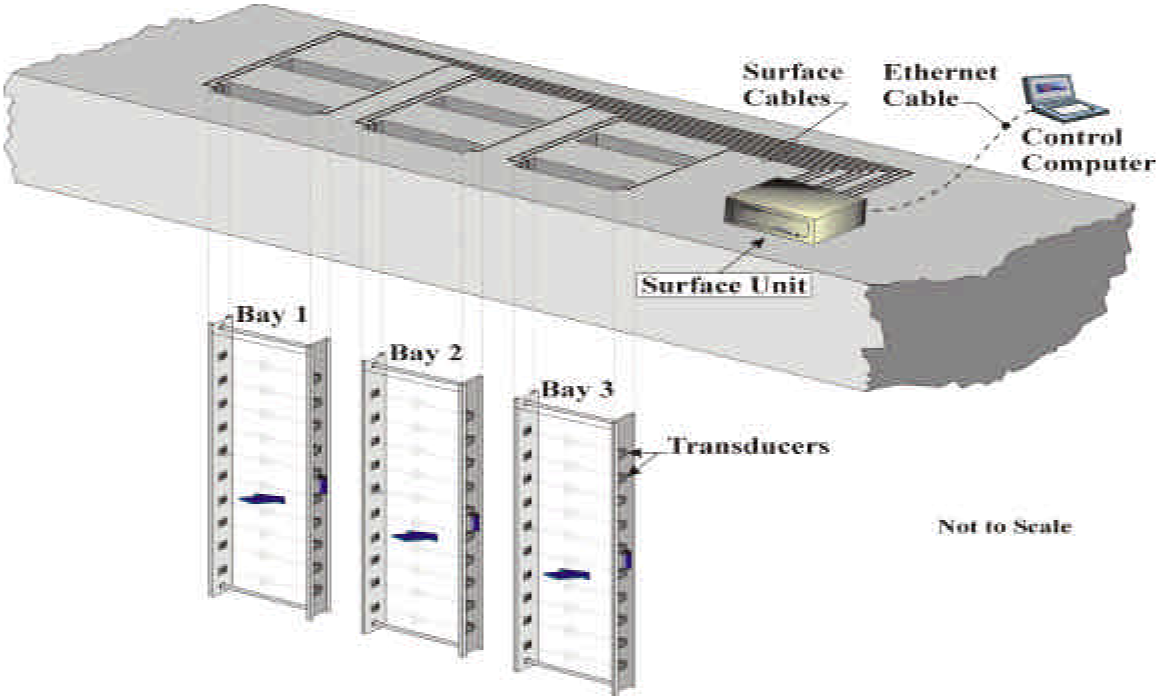

Fig. 2: ASFM Typical Arrangement

ASFM History

Acoustic scintillation is an old and well-proven technology. It has been used to measure, successfully,
- solar winds with radio waves since 1940s,
- atmospheric winds with lasers since 1970s,
- ocean currents with sound signals since the 1980s.

So only a relatively small incremental step was required to start using this technology for hydroelectric turbine flow measurements in the early 1990’s. The ASFM has been used to verify efficiencies of the aging or refurbished units, to tweak their operation to achieve optimum efficiency and to confirm compliance with prescribed water releases. It has also been successfully used in calibrating Winter-Kennedy index readings, in measuring the effects of fish screens and deflectors on turbine efficiency and in comparisons with current meter measurements. The following is a listing of powerplants where the ASFM has been used in the last 5 years:

2002 –Lower Monumental, USACE, USA
2001 –The Dalles, USACE
    John Day, USACE
    Deep Brook, Nova Scotia Power, Canada
2000 –The Dalles, USACE
    Bonneville, USACE
    Rocky Reach and Rock Island, Chelan County PUD, USA
1999 –Seven Sisters, Manitoba Hydro, Canada
    Wheeler, Tennessee Valley Authority, USA
    Stave Falls, B.C. Hydro, Canada
    Bonneville, USACE
    McNary, USACE
1998 –Bonneville, USACE
    McNary, USACE
1997 –Laforge-2, Hydro Quebec, Canada
    Fort Patrick Henry, Tennessee Valley Authority

Based on the experience gained in the above applications, guidelines are being developed for the installation and operation of the ASFM for flow measurement in short intakes. The progress made to date is described in the following paragraphs.

Sensor Mounting, Operating and Sampling Considerations

The chief requirement for mounting ASFM arrays is that they be stable and free from vibration, and positioned so that there are no interfering echoes from boundary surfaces such as the intake floor or roof. The ASFM data processing requires that the fluctuations in the acoustic signal be produced entirely by the effects of the turbulence in the flow. If vibration in the mounting supports causes the arrays to move, spatial differences in the sound field will appear as amplitude fluctuations in time, and interfere with the variations arising from the flow. To avoid such interference, the design of the mounting must ensure that the arrays do not vibrate with amplitude greater than 1 mm at frequencies between 5 and 30 Hz, and that the amplitude of any vibration outside that frequency range is less than 5 mm. All recent ASFM mounting frames have been sufficiently rigid to fulfill this requirement.

Similarly, sound pulses, which have been reflected from a surface, will introduce fluctuations in the signal amplitude both from the water path they have followed and from the irregularities of the reflecting surface itself. Since variations in the flow will cause the reflection point to vary slightly, surface irregularities will cause time fluctuations in the acoustic amplitude, which again will interfere with the calculation of the flow velocity. This limits the distance an ASFM path can be placed from a boundary. The ASFM uses short sound pulses (16 μsec in length) to make the minimum distance of approach as small as possible. The minimum is the distance at which the travel time difference between the direct and reflected paths is equal to one pulse width. In a 6 metre wide intake, that distance is 26 cm.

There is only one critical aspect to the alignment of the ASFM arrays. Their orientation with respect to the horizontal must be measured to within 2 degrees so that the horizontal component of the velocity can be calculated accurately for use in the discharge integration. Their angular orientation otherwise needs only to be good enough to ensure detection of the signal at the receiver; since the beam width is 10 degrees, alignment within 5 degrees in the vertical and along-stream directions is sufficient. Therefore, the alignment of the ASFM arrays presents no difficulties in the field.

The 2 to 5 m/sec velocities typically encountered in low-head intakes require rapid sampling of the acoustic signals to avoid undersampling and consequent aliasing. That sampling rate is the ASFM's pulse repetition frequency; one sample of the acoustic amplitude is acquired with each signal that arrives at the receiver.

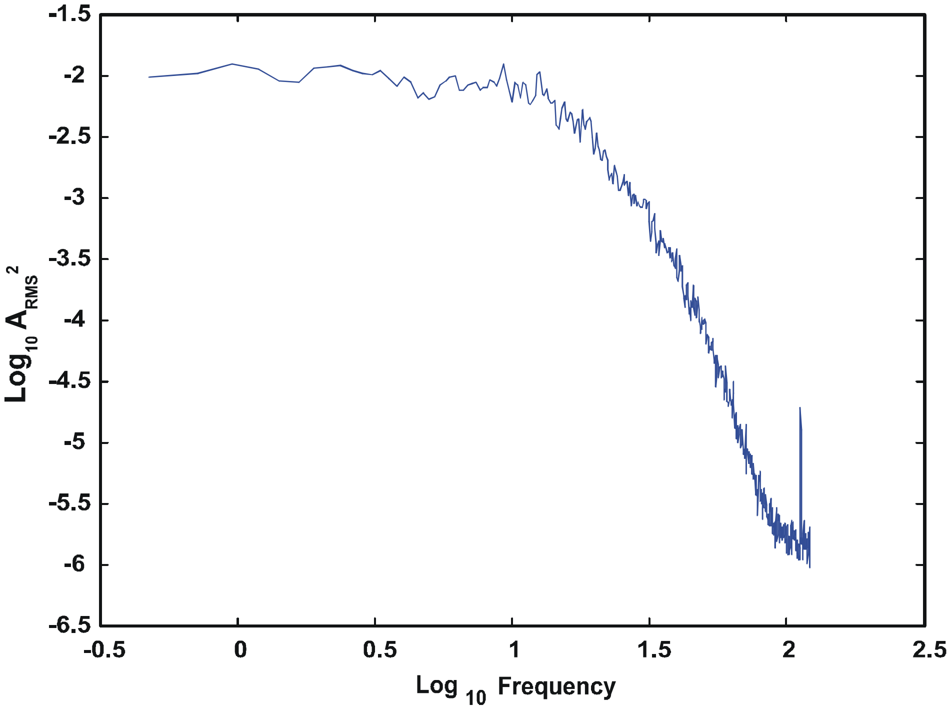

Fig. 3: Typical power spectrum of acoustic amplitude scintillations in a turbine intake.

As Figure 3 shows, significant energy is present in the spectrum of the amplitude fluctuations at frequencies above 50 Hz. The normal pinging frequency for an ASFM is thus 250 Hz to avoid aliasing. In most intakes, therefore, there are always two pings in transit across the intake. There are also earlier pings, which have reflected from the sides of the intake, and which may persist for several reflections before dying away. If the transit time for some number of reflections is a multiple of the ping period, the multiple-reflected signals will interfere with the direct arrivals and degrade the quality of the data. That degradation usually is apparent as strong low-frequency variations in the amplitude signal, as may be seen in the example in Figure 4. Such interference can be eliminated by choosing the pinging frequency, such that there is no overlap between the multiple reflections and the direct signal until the reflections have decreased to an insignificant level.

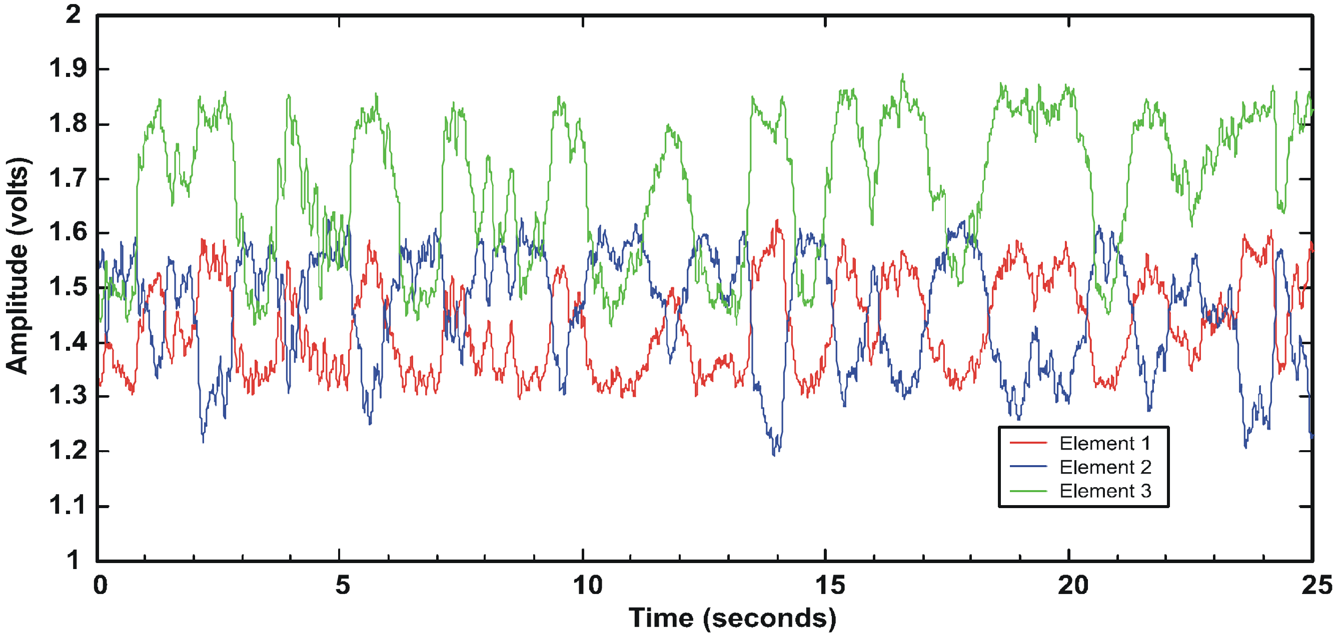

Fig. 4: Low frequency acoustic amplitude fluctuations arising from multiple reflection interference.

The number of reflections required for the reflections to die away depends on the reflection coefficient of the intake sides where the arrays are mounted. If it is the smooth surface of a steel frame, the signals can persist for as many as 8 reflections from each side. The existence of overlap between a reflection and the direct signal depends as well on the transit time, which is a function of the sound speed, which in turn is a function of the water temperature. Changes in water temperature therefore require adjustment of the ASFM pinging frequency to avoid overlap interference. This feature was not previously available in the ASFM, but has now been added to it.

The ASFM samples one acoustic path in each bay simultaneously. Collection of the data to compute the discharge requires time equal to the number of levels per bay multiplied by the measurement time at one level. That time must be long enough to produce a stable estimate of the velocity, and short enough that the overall flow conditions do not change by the time the last level is completed. In a typical 10 paths per bay installation, the single-path measurement time is normally set to 2 minutes, so that 20 minutes are required to compute the discharge. Comparisons between repeat measurements in the field indicate that this is an acceptable compromise between minimizing the random error in each velocity measurement and the length of time required to complete the discharge measurement.

Transducer Spacing Considerations

Given that the ASFM flow measurement technique derives its estimates of flow velocities from the spacings of transducer pairs divided by measured time delays, the accuracies of estimated flow velocities can be no greater than the accuracies associated with the transducer spacings. Based upon precision machining tolerances and verification by caliper measurements in a representative number of sample units, uniform transducer spacings within +/- 0.2% of the design value were accepted for the first sets of ASFM measurements.

As part of an intensive program to quantify and reduce ASFM measurement errors, a test facility was devised to measure spacings of transducers in both the first generation ASL transmit/receive units (used until November 2001) and in the latest units being incorporated in a new state-of-the-art Advantage version of the ASFM. This facility explored the distinction between a transducer's geometric center (measured by calipers) and its acoustic center as measured, in this case, in a water-filled 1m × 1m × 1m test tank with an acoustic technique. In simple terms, this technique measured spacings by translating the transmit/receive units (operating in the receive mode) perpendicularly across an incident acoustic beam and accurately measuring the positions associated with phase minima in the received signals. Differences in these positions were equated to the spacings between the acoustic centers of adjacent transducers.

The results showed the following and at the first look alarming differences in the distributions of spacings respectively associated with the transducers. The latest units, designed with tighter tolerances, exhibited a Gaussian distribution exactly centred on the geometric/design spacing value and a standard deviation of about 0.5 mm. As well, however, somewhat less than 10 % of the spacings in the latest units were well off the Gaussian curve, representing deviations as large as 20% of the design spacing value. The first generation transducers were free from such outliers but showed a slightly broader Gaussian distribution (standard deviation of 1 mm) centred on a spacing about 0.8 % higher than the design value.

These acoustic center spacing variations are of course much larger than the +/-0.2% tolerance achieved for geometric spacings. Fortuitously, mathematical modeling of transducer responses over the much longer (by an order of magnitude) path lengths experienced in hydroelectric intake ASFM measurements suggests that the observed small deviations from the design-value transducer spacings may not be detectable in the amplitude signals employed by the ASFM technique. Such a result would suggest that, for ASFM purposes, differences between the geometric and acoustic centres of adjoining transducers can be ignored. Field testing of this hypothesis has begun in January 2002 in conjunction with ASFM measurement programs being carried out for the U.S. Army Corps of Engineers. Preliminary results appear to support the hypothesis except perhaps in the above-noted outlier pairs of ASL's latest transmit/receive units.

Boundary Layer Flows

The procurement costs of most flow measurement tools go up significantly when increasing numbers of measurement paths are required to obtain an acceptable accuracy. However, the flexible nature of the ASFM permits the number of measurement paths to be increased without purchasing the associated additional equipment. Instead, additional closely spaced holes are provided at critical elevations in the mounting frame, and the available transducers are temporarily installed there for the initial definition of the boundary layers. As the form of the profile of the horizontal velocities in these zones has been shown repeatedly as being invariant over the range of velocities normally found in hydroelectric intakes, such calibration can be used to augment the results obtained with reduced numbers of measurement paths during subsequent measurements at intakes of similar shape.

This process has been successfully used at a number of projects where the ASFM was used to measure the turbine flows. The Dalles plant, USACE, Oregon, United States, application will be illustrated here. For the November 2000 measurements, USACE's own 10-path ASFM system, mounted on frames at typical 10-level spacings, was supplemented by an additional 10-path system mounted in the lower and upper boundary zones (one of three frames shown schematically in Fig. 5). These 20 levels covered almost the entire height of the intake in sufficient detail, so that the subsequent round of measurements (after all metal surfaces were painted to improve hydraulic efficiency) in June 2001 could be carried out successfully with only the 10-path system.

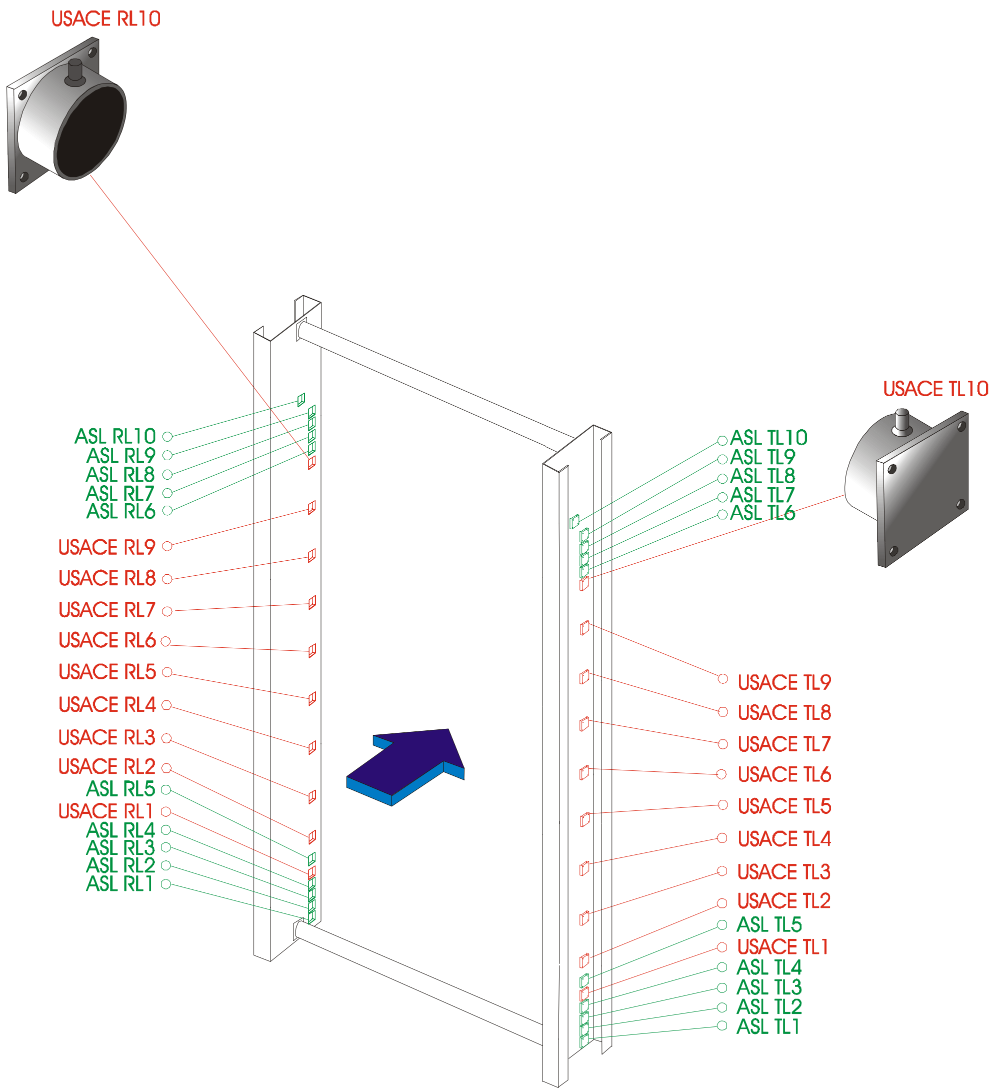

Fig. 5: 20-level transducer arrangement

As illustrated in Fig. 6, the boundary condition at the floor is complicated by the presence of the lower cross-pipe. Detailed 20-path ASFM velocity measurements were taken at El. 0.326m and above, therefore the flow below this level had to be estimated. The results from a recent CFD simulation (Bouhadji & Djilali, 2001), for a similar intake at the USACE McNary dam, were used for this estimate (shown normalized to common scale in Fig. 6). The CFD results differ from the ASFM measurements at the second and third measurement levels. The ASFM measurements show a larger deficit in the velocity caused by the cross-pipe. This could be the effect of the thick rope that was wrapped around the cylinder in order to reduce acoustic reflections. This rope was not taken into account in the CFD simulations.

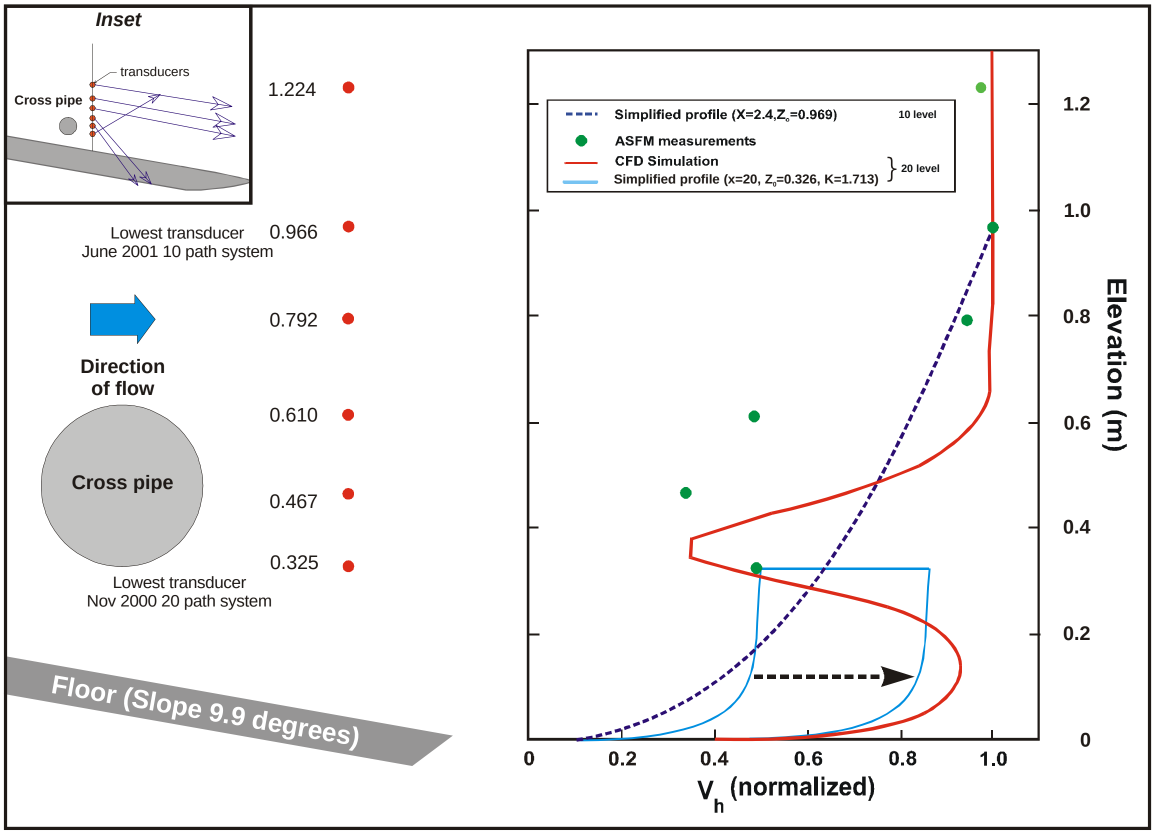

Fig. 6: Lower boundary layer

A simplified profile, having the same discharge when integrated between the floor and El. 0.326m, was used in calculating the total discharge. For a curve of the form

$$K\,(z/z_o)^{1/x}$$

the best fit was found with x=20, z_o=0.326 and K=1.713. The scaling factor K was necessary to compensate for the unmeasured jet of water indicated by simulation as passing underneath the cross-pipe.

Based on the results from the 20-path measurement, the simplified profile for the 10-path measurement of June 2001 was fitted between the floor and El. 0.969m as also shown in Fig. 6 (x=2.4, z_o=0.969, K=1).

As illustrated in Fig. 7, the highest transducer of the 20-path system was placed slightly upstream of the measurement plane to avoid multipath reflections from the wall. To calculate the total discharge, the roof boundary (El. 13.564m) was set as an open boundary, with the horizontal velocity equal to that measured at the highest transducer (El. 13.666m). As the vertical components of measured

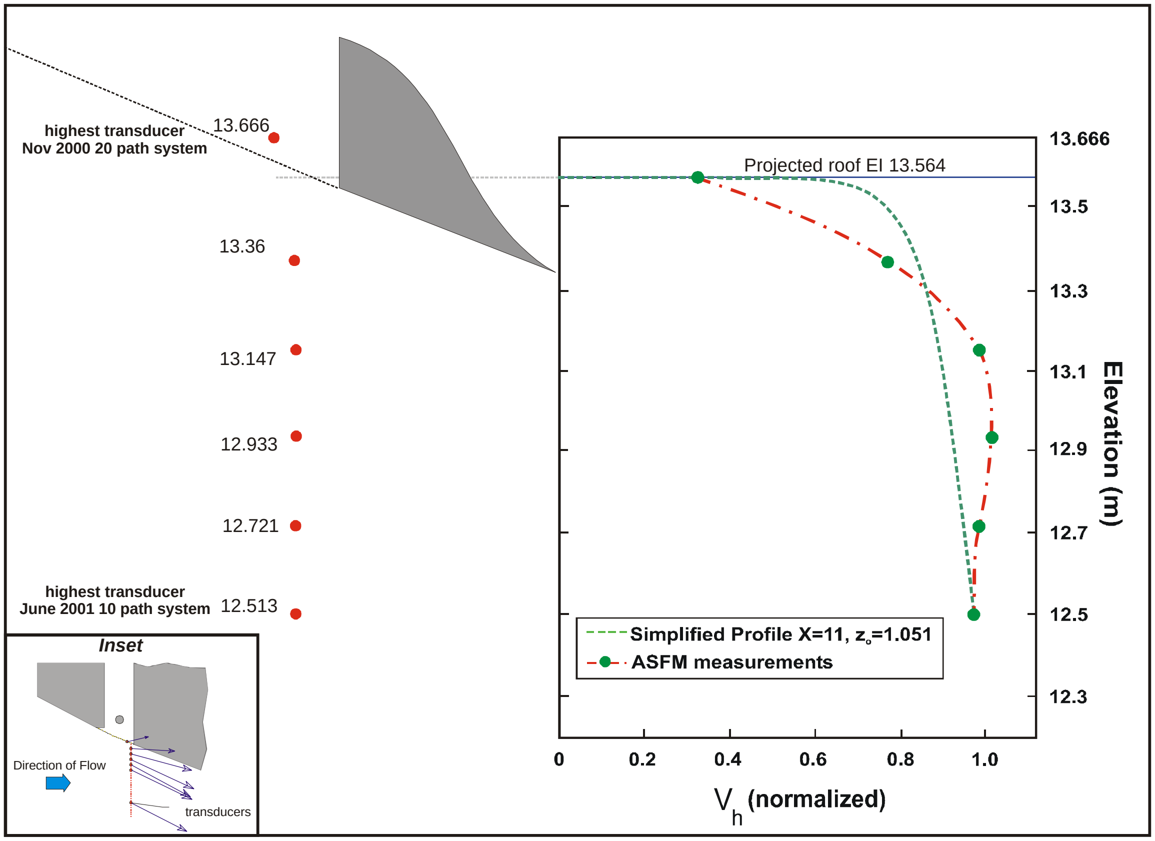

Fig. 7: Upper boundary layer

velocity at El. 13.666m were very small and very slightly upwards, zero vertical velocity was accepted at El. 13.564m.

Based on the results for the 20-path measurement, the simplified profile for the 10-path system was fitted between the El. 12.513m (the highest transducer of the 10-path system) and the roof (El. 13.564m) as shown in Fig. 7 (x=11, z_o=1.051, K=1).

Future Developments

The hydraulic environment in close-coupled intakes makes obtaining accurate turbine discharge measurements extremely difficult. We have described the guidelines developed to date for using the ASFM in those environments, but further work is necessary to develop the understanding needed to consistently achieve the accuracy and reliability the hydro industry desires. Work is continuing to develop these guidelines further. It is presently focussed on obtaining data to improve our understanding of the effects of variability in the distribution of the flow in the intake, and the effects of side boundary layers and associated variations in the level of turbulence in the intake. Data are being collected in conjunction with regular ASFM measurement programs wherever possible to address those issues.

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References

Brown, J. Guthrie, Haldane, T.G.N., and Blackstone, P.L., Hydro-electric Engineering Practice, Blackie & Son, 1970

Bouhadji, L. and Djilali, N., Numerical Study of Flow Characteristics in Hydroelectric Plant Intakes, University of Victoria, 2001

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