UNDERSTANDING CAUSES FOR SYSTEMATIC ERROR IN ASFM MEASUREMENTS OF TURBINE DISCHARGE

D. D. Lemon, D. R. Topham, L. Bouhadji, and J. Lampa,
ASL AQFlow Inc., Sidney, BC, Canada

Abstract

The Acoustic Scintillation Flow Meter (ASFM) has been used to make turbine discharge measurements in over 25 different low-head intakes in the course of the past 8 years. These measurements were highly repeatable (random uncertainty < ±0.5%), but in some cases, apparent systematic errors, ranging from ± 1% (the limit of verification accuracy) to –7% were observed. An intensive review of potential sources for systematic error in the hydraulic environment of short intakes was therefore undertaken. The chief sources considered were the element spacing in the sensor arrays, boundary effects at the intake passage walls, the implementation of the flow algorithm, and the effects of non-uniformities in the velocity and turbulence fields caused by major trashrack supports in the intake upstream of the ASFM location.

The results of this review are summarized; they show that significant contributions to systematic error arise only from the effects of spatial variations in velocity and turbulence produced by upstream structures. Compilation of data shows the systematic error to be dependent on the product of the width, number and drag coefficient of large vertical trashrack supports at the intake entrance. In the absence of such supports, or at locations far enough downstream, systematic errors are consistently negligible. ASFM flow measurement algorithms implicitly assume uniformity along the path for either the flow velocity or for the local turbulence intensity. Errors in the path-averaged velocity are introduced if a non-uniform velocity distribution along a path is accompanied by a non-uniform distribution of turbulence. Since the wakes of trashrack supports are regions of reduced velocity and elevated turbulence, the wakes from supports oriented perpendicularly to the ASFM sampling path will produce a negative bias.

Simultaneous measurements along coplanar horizontal and vertical ASFM paths at a low-head plant on the Columbia River are presented to illustrate this effect, and show that the bias can be corrected with knowledge of the form of the velocity and turbulence variations.

Introduction

In the course of the past eight years, the Acoustic Scintillation Flow Meter (ASFM) has been used to make flow measurements in over 25 low-head intakes. The results have been highly repeatable, with random uncertainty typically less than ±0.5% (1). In some cases, direct measurement comparisons have shown agreement in absolute discharge to within ±1% (2); calibration measurements in a tow tank produced the same degree of agreement (3). Nevertheless, systematic errors in ASFM measurements as large as negative 7% were encountered in other tests carried out in the same period, based upon comparisons with either near-simultaneous alternative flow estimates or with expectations in terms of attainable plant efficiencies. An intensive review of the ASFM instrument and the hydraulic environment in low-head intakes was therefore undertaken to investigate the sources of these errors.

Possible Error Sources

The review identified the following possible sources for systematic error: the element spacing in the sensor arrays, boundary effects at the passage walls, the implementation of the flow algorithm, and the effects of non-uniformities in the velocity and turbulence fields caused by major structures in the intake upstream of the ASFM location.

Element spacing

The accuracy of the ASFM velocity measurement depends directly on the accuracy with which the spacing between the acoustic paths is known (3, 4). That in turn is determined by the accuracy of the placement of the elements in the ASFM's transducer arrays. The separation of the geometric centres of the elements can be controlled during assembly to within ±0.25% (or 0.1mm), however the effective path spacing depends upon the separation of the acoustic centres of the elements, which may not be coincident with the geometric centres. Attempts to develop a laboratory method for measuring the acoustic separation of the elements have to date not been fully successful. Relative measurements of the effective spacing of pairs of arrays (transmit and receive) were made during field test programmes at Lower Monumental and Little Goose Dams (Snake River). Five juxtaposed pairs of arrays (Figure 1) were placed in each of the three intake bays in a region where the flow was expected to be spatially uniform. The results showed that the largest differences in relative separations were less than 0.5% for the newer design transducers and less than 1.6% for the older designs (5). In all cases, the differences appeared randomly distributed. Given the magnitude and random distribution of the relative element spacings, it is highly unlikely that any combination of them could have produced discharge biases of as much as -7% in some plants and not others. An overall systematic bias in the spacings is also unlikely, since the apparent bias was not seen in all plants. Therefore it was concluded that errors in the spacing of the transducer elements were of relatively minor significance for discharge bias.

Boundary layer

Direct measurements of the mean and fluctuating velocities in the boundary layer at the wall of the Lower Monumental plant were also made when the relative spacing tests were done. The results showed that the boundary layer was too thin (6), and the increase in the level of turbulence in it was too small to produce biases as great as -7%. Again, since several of the plants on the Columbia system had similar intake characteristics, and could be expected to have wall boundary layers similar to those observed at Lower Monumental, but had apparent systematic discharge errors ranging from near zero to -7%, it was concluded that the boundary layer at the intake wall could be of only minor significance in contributing to the observed bias.

Figure 1: Five arrays in a cluster (right centre). The regular ASFM transducers are along the top of the frame (the downstream edge when the frame is deployed vertically in the intake during measurement); the other instruments visible were used for boundary layer measurements

Measurement algorithm

Review of the flow algorithm found no implementation errors (6), and since the systematic error varies with location, its source is more likely to be found in the physical environment than in the algorithm itself.

Elimination of the above three factors therefore left the effects of upstream structures on the mean velocity and turbulence fields experienced by the ASFM as the most likely remaining source of systematic error.

Review of ASFM Performance

The algorithms employed by the ASFM to derive the path averaged flow velocity implicitly assume uniformity along the path for either the flow velocity or the local turbulence intensity. Errors in the path-averaged velocity are introduced if a non-uniform velocity distribution is accompanied by a non-uniform distribution of turbulence intensity. The sign of the bias depends on the form of the variations: if regions of more intense turbulence coincide with higher velocities, a positive bias will result; if the regions of more intense turbulence coincide with reduced velocities, the bias will be negative.   A typical trash rack is comprised of vertical and horizontal structural members supporting closely spaced vertical bars. Non-uniformities in both local velocity and turbulence are introduced when the wake from a structural member intersects the acoustic paths, with the degree of bias introduced being dependent on the contrast between the turbulence level of the intersecting wake and that of the remainder of the acoustic path. The bias in the flow derived from the ASFM output is thus critically dependent on the nature of the trash rack support design and the orientation of the acoustic paths of the ASFM. In most cases, such wakes will produce a negative bias, because the lower velocities in the wake are accompanied by elevated levels of turbulence. The magnitude of the bias depends on the development of the wakes and their interaction with rest of the flow field at the ASFM plane.

The local properties of the wake from a two-dimensional obstacle, such as a single I-beam placed in a uniform stream, are determined by the dimensions and shape of the obstacle, the orientation and velocity of the on-coming fluid, and the distance downstream. The obstacle and its orientation can be characterized by the product of the effective drag coefficient C_D and an appropriate length scale, in this case the transverse dimension of the obstacle, hereafter referred to as the ‘width’, D. This product provides the scaling parameter for the momentum loss introduced by the obstacle. The properties of such wakes far downstream of the obstacle where the velocity deficit has become small have been intensively investigated for the past 70 years, culminating in the detailed study of Wygnanski et al (7).

Sufficiently far downstream, typically in excess of 40 obstacle widths, the velocity profiles of the wake attain a universal similarity. The associated turbulence distributions also become similar, but have a profile shape weakly dependent on shape of the generating obstacle. The characteristic length and velocity scales of the profiles are the wake half width $b_{1/2}$ and the centerline velocity deficit u_{10}. Under these conditions, the width of the wake and the centerline velocity deficit, respectively, vary directly and inversely as the square root of the distance downstream:

$$\frac{b_{1/2}}{\theta} = B\left(\frac{(X + X_0)}{\theta}\right)^{1/2} \tag{1}$$

and

$$\frac{u_{10}}{U_\infty} = A\left(\frac{(X + X_0)}{\theta}\right)^{-1/2} \tag{2}$$

where A and B are constants, weakly dependent on the shape of the obstacle, θ is the wake momentum thickness ($2\theta = C_D D$) and U_∞ is the oncoming fluid velocity. The profile length scale $b_{1/2}$ is defined as the half width at the 50% velocity deficit level. The downstream distance includes an offset X_0 from a virtual origin dependent on the obstacle shape, which accounts for the early development of the wake before the flow has attained a self-preserving state.

Of interest here are the wakes generated by a combination of horizontal and vertical members typical of a trash rack (see the example in Figure 2). The main members are I-beams consisting of 4 inch by 2 inch (101.6 x 50.8 mm) end members, separated by a 3/8 inch x 20 inch (9.53 x 508 mm) web. The wakes of the main members develop within an overall background level of turbulence generated by the fine vertical bars. As the flow progresses downstream, the wakes of adjacent members merge, reducing the velocity contrast and rapidly raising the background level of turbulence. In typical trash rack designs, the horizontal members are spaced more closely than the vertical members, or the vertical members are omitted altogether.

In a normal ASFM installation, the acoustic beams are horizontal, and it is therefore the wakes from the vertical structural members which have the potential for introducing bias in the ASFM measurement. Since the bias magnitude is strongly dependent on the contrast between the turbulence of the vertical wakes and the remainder of the acoustic path, the point at which the horizontal wakes merge is a critical determinant of the bias. Figure 3 compares situations where the plane of the ASFM transducers intersects the horizontal wakes before and after the merging point. In the former case, acoustic beams positioned between the horizontal wakes have the potential for large biases, introduced by vertical wakes, compared to those placed within the horizontal wakes. Where the acoustic paths are placed downstream of the merging point, the overall turbulence contrasts will be small, and small biases can be expected on all paths.

Figure 4 illustrates the calculated effect of wake merging on the bias of a single acoustic path placed between the horizontal wakes at progressively greater downstream distances. The calculations are for the trash rack design of Figure 2, where a 6m long acoustic path is intercepted by the wakes of the three vertical members. The crosses are for direct CFD simulations of a set of merging wakes, the open circles are derived

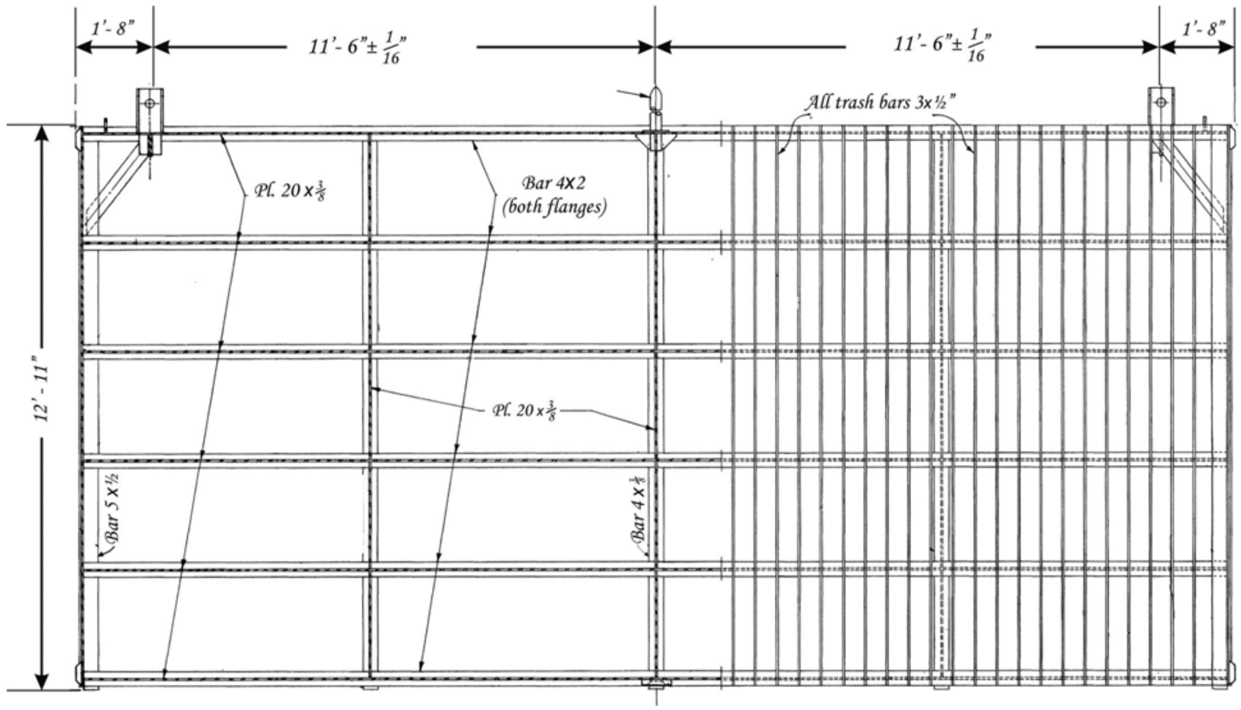

Figure 2: Typical trashrack structure

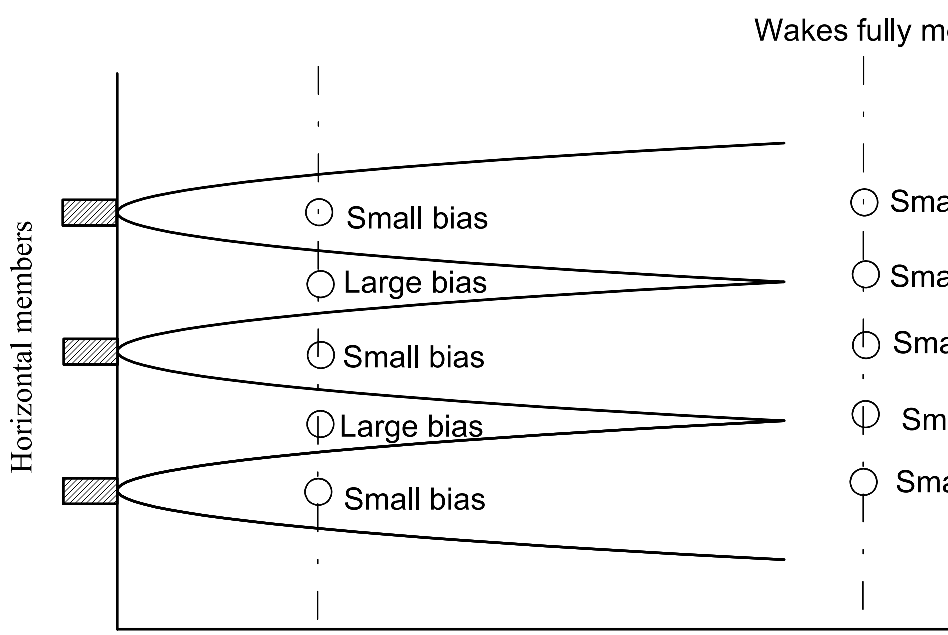

Figure 3: Illustration of the relationship between horizontal wake merging and the potential for ASFM bias

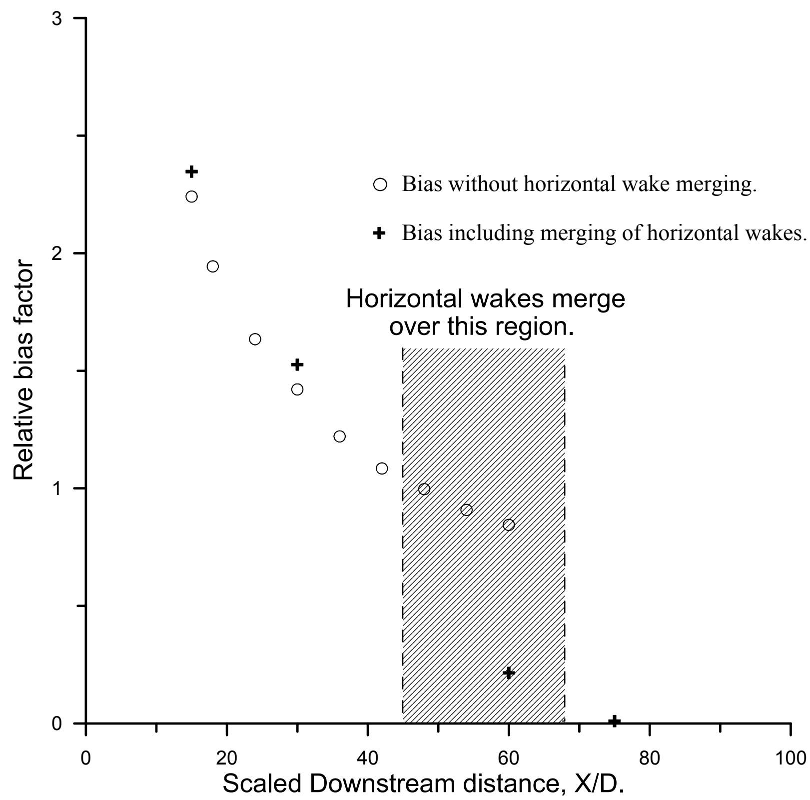

Figure 4: Effect of wake merging on the bias of a single ASFM acoustic path

from the similarity scaling laws of equations (1) and (2) for a case where merging does not occur. The general trend of reduction in the magnitude of the bias magnitude as the acoustic paths are moved downstream is a reflection of the reduction in the velocity deficit and turbulence level of the vertical wakes. The rapid reduction in bias level as the plane of the acoustic transducers moves downstream of the wake merging point is clearly evident.

The determination of the merging point of the wakes of horizontal trash rack members provides an initial indication of the relative potential for biased ASFM readings at a particular intake. Where the acoustic paths are downstream of the wake merging region, the magnitude of the overall bias will be small and insensitive to the vertical distribution of the acoustic paths. Conversely, where the acoustic paths are positioned upstream of the wake merging point, the magnitude of the bias of a given acoustic path depends on the number and design of the vertical support members, as well as on the placing of the paths relative to the horizontal wakes themselves. These concepts will now be applied to a number of plants where ASFM bias estimates have been obtained.

Table 1 summarizes the estimated bias for 16 hydro-electric plants, together with comments on the test results. Of those listed, two are excluded from the present discussion: Dalles Unit 9 and Rock Island Power House 1, Unit 2. The bias at these particular units is believed to arise from non-uniformity of the inlet flow due to separation and/or oblique inflow conditions, a situation which is not covered in this paper.

Table 1: Summary of measured and estimated biases

Plant	ASFM posn, m.	ASFM bias %	Comments
Rock Island PH1 Unit 6	5.0	**-1 to 0**	CM/ASFM W-K calibrations agree to within data scatter.
Bonneville Unit-5	14.5	**-1 to 0**	Efficiencies agree with CM results for matching blade angles and servo stroke %.
Wells Unit-3	4.6	-1 to 0	Turbine runner replaced. No comparable CM measurements.
Fort Patrick Henry	4.5	**-1 to 0**	Concurrent measurements with profiling CM array. Two discharges only.
McNary Unit-5	22	**-1 to 0**	No direct CM measurements, adjacent units only. Efficiencies very close, cam curves differ.
Rock Island PH2 Unit 6	6.7	**-1 to 0**	Efficiencies 1.5% above CM tests and approximately 1% below model tests.
John Day Unit-9	22	-1 to -2	No CM measurements available.
Lower Monumental Unit-2	23	-2 to 0	No CM measurements available.
Bonneville Unit-6	14.5	-2 to 0	No comparable CM measurements available. Turbine runner replaced after CM testing.
Dalles Unit-21	23	-2 to 0	No CM measurements for Unit-21, other units have peak efficiencies approaching 90%.
Rocky Reach Unit-5	7.5	-3 to -1	No comparable CM measurements. Turbine runner replaced.
Rocky Reach Unit-8	7.5	-3 to -1	No comparable CM measurements. Turbine runner replaced.
Rock Island PH1 Unit-2	5.0	**-4 to -3.5**	Known to have poor entry flow distribution with flow separation. High scatter in W-K readings. Both CM and W-K calibrations & efficiencies give ASFM similar bias.
Dalles Unit-9	23	**- 6 to -7**	Separated entry flow suspected. High trash rack loss. Flow bias derived from W-K calibration against CM.
Wheeler Unit-9.	6.7	**- 6 to - 5**	Concurrent measurements with profiling CM array. Trash rack has large (41cm) vertical concrete support.
Stave Falls	3.8	**-7 to -6**	Flow compared with time of flight system. Trash rack has two 40 cm wide vertical members.

CFD computations of the velocity and turbulence distributions generated by an array of generic trashrack support structures have been used to derive the coefficients A and B of the scaled equations (1) and (2). These have then been applied to the trash-rack members of the 16 plant intakes to provide a first order estimate of their potential for bias arising from the vertical structural members (Table 1). Table 2 lists the estimated merging points of the horizontal wakes, and it can be seen that in all cases where the magnitude of the bias is high, the acoustic paths are placed upstream of the estimated wake merging point, and sizable vertical supports are present.

Table 2: Wake merging distance and estimated bias potential

Plant	Horizontal member		Vertical member	Wake merging distance, m	ASFM distance from trash rack, m	ASFM total flow bias %
	Width, mm	Spacing, m	Width, mm x no.			
Rock Island PH1 Unit 6	76.2 Flat plates	0.94	15.9 x 3 Flat plates	9.7	5.0	-1 to 0
Bonneville Unit-5	101.6 I-beam	0.82	101.6 x 3 I-beam	4.4	14.5	-1 to 0
Bonneville Unit-6	101.6	0.82	101.6 x 3 I-beam	4.4	14.5	-2 to 0
Wells Unit-3	152.4 I-beam	1.77	76.2 x 3 Angle iron	13.7	4.6	-1 to 0
Fort Patrick Henry	31.6 Flat plates	1.45	n/a	95.0	4.5	-1 to 0
McNary Unit-5	127 U-beam	0.91	12.7 x 8 Round diagonals	4.3	22.0	-1 to 0
Rock Island PH2 Unit 6	220.0 Streamlined	3.64	101.6 x 2 Streamlined	50.2	6.7	-1 to 0
John Day Unit-9	101.6 I-beams	0.78	101.6 x 3	4.0	22.0	-2 to -1
Lower Monumental Unit-2	101.6 I-beams	0.76	101.6 x 3 I-beams	3.8	23.0	-2 to 0
Dalles Unit-21	101.6 I-beams	0.89	101.6 x 3 I-beams	5.2	23.0	-2 to 0
Rocky Reach Units 5 & 8	152.0 Angled box	1.70	127 x 3 I-beams	10.6	7.5	-3 to -1
Wheeler Unit-9.	510.0 Streamlined	4.0	406.4 x 1 Streamlined	44.8	6.7	-6 to-5
Stave Falls	220.0 I-beams	1.8	400 x 2	7.4	3.8	-7 to -6

Further consideration of the properties of the wakes from vertical structural members enables those plant intakes where the acoustic paths are upstream of the wake merging point to be further ranked in terms of potential bias. Figure 5 compares the ranking of a selection of these intakes with the actual test bias values. This confirms that the bias potential of a given plant can be estimated from the configuration of the trash rack structure and its distance from the plane of the acoustic paths, noting that measured bias values of the five plants within the low bias group are not effectively distinguishable.

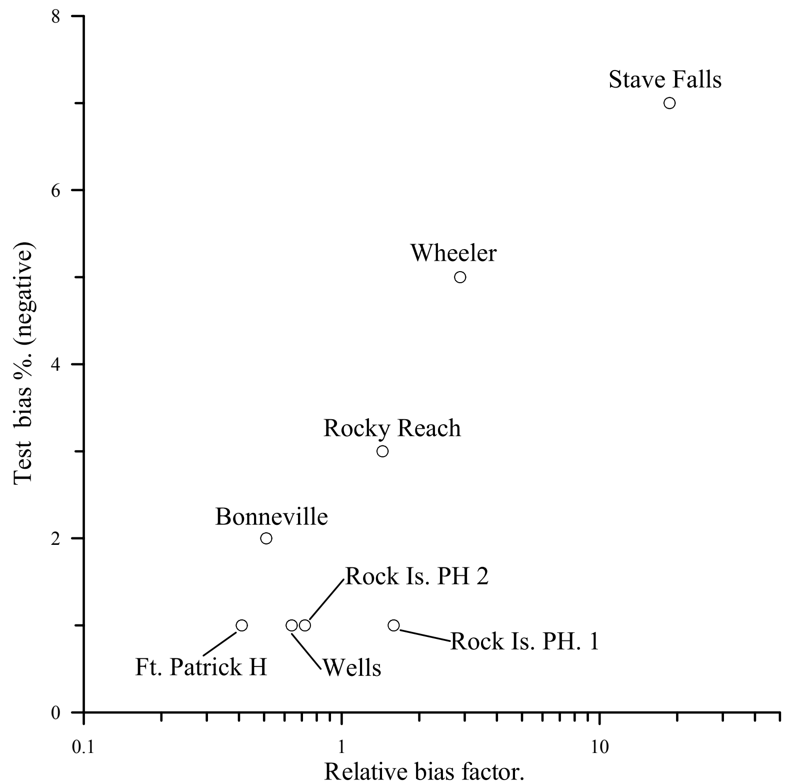

Figure 5: Comparison of estimated bias with actual bias

An Example of Bias Correction

One of the recent ASFM installations afforded an opportunity to test the bias correction. As part of a program of turbine efficiency tests with the ASFM at Wells Dam on the Columbia River in 2002, a series of preliminary measurements were made in one of the units to determine the optimal placement of the sampling paths. The distance between the trashrack and the ASFM measurement plane was relatively short (4.6 m) and the trashrack contained 5 major horizontal members, 15 cm high and 55 cm deep.

The proximity of the trashrack was thought likely to result in significant wakes from the major horizontal cross members at the ASFM plane. As measurements were to be conducted with 10 horizontal ASFM paths deployed in each of the three intake bays, placement of the paths to obtain accurate discharges required detailed knowledge of the flow profile with elevation. Thirty horizontal paths were therefore installed (in succession) in each bay to delineate the profile. Ten ASFM paths oriented vertically were added to the frame, to detect any cross-intake gradient in the flow. The full arrangement of ASFM paths is shown in Figure 6.

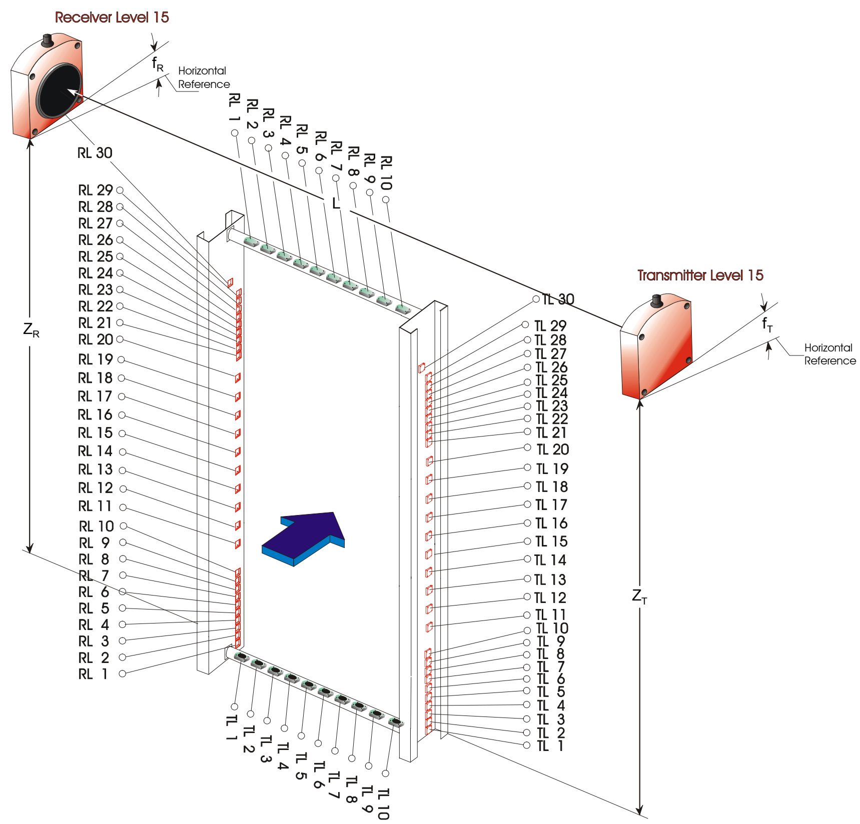

Figure 6: Configuration of horizontal and vertical ASFM paths at Wells Dam

The horizontal flow profiles from the vertical ASFM paths showed no significant gradients, and their forms were invariant with discharge. Velocities measured by the horizontal ASFM paths were therefore expected to be unbiased and to result in accurate discharges. The data from the horizontal paths showed that the profile structure of the velocity with elevation was independent of discharge (see the normalized plots in Figure 7). The velocity in the intakes increases with elevation, with the greatest increase in Bay A, less in Bay B and very little in Bay C. The variance of the ASFM's acoustic signal is a measure of the level of refractive-index turbulence. Figure 8 shows normalized profiles of the acoustic variance for the three bays, which show a structure similar to that of the velocity profiles (an overall increase with elevation).

The coincident increases in velocity and turbulence level with elevation would therefore be expected to produce a positive bias in the ASFM measurement. The wakes from the horizontal trashrack supports are also apparent in the upper part of the intake, but their velocity deficits are small compared to the overall velocity gradients in Bays A and B, so their effects would be overwhelmed by the overall gradients. To test the hypothesis that bias could be corrected with knowledge of the velocity and turbulence distributions, discharges were computed from the vertically oriented paths; they were found to exceed those computed from the horizontal paths in Bays A, B, and C by 9%, 5% and 1%, respectively. Bias correction factors for the vertical-path discharges were then

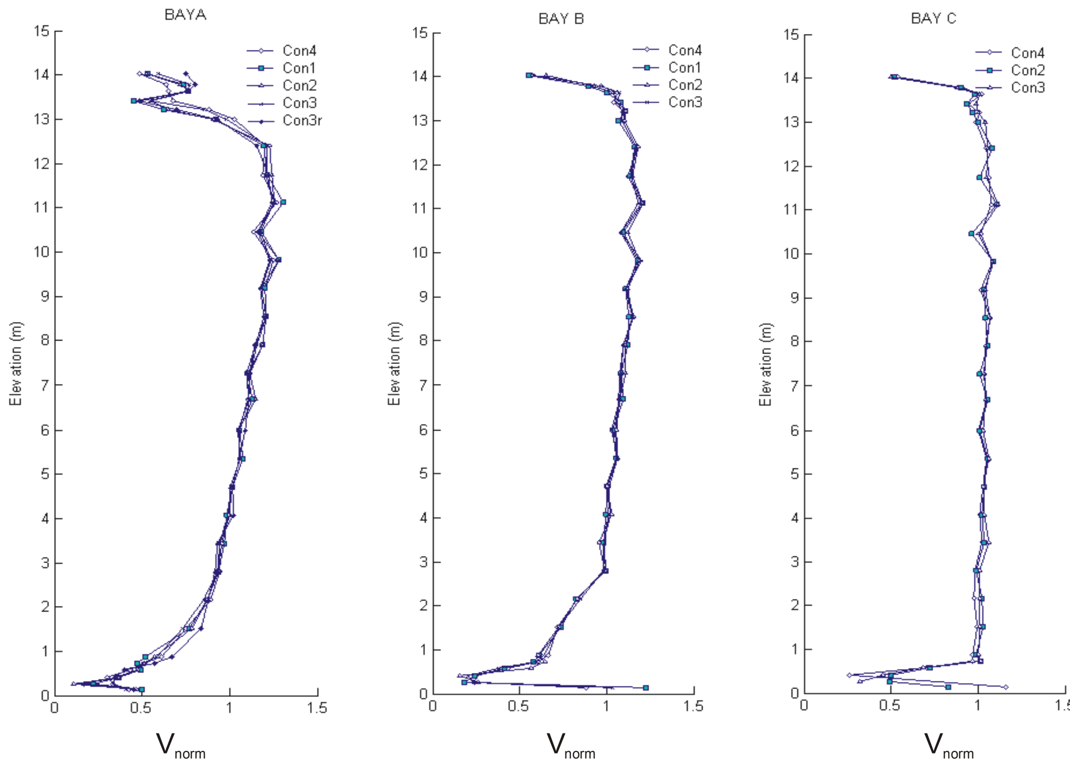

Figure 7: Normalized vertical profiles of velocity at Wells Dam

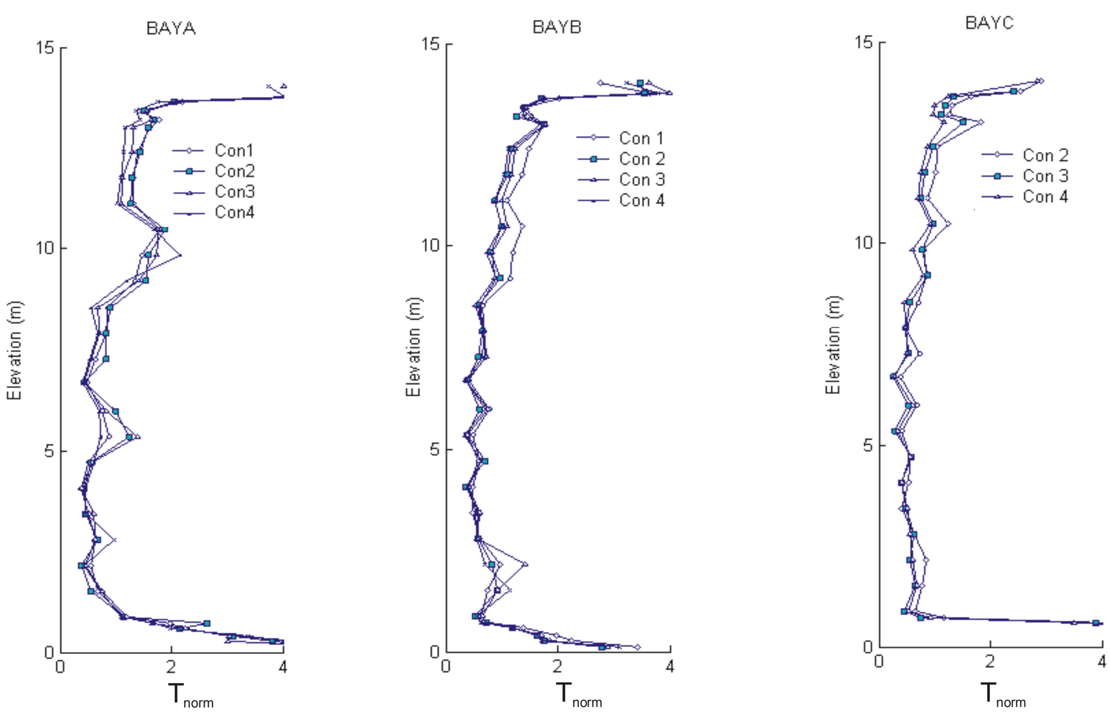

Figure 8: Normalized vertical profiles of acoustic variance

calculated from the velocity and turbulence intensity profiles in Figures 7 and 8 and used to correct the discharges derived from the vertical path data. The results reduced all the differences with the discharges computed from the horizontal paths to less than 1% (Figure 9).

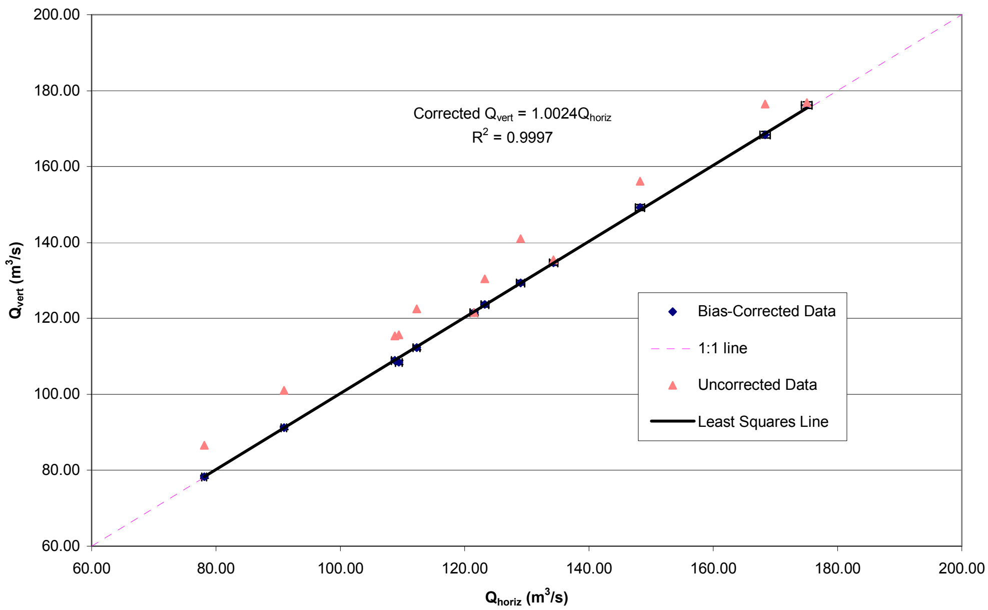

Figure 9: Discharge from vertical paths (uncorrected and corrected for bias) vs. discharge from horizontal paths

Quantitative corrections for biases in ASFM velocities produced by non-uniform distributions of velocity and turbulence are therefore possible if those distributions are known. In this case, the systematic errors were reduced to less than 1%. Knowledge of the distributions may be gained either through measurement (from the ASFM or other instruments) or by CFD simulation of the velocity and turbulence fields in the intake (8).

Summary

ASFM discharge measurements have shown significant negative systematic errors, as great as –7% in some intakes while in many others, systematic errors have been small or negligible. In either circumstance, the measurements were highly repeatable, having random uncertainty of less than ±0.5%. An intensive analysis of the results from ASFM measurements in a number of low-head plants has led to the conclusion that the chief cause for such systematic errors is the effect of upstream structures, usually trashrack elements, on the distribution of velocity and turbulence at the ASFM measurement plane. Negative biases arise from the combination of reduced velocity and elevated turbulence levels in the wakes from major trashrack supports oriented perpendicular to the ASFM sampling paths. Zones where elevated turbulence levels coincide with above-average velocities produce positive bias.

Application of analytic models of wake development based on laboratory experiments reported in the literature and CFD models of typical intakes has shown that once wakes from trashrack supports parallel to the ASFM paths merge, the turbulence field becomes sufficiently uniform that bias errors become small. The results from these models may be used to establish the likelihood of significant bias errors in a specific intake.

A method has been developed to predict or correct the bias, provided the distributions of turbulence and velocity are known. In the test case described above, it reduced systematic discrepancies in total discharge to less than 1%.

Acknowledgments

The authors wish to thank the personnel at the various plants where the ASFM has been used for flow measurement and special testing for their cooperation and assistance.

References

1. Lemon, D.D., D. Billenness and J. Lampa, 2002. Recent advances in estimating uncertainties in discharge measurements with the ASFM, Hydro 2002, Kiris, Turkey

2. Lemon, D. D., C. W. Almquist, P. A. March, and T. A. Brice, 1998. Comparison of turbine discharge measured by current meters and Acoustic Scintillation Flow Meter at Fort Patrick Henry power plant. Proc. HydroVision '98, Reno, Nevada.

3. Lemon, D. D. 1995. Measuring intake flows in hydroelectric plants with an Acoustic Scintillation Flow Meter. Proc. Waterpower '95, ASCE.

4. Farmer, D. M. and S. F. Clifford, 1986. Space-time acoustic scintillation analysis: a new technique for probing ocean flows. IEEE J. Ocean Eng. OE-11 (1), 42-50.

5. Marko, J. R. and D. D. Lemon, 2002. Negative bias in ASFM discharge measurements in short intakes – transducer spacing. Proc. IGHEM 2002, Toronto ON

6. ASL AQFlow Inc., 2003. Factors affecting the accuracy of the Acoustic Scintillation Flow Meter. ASL AQFlow Inc., Sidney BC (internal report)

7. Wygnanski, I., F. Champagne and B. Marasli, 1986. On the large scale structures in two-dimensional, small-deficit, turbulent wakes. J.Fluid Mech. Vol. 168, pp. 31-71.

8. Bouhadji, L., D. D. Lemon, D. Billenness, D. Fissel and N. Djilali, 2003. Computational analysis of turbulent flow in hydroelectric plants. Proc. Waterpower XIII, Buffalo NY. HCI Publications, Kansas City, MI.

The authors

David Lemon, M.Sc., graduated in Oceanography from the University of British Columbia, Vancouver, in 1975 and has worked for ASL Environmental Sciences since 1978. He has worked extensively on the application of acoustics to measuring flow, and has been responsible for the development of the ASFM. He is currently a Director of the firm, with responsibility for Research and Development.

Latif Bouhadji, Ph. D. graduated in Fluid Mechanics from the Fluid Mechanics Institute of Toulouse, France, in 1998. He was a research associate at the University of Victoria's CFD Laboratory before joining ASL in 2002. He is a CFD modeler at ASL Environmental Sciences.

David Topham, Ph. D. graduated in aeronautical engineering in 1959, from Loughborough College, U.K., and obtained his Ph.D. in 1970 in the field of high circuit voltage interruption. In 1973, he joined the Federal Govt. of Canada working on Arctic related environmental problems of oil and gas exploration. He is currently working with ASL on the ASFM development.

Josef Lampa, P.Eng., has been involved in studies, design, construction and operation, maintenance and surveillance of hydro projects in all parts of the world. He has been hydroelectric consultant to ASL since his retirement from BC Hydro, Canada, in 1999.