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Recent Advances in Resolving Bias in Discharge Measurement by Acoustic Scintillation

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Recent work has improved understanding of the performance of the Acoustic Scintillation Flow Meter (ASFM) in hydroelectric intakes, particularly the factors affecting the accuracy of the results. The primary cause for systematic (or bias) errors was found to be coincident, strong inhomogeneities in the intensity of small-scale turbulence and the mean velocity in the measurement plane, such as are typically found in the wakes behind large supporting members in the trashracks, oriented perpendicularly to the ASFM's acoustic paths. High background levels of turbulence, such as those produced when the wakes from horizontal members merge, suppress the effect. Guidelines have been established for determining conditions under which an ASFM can be used without significant bias.

It has also been found that anisotropy (variation with direction) in the turbulence can produce bias errors; that condition is frequently found near boundaries. The investigation of the effects of turbulence anisotropy has led to a revision of the algorithm used to compute the flow velocity. This revision improves ASFM's performance in regions of strong turbulence and unsteady flows; these conditions are often found near the roof boundary, and behind fish diversion screens. The revised algorithm was most recently used in the tests conducted in December 2004 at Lower Granite Dam on the Columbia River; the assessment of probable bias in the resulting flow measurements, when compared to expected turbine performance from model tests, indicated that it was less than ±1%. The revision has also been applied to several of the previous measurements at other Columbia River plants and in all cases, the re-analysis led to increases in the discharge, with corresponding reductions in the negative bias previously experienced. Examples from several of these plants, illustrating the effect of the revision on the velocity profiles, discharge, and repeatability are given.

Introduction

Acoustic scintillation was first applied as a method for measuring flow in the intakes to low-head hydroelectric turbines in 1992. The first few applications were performed using instruments adapted from oceanographic use. The first version of an instrument designed specifically for use in hydroelectric intakes (the Acoustic Scintillation Flow Meter, or ASFM) was used at McNary Dam on the Columbia River in 1998. Figure 1 shows the typical arrangement for installation in a 3-bay low-head intake.

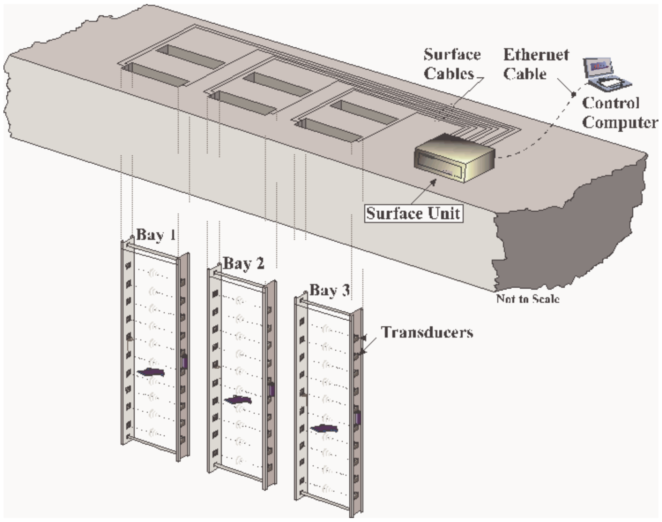


Figure 1: Typical installation arrangement for an ASFM.

The principles upon which flow measurement by acoustic scintillation is based are described in detail in Lemon, Billenness and Lampa (2002), Farmer and Clifford (1986) and Clifford and Farmer (1983). Briefly, the acoustic scintillation technique utilizes the natural turbulence embedded in the flow, as shown in Figure 2. In its simplest form, two transmitters are placed on one side of the intake, two receivers on the other. The signal amplitude at the receivers varies randomly as the turbulence along the propagation paths changes with time and the flow. If the two paths are sufficiently close (Δx), the turbulence remains embedded in the flow, and the pattern of these amplitude variations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, Δt. This time delay corresponds to the position of the peak in the cross-correlation function calculated for Signal 1 and Signal 2. The mean velocity perpendicular to the acoustic paths is then $\Delta x/\Delta t$, and because three transmitters and three receivers are used at each measurement level, the average inclination of the velocity is also obtained. The total flow is then calculated by integrating the average horizontal component of the velocity at several pre-selected levels over the total cross-sectional area of the intake.

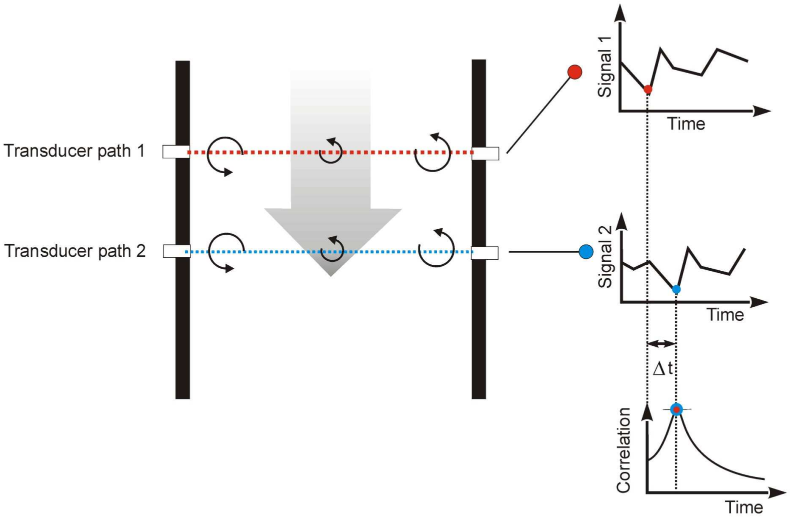
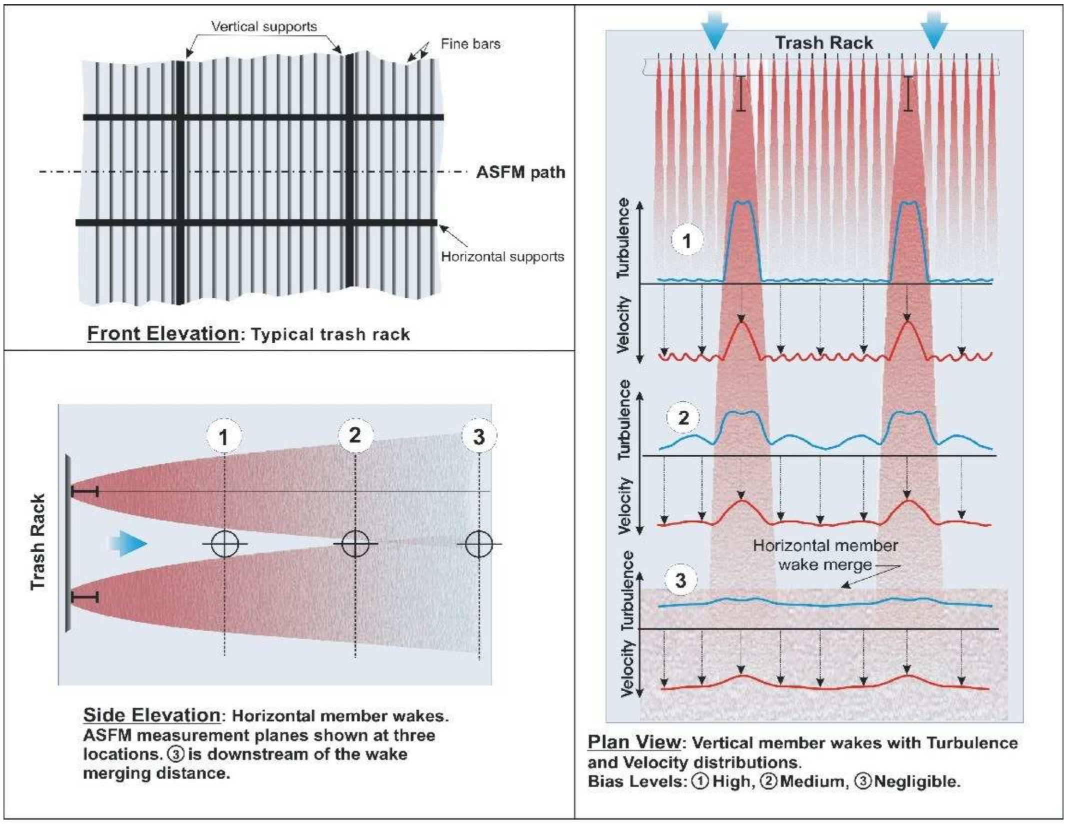


Figure 2: Schematic representation of the acoustic scintillation principle.

Since 1998, the ASFM has been used in measurements at more than 25 intakes. In some of these cases, the discharge values appeared to be biased; the existence of the bias was inferred from the computed turbine efficiency, which was higher than expected (usually based on model tests). The apparent systematic errors in flow ranged from near zero to as much as 6 to 7% undervaluation. The bias varied from plant to plant, but appeared to be constant for any one unit. Consequently, the ASFM could be used for index testing, but without improved understanding of the causes of the bias, it could not be relied on for absolute flow measurements.

Causes for Systematic Error

An intensive review of the performance of the ASFM at each of the plants where it had been used was carried out, searching for correlations between plant characteristics and the occurrence of systematic errors. The primary cause for the larger systematic (or bias) errors in the ASFM data was found to be coincident, strong inhomogeneities in the intensity of small-scale turbulence and the mean velocity in the measurement plane, such as are present in the wakes behind large supporting members in the trashracks, oriented perpendicularly to the ASFM's acoustic paths (Lemon, Topham et al., 2004). Figure 3 shows a schematic example. The algorithms employed by the ASFM to compute the path-averaged velocity implicitly assume relative uniformity along the path for either the local turbulence intensity or the flow velocity. A negative bias in the path-averaged velocity occurs if the path crosses the wake behind a vertical trashrack support, because the lower velocities in the wake are accompanied by elevated levels of turbulence. The effect increases if the flow enters the intake at an angle, as that increases the projected width of the support members. High background levels of turbulence, such as those produced when the wakes from horizontal members merge, suppress the effect.



Front Elevation: Typical trash rack

Side Elevation: Horizontal member wakes. ASFM measurement planes shown at three locations. ③ is downstream of the wake merging distance.

Plan View: Vertical member wakes with Turbulence and Velocity distributions. Bias Levels: ① High, ② Medium, ③ Negligible.

Figure 3: Schematic representation of bias errors produced by large vertical trashrack

members.

The wake effects will not be great enough to degrade the accuracy of the ASFM if the instrument is installed in classical shape low-head short intakes where

a) the trashrack structural supports are not wider than 100 mm and not closer than 6 m from the measurement plane, and the trashrack has been cleaned prior to the testing,

b) the angle in the horizontal between the inflow velocity vector and the axis of the intake does not exceed 5 degrees, and the operation of the neighbouring units and the spillway, if applicable, is controlled to the degree necessary to stay within this limitation during the period required to perform the measurements, and

c) there are no unusual shape or convergence irregularities.

If these conditions are not fulfilled, but the wakes from the major horizontal trashrack supports have merged before they reach the measurement plane, then it is very likely that the bias due to the wakes from the vertical support members will be reduced to a negligible amount. The distance downstream of the trashrack, X_{merge} required for the wakes from the horizontal members to merge may be estimated as

$$\frac{X_{merge}}{D} = 1.44\left(\frac{H}{D}\right)^{2.2}$$

where H is the vertical separation between the major horizontal trashrack supports, D is their width in the vertical and X is the distance between the trashrack and the measurement plane (all quantities in the same units).

There will be instances where there are significant wakes from vertical members, and the wakes from the horizontal members have not merged to produce a sufficiently uniform turbulence background, or other aspects of the intake conditions have resulted in non-uniform distributions of turbulence and velocity. If the forms of the distributions are sufficiently well known, the bias produced by this mechanism may sometimes be corrected. That information may be obtained either by measurement (Lemon, Topham et al., 2004) or, in some cases, by numerical simulation (Lemon, Bouhadji et al., 2004).

There are, however, other effects that can produce biases in the ASFM data, even in intakes without large vertical members in the trashracks and that are otherwise favourably configured. Anisotropy (variation with direction) in the turbulence can also produce bias errors; that condition frequently occurs near boundaries and immediately downstream of trashracks. Investigation of the effects of turbulence anisotropy has led to a revision of the algorithm used in the ASFM to compute the flow velocity. The revision improves ASFM performance in regions of strong acoustic fluctuations and unsteady flows; in Columbia River plants, these conditions are often found near the roof boundary, and behind fish diversion screens. The revision to the algorithm takes into account the magnitude of the cross-correlation between the acoustic signals for each of the three pairs of signal paths in the array in addition to the peak timing. Using the additional information results in a more accurate, robust measure of the flow inclination angle.

Figure 4 shows an example of the velocity vectors from a measurement at Lower Monumental Dam, computed using both the original and revised algorithm. No fish diversion screens were in place. Over the majority of the height of the intake, there are small but significant differences between the velocities produced by the two algorithms, indicating that the small-scale turbulence field is not fully isotropic. The largest differences occur near the roof, where the revised algorithm produces flow angles more closely aligned with the roof slope. Overall, the calculated horizontal component of the velocity is therefore larger, and results in an increase in the discharge. The anisotropy in the turbulence field caused the original time-delay method to systematically overestimate the inclination angle in most of the intake, and thus underestimate the horizontal component and the discharge. The discharge computed by the revised method is 3.4% greater than that computed by the original algorithm, counteracting the negative bias found with the original algorithm.

Figure 5 shows a velocity profile from the same intake, with fish screens (STS or Submerged Travelling Screen type) in place, for a discharge similar to that in Figure 4. The disagreement between the two algorithms is greater, because of the distortion of the flow field by the screens. The discharge computed by the revised algorithm is 7.2% greater than that produced by the original algorithm. Before reprocessing with the revised algorithm, the overall unit efficiency calculated using the ASFM discharge data was greater with screens in than it was with screens out. After reprocessing with the revised algorithm, the efficiency relationship was reversed, producing a more realistic result, and efficiency values for both cases closer to expected values.

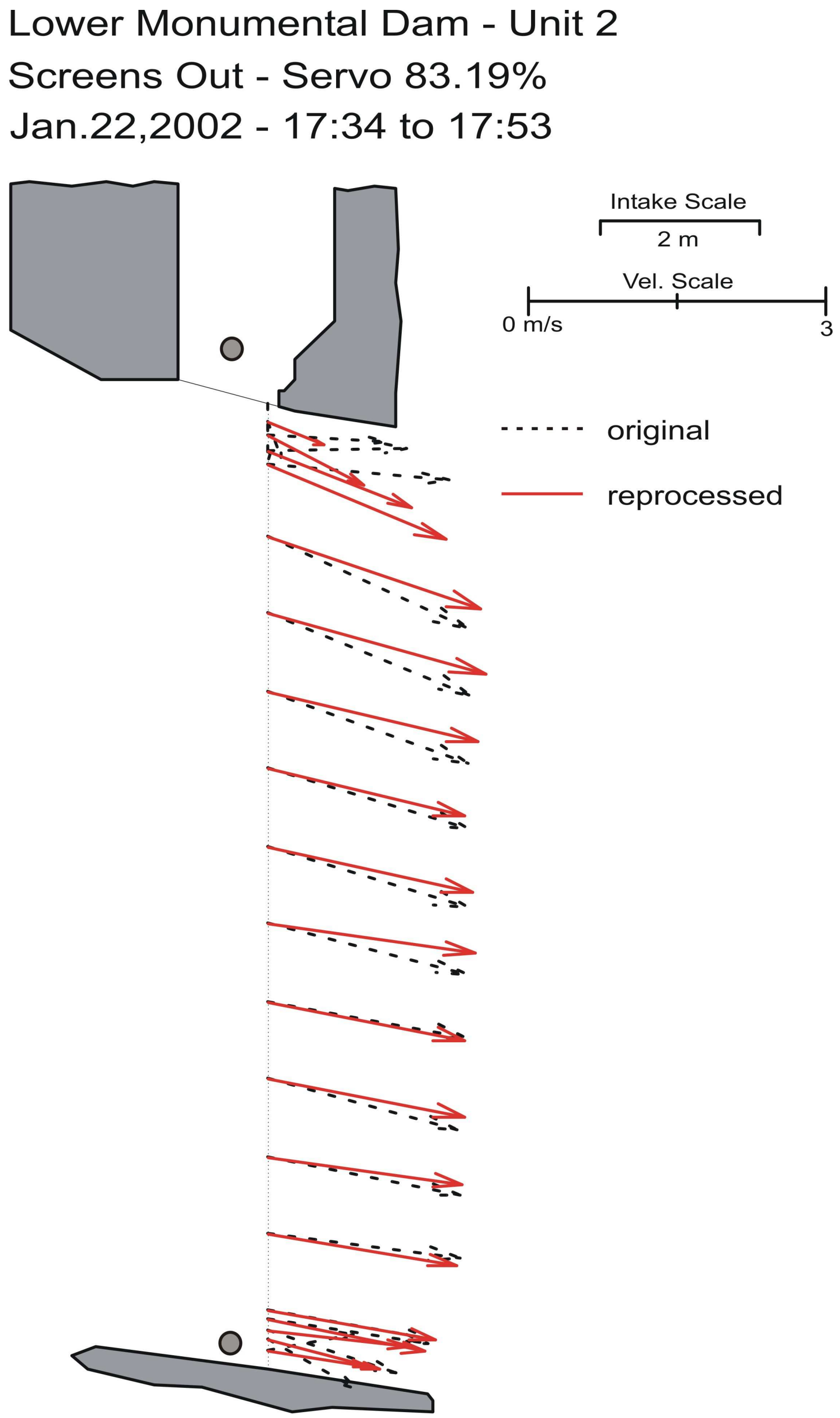


Figure 4: Example of flow profile measured with the original (black, dotted arrows) and revised (red, solid arrows) algorithms.

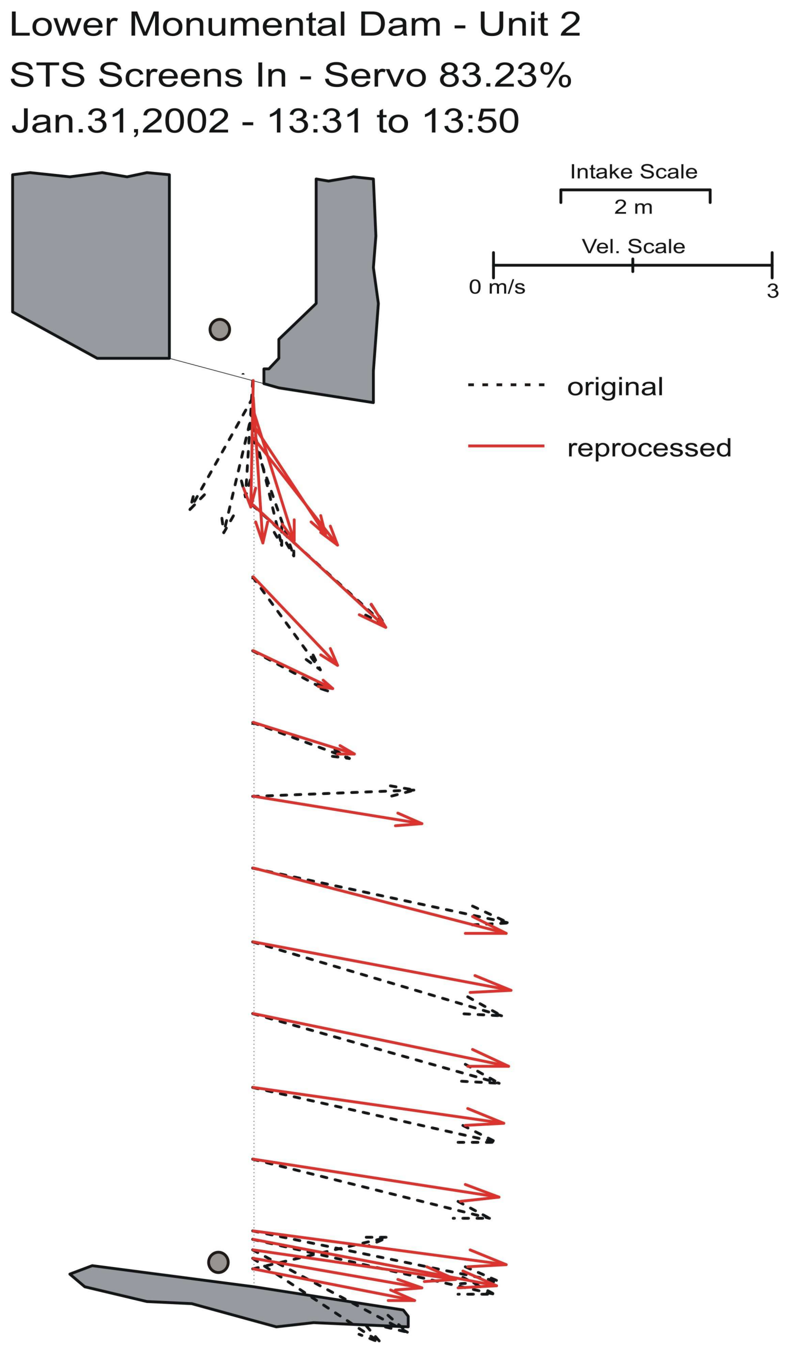


Figure 5: Example of flow profile measured with the original (black, dotted arrows) and revised (red, solid arrows) algorithms.

The revised algorithm was used in the tests conducted at Lower Granite Dam, Unit 4 in December 2004; the assessment of probable bias in the resulting flow measurements, when compared to expected turbine performance from model tests, was that it was less than ±1% (Figure 6 below, from Wittinger, 2005).

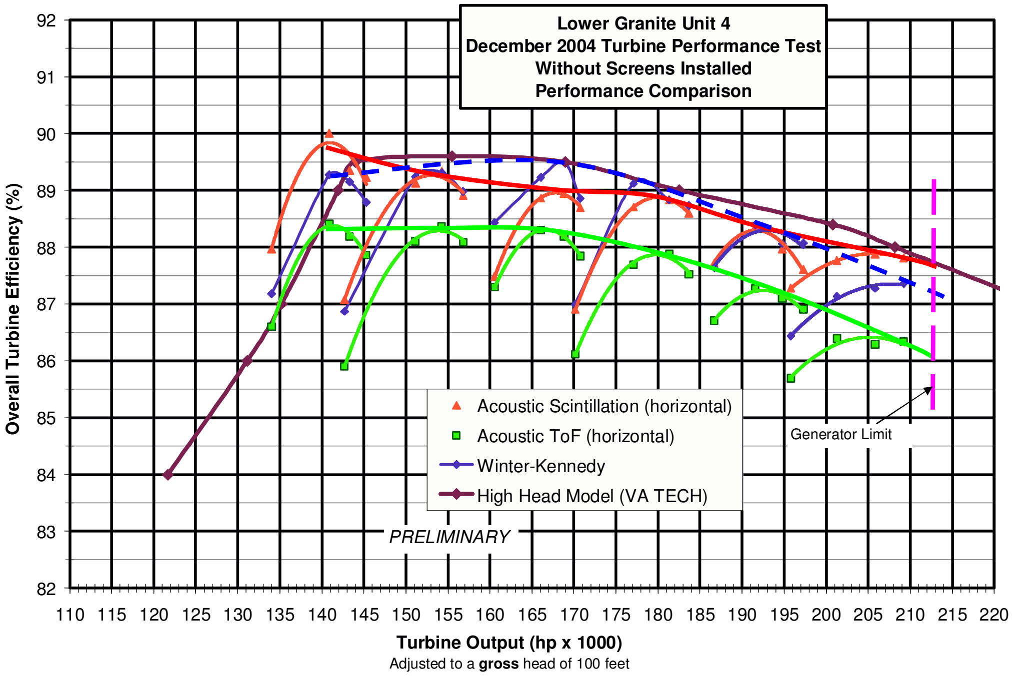


Figure 6: Turbine performance curve, Unit 4, Lower Granite Dam (from Wittinger, 2005).

The figure shows the overall turbine efficiency, calculated using the gross head. The values produced from the ASFM discharge data, using the revised algorithm, are within 0.5% of the model results, except at the lowest power setting, where they are about 1% higher.

The revised algorithm has been applied to several of the previous measurements at other Columbia River system plants; the results are summarized in Table 1 below. The table lists, for each unit tested, the minimum, mean and maximum discharge increase found in the test series after reprocessing (each series usually consisted of 5 to 12 conditions). In all cases, the re-analysis led to increases in the discharge, with corresponding reductions in the calculated unit efficiencies. Figure 7 shows the effect of the algorithm revision on a set of performance measurements made at the Chelan County Public Utility District's Rocky Reach Dam on the Columbia River. The figure shows the Unit 5 performance curve using the original data, and after reprocessing with the revised algorithm. The efficiency curve computed using the revised algorithm is about 2.5% lower than the original, and the points are somewhat better clustered about the line; again, a more realistic result. These results support the assessment made from the Lower Granite tests, that the revision to the velocity algorithm has reduced or nearly eliminated the negative bias in ASFM flow measurements, when used in plants with suitable intake conditions.

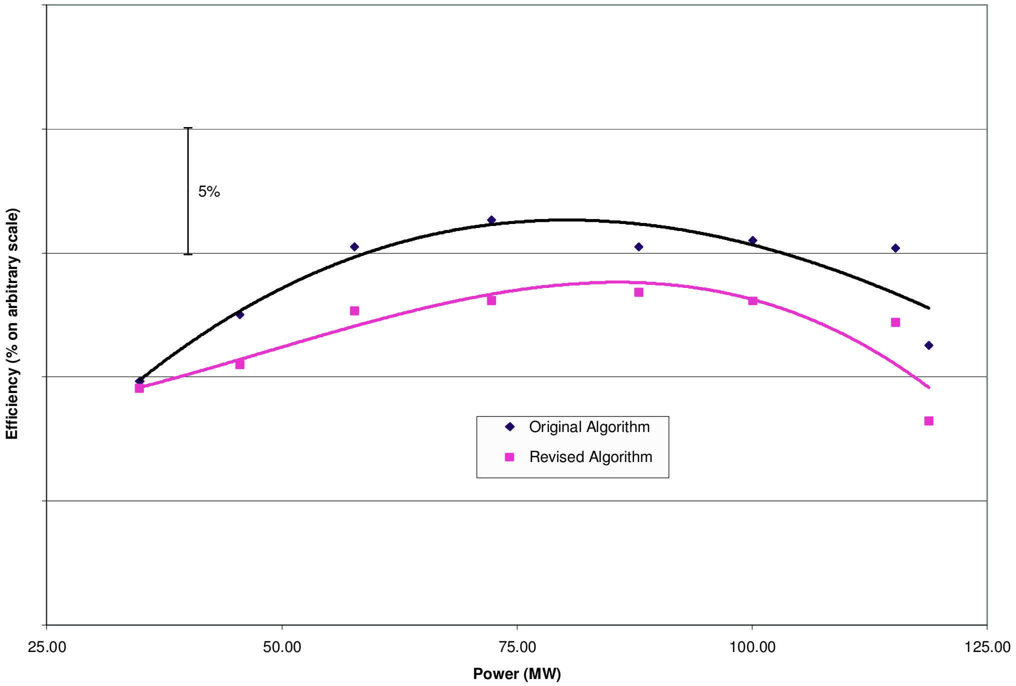


Figure 7: Effect of algorithm revision on computed efficiency curve for Rocky Reach Dam, Unit C5.

Table 1: Summary of Effect of ASFM Algorithm Revision on Discharge at Columbia System Plants

Site	Configuration	Increase in Discharge (%)		
		Minimum	Mean	Maximum
Bonneville PH1 U6, 1999	On cam, screens out	1.6	3.2	6.1
Bonneville PH1 U6, 2000	On cam, screens out	2.6	3.0	3.4
Little Goose Unit 3 January 2003	On cam, Screens out	2.7	3.2	4.1
	On cam, Screens in	1.1	2.4	3.3
Lower Monumental Unit 2 January 2002	On cam, Screens out	3.0	3.1	3.4
	On cam, Screens in	6.0	6.7	7.3
Lower Monumental Unit 6 February 2002	On cam, Screens out	2.5	2.7	2.9
	On cam, Screens in	5.3	6.0	6.6
Rocky Reach Dam Unit C5 July 2000	Off Cam, 84' head	1.3	2.4	6.2
	Off Cam, 92' head	0.4	2.9	5.4
Rocky Reach Dam Unit C8 July 2000	Off Cam, 84' head	1.3	2.6	5.9
	Off Cam, 91' head	1.5	2.4	4.8
The Dalles Unit 9 November 2000	On cam	3.5	4.2	4.7
	Off Cam, Blade Angle 23.3	3.6	4.1	4.6
The Dalles Unit 9 June 2001	On cam	3.9	4.1	4.3
	Off Cam, Blade Angle 23.3	3.0	4.1	4.6

It is interesting to note that in the results from these large plants on the Columbia system, the revised algorithm had little effect on the repeatability of the discharge values; it remained essentially the same for both algorithms, at about 0.4% standard deviation. However, at some smaller plants, where the hydraulic conditions in the intakes were more irregular, reprocessing with the revised algorithm reduced the variability of repeat discharge measurements significantly (e.g. at the small Hydro Kennebec plant in Maine, the standard deviation of repeat measurements was reduced to 0.4% from 0.7% and 0.9% in the two units measured).

Conclusions

One of the primary causes of systematic error in ASFM discharge measurements is the presence of wakes from large vertical obstructions (such as trashrack supports) in the intake upstream of the ASFM measurement location. The combination of higher turbulence intensity and lower flow velocity in the wakes produces a negative bias in the ASFM data, unless the measurement plane is far enough downstream for the turbulence field to have become sufficiently uniform. Angled approach flows can exacerbate the effect.

Anisotropy in the turbulence can also produce systematic errors, even in the absence of upstream obstructions. An improvement to the ASFM velocity algorithm has been implemented which utilizes the magnitude as well as the timing of the cross-correlation peaks. The revision to the processing algorithm has been tested on data from a number of previous measurements, and has been field tested at Lower Granite Dam. The results of the reprocessing and the field tests demonstrate that the revision to the processing algorithm has reduced or nearly eliminated the negative bias in ASFM flow measurements for intakes where there are no significant upstream obstructions or unusual approach conditions.

The reduction or near elimination of bias due to turbulence anisotropy through the velocity algorithm improvement, and the improved understanding of the effects of wakes from upstream structures define the characteristics of intakes in which the ASFM can be used for accurate absolute discharge measurements. This, we believe, will assist both the IEC 41 and ASME PTC-18 code committees in evaluating acoustic scintillation as an absolute flow method in the course of their current efforts to address flow measurement in short-intake plants.

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