Acoustic Scintillation Tests at the St. Lawrence -FDR Power Project

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Abstract

The hydroelectric industry has recognized the importance of developing cost-effective flow measurement methods for short, converging intakes, common at many projects. In response, ASME PTC-18 undertook the Short Converging Intake Project to evaluate different technologies to measure flow in such intakes. The work described in this paper was also supported by the Electric Power Research Institute (EPRI).

The New York Power Authority's St. Lawrence – FDR Power Project was selected as a site for feasibility and comparison testing. The Authority had already begun upgrading and modernizing this 16-unit project in 2000. As part of the process, a testing program to determine the field efficiency of the upgraded units, and allow sharing of the waters of the St. Lawrence River with Canada under an existing Treaty between the United States and Canada, was implemented based on the use of current meters. The cost and time required for this method led to continued interest in other potential flow measurement methods for short, converging intakes.

In 2007 tests were conducted to compare the flows measured using acoustic scintillation to those measured using current meters. The Project has historically been operated without trash racks. It was found that the low flow velocities and deep straight approach channel did not generate sufficient turbulence in the flows to allow reliable measurements using the acoustic scintillation method. The tests were repeated in 2008 at a location deeper in the intake, where converging flows might provide for higher signal coherence. While coherence was improved, the resulting signal strength remained too low to reliably measure the flow rate. The data presented in this paper provide information on the lower turbulence limits of the acoustic scintillation method, relevant to planning tests with this method. It also includes a brief review of previous work on the prediction accuracy of prototype efficiencies and flows from model data based on industry accepted methods and the comparison to current meter test results.

Introduction

The hydroelectric industry has a need for an accurate and cost effective method to measure flow and turbine efficiency in low-head plants that often have short, converging intakes. While sometimes referred to as low-head intakes, the term refers to the design of the intake itself, and such intakes are therefore also typical of many high head projects. At present, neither the ASME PTC-18 nor IEC 600041 test codes include any intake flow measurement method for such plants, although the IEC does provide guidelines for the use of current meters. In recent years, some acoustic methods have been adapted for use in intakes, and the challenge today to assess their accuracy, reliability and the range of conditions for which each is applicable. Laboratory tests have not been considered adequate to analyze these issues due to the difficulty in finding facilities large enough to model an intake of sufficient size, and uncertainties in scaling results to full size. To assess the performance of the alternative methods it's therefore necessary to conduct tests against other code-accepted methods in plants where a code-accepted method can be used together with the intake methods, by tests in plants where the performance characteristics are sufficiently well-known to assess the accuracy of the intake methods, and finally, by inter-comparisons among the various intake methods under the same conditions.

A project was therefore undertaken to test the performance of acoustic scintillation drift for measuring intake flow at the New York Power Authority's St. Lawrence - FDR Power Project. The test was to be done in conjunction with field efficiency tests scheduled for the fall of 2007 on an upgraded turbine for which the flow data were to be provided by arrays of current meters in the intake. Intake current meters have been used successfully numerous times at the St. Lawrence plant, and good correlations of prototype predictions from model test data to the results of current meter tests have been obtained for both of the new turbine designs at this plant, (Loiseau et al, 2009, Mikhail et al , 2001, St-Hilaire et al, 2004). The plant was in part selected for its favourable straight and uniform intake flow conditions not found at most plants, for which current meters would be expected to be successful due to the even and stable velocity distributions. The flow results obtained from the Acoustic Scintillation Flow Meter (ASFM) were then to be compared with those obtained from the current meters.

Various operational difficulties resulted in an incomplete data set being obtained in 2007, which did not allow meaningful comparisons to be made with the current meter measurements. The data quality of the data collected by the ASFM was also lower than normal. The cause was suspected to be the low level of turbulence present because the St. Lawrence – FDR plant is operated without trash racks, the approach conditions provide ideal straight-on flows in a deep river channel, and the intakes are large, providing for low flow velocities. A second series of measurements was performed in December 2008, with the acoustic scintillation instrument installed further inside the intake, where higher levels of turbulence and coherence were expected. Since the 2007 tests provide incomplete results, that program will be only briefly described, and the focus of this paper will be the 2008 measurements.

Principles of Flow Measurement by Acoustic Scintillation Drift

Acoustic scintillation drift uses forward scattering of underwater sound by turbulence to measure the flow velocity perpendicular to a number of acoustic paths established across the intake. Fluctuations in the acoustic signals transmitted along the paths result from turbulence in the water carried along by the current. The ASFM measures those fluctuations, known as scintillations, and from them computes the average along the acoustic path of the velocity perpendicular to each path (Clifford & Farmer, 1983; Lemon et al, 1998). Three transmitters and three receivers are used at each measurement level, thus obtaining the average inclination of the velocity as well as its magnitude. The total flow is then calculated by integrating the average horizontal component of the velocity at each of the levels over the total cross-sectional area of the intake.

Installation at St. Lawrence – FDR Power Plant

The New York Power Authority's St. Lawrence – F. D. Roosevelt Power Project is located on the St. Lawrence River in Massena, NY. The plant is located in the Moses-Saunders Power Dam, which also contains Ontario Power Generation's R. H. Saunders St. Lawrence Generating Station, near Cornwall, Ontario. The two generating stations share the river flow under the terms of an international treaty. Figure 1 shows a schematic of the intakes at the plant.

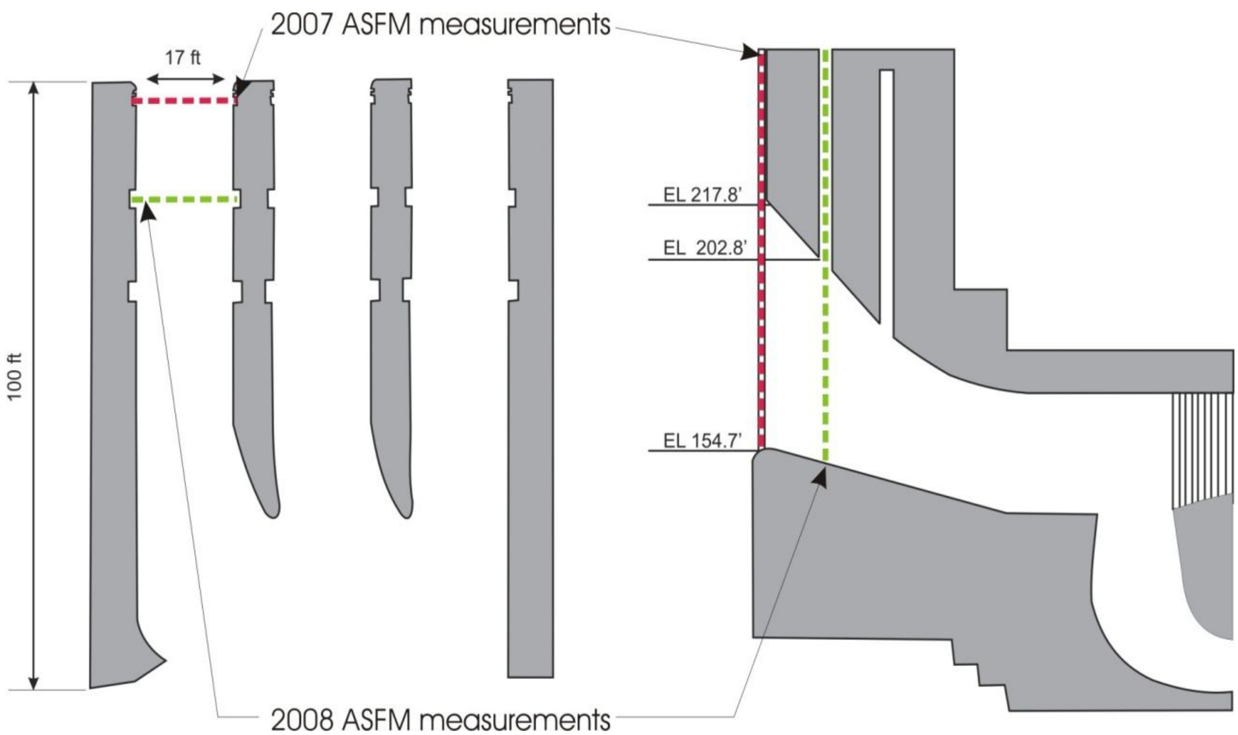

Figure 1: Plan and section views of the St. Lawrence – FDR intake, showing the 2007and 2008 test locations.

Referring to Figure 1, each unit has a reinforced concrete intake structure integral with the powerhouse. Each unit's intake has three intake bays, and each bay is equipped with stop log slots, trash rack slots, and an intake gate with a motor-operated hoist. The units operate at 94.7 rpm under an average head of about 81 feet. The 16 U.S. units are numbered 17 though 32.

The project has 16 vertical fixed blade propeller turbine units, each rated 60 MVA, but of two different designs. Eight of the units were originally built by the BLH Corporation, and have all been replaced by a new Alstom design. The other eight units were provided by Allis Chalmers, and are currently being replaced with a second new Alstom design. All of these designs have been tested using the current meter method.

2007 Testing Program

The 2007 test was performed together with field efficiency tests scheduled for October and November on the upgraded turbine of Unit 22, for which flow data were to be provided by arrays of current meters in the intake. It had been intended that the measurements be made simultaneously, with the ASFM installed in the trash rack slots upstream of the current meters, which were to be installed in the stoplog slots (see Fig. 1). The trash racks had been removed from the plant early during its operation, and with its deep intakes has historically operated without them. Under this plan, the discharges measured by the two methods would be compared directly. In practice however, there was insufficient space and time to allow both measurement systems to be operated simultaneously, so the ASFM measurements were scheduled to begin after the current meter work was completed. The operational characteristics of the plant are very stable and well-known, and the head is very constant, so that it would still be possible to compare the discharge from the two methods as the operating conditions can be reproduced with a high degree of repeatability. However, because the velocity profiles were measured at two different locations in the intake, between which the height of the intake changed significantly, direct comparisons of the laterally-averaged velocity profiles could not be made.

A number of operational and scheduling difficulties resulted in it being possible only to collect ASFM data from one frame which was partially deployed into Bay A, with only the lower 6 acoustic paths inside the intake passage. Figure 2 shows the velocity vectors measured at those positions for two repeat runs at 70% gate.

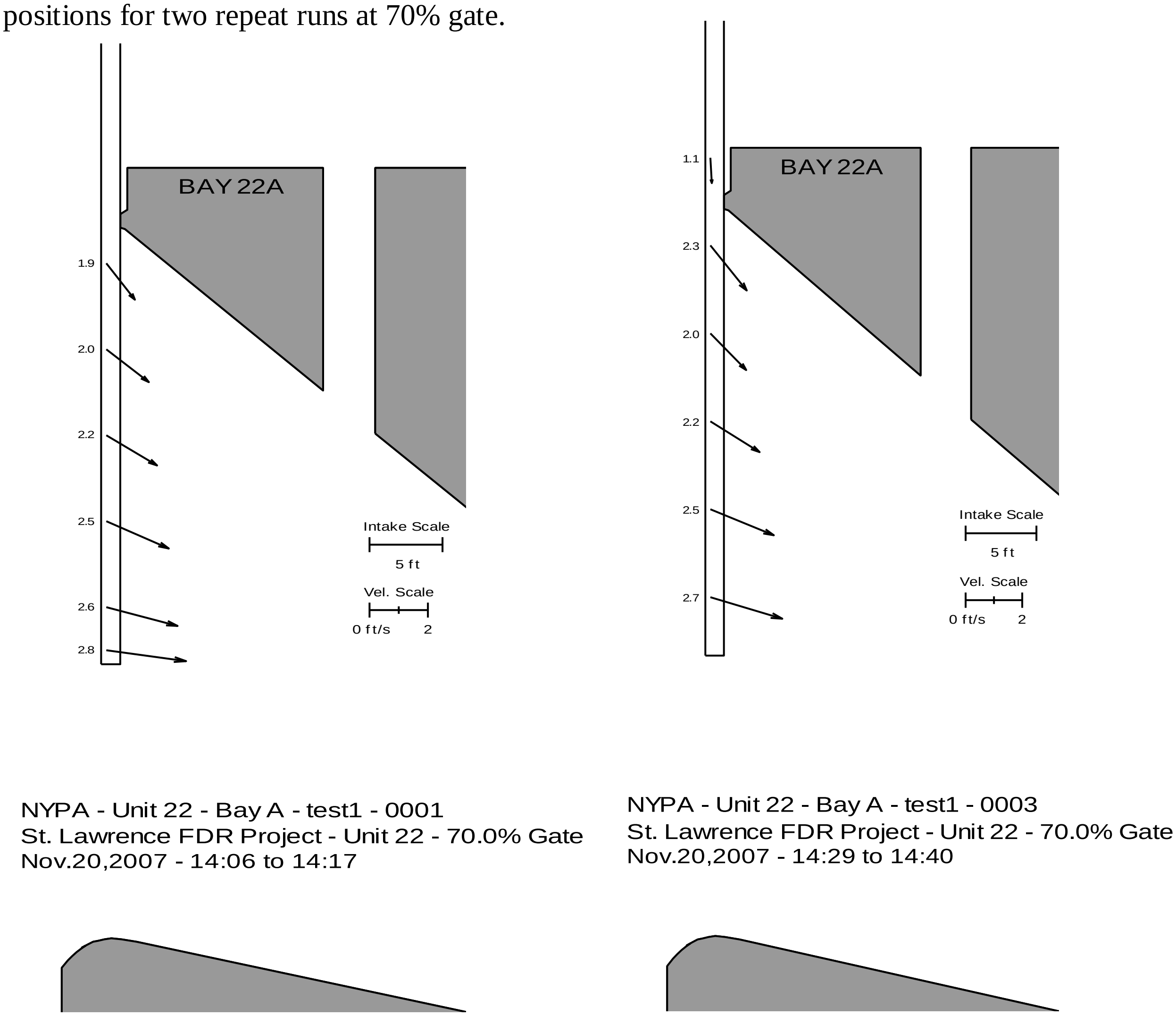

Figure 2: Sample velocity vectors, Unit 22, Bay A, 70% gate.

The quality of the ASFM data obtained in this test (as indicated by the value of the correlation scores between the data from the array elements) was much lower than normally observed. In the majority of cases the data, despite the low quality, produced velocities plausible for the flow condition and the position in the intake. Direct verification against the current meter results was not possible, however, because of the uncertainty produced by the different locations in the intake. The low data quality was likely the result of the level of refractive-index turbulence (as indicated by the variance of the acoustic amplitude signal) being much lower than usual. The low turbulence levels were caused by the absence of trash racks upstream of the measurement section, combined with a low ambient level of turbulence in the reservoir. In other plants, with trash racks in place upstream of the measurement section, the amplitude fluctuations relative to the mean signal amplitude are 5 to 10 times greater than those observed in Unit 22.

However, data collected at another low-head at plant in Europe did not support that conclusion. That plant was also operated without trash racks, but the data quality indicators were at nearly normal levels, despite a similarly low level of turbulence as indicated by the variance of the acoustic signal. The European plant had flow velocities and intake dimensions similar to those at St. Lawrence, but the measurement section was in a stop-log slot inside the intake, rather than at the entrance as used at St. Lawrence. The level of turbulence was low at both plants, in fact slightly lower at the European plant, but the correlation among the signals on the path elements was greater at the European plan, yielding better results. It was possible, therefore, that the low data quality at St. Lawrence was due not only to the low turbulence present, but possibly to the position of the measurement section at the very front of the intake. If there were significant along-path flow components there, they could have reduced the correlation between element signals, given the low turbulence level. That suggested that better results might be obtained at St. Lawrence by moving the measurement section further downstream to the stop-log slot used by the current meters. Rather than continue with the 2007 tests, the 2008 tests were planned to test that hypothesis.

2008 Testing Program

A single path ASFM system was installed in the stop-log slot of Bay A in Unit 27 in December 2008. Figure 3 shows a schematic diagram of the components of the ASFM system as used for this test. The ASFM was mounted on a moveable current meter frame provided by Hydro Power Performance Engineering Inc., responsible for the current meter measurements. The frame was equipped with extension plates and spacers for the ASFM transducers to allow simultaneous data collection. Figure 4 shows the frame after installation of the ASFM and current meters.

Flow measurements were collected at a single level near the roof at roughly 73% gate while the current meters were being checked. Two flow profiles were then collected; the first at 70% gate at 20 levels and the second at 100% gate and 10 levels. Each level was sampled for 120 seconds at 70% gate and 90 seconds at 100% gate. Table 1 summarizes the data collection sequences.

The current meter tests used more than the IEC code suggested number of current meters and measuring elevations. In each of the three bays, 11 current meters were set on frames that were lowered simultaneously to each of the measurement elevations.

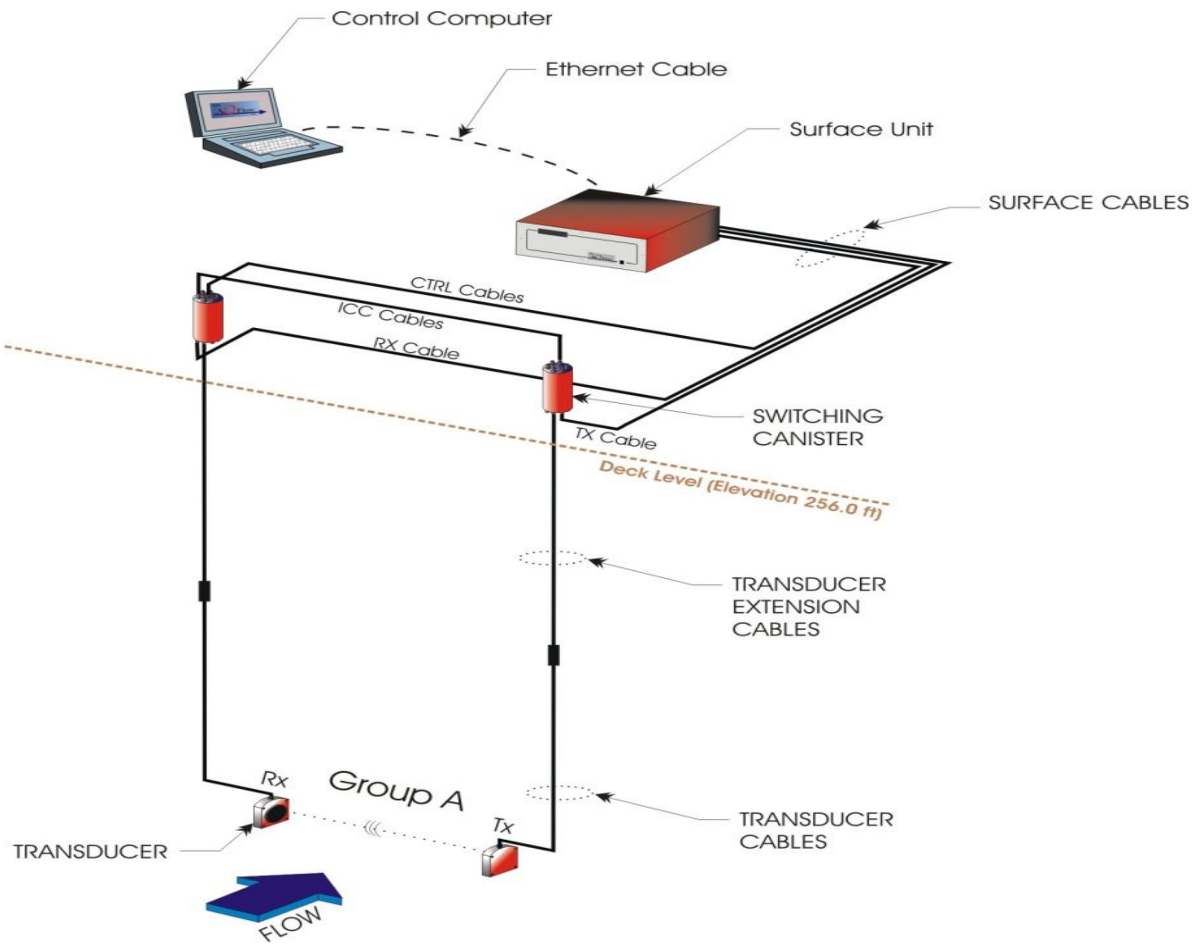

Figure 3: Components of the single-bay, 1-path ASFM Test System.

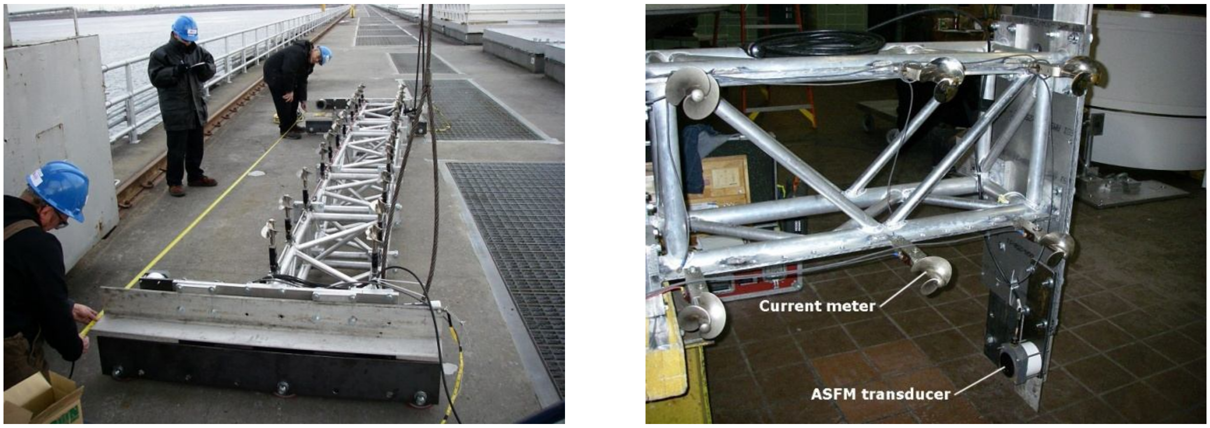

Figure 4: Current meter support frame with ASFM transducer array mounts.

Table 1: Schedule of data collection, 2008.

Condition	Name	Date	Start Time	End Time	Unit 27 Gate	Comment
1	Test at 53 ft	12-4-08	10:48	11:08	73%	Single Pt Time Series
1	Test at 53 ft Repeat 1	12-4-08	11:16	11:36	73%	Single Pt Time Series
1	Test at 53 ft Repeat 2	12-4-08	11:45	12:04	73%	Single Pt Time Series
2	Run at 70% Gate	12-4-08	12:44	14:05	70%	20 Path Profile
3	Run at 100% Gate	12-4-08	14:25	14:58	100%	10 Path Profile

Results – 2008 Program

In the time since the 2008 data were collected, a number of revisions have been made to the ASFM data processing algorithms to improve their performance under poor hydraulic conditions (Lemon, Topham & Billenness, 2010). The 2008 data have been re-analyzed with the current version of the processing algorithms, and all the results presented here are from that re-analysis. The velocity data for the two profiles collected are shown graphically on sections of the intake on Figures 5a and 5b. The base of each vector is located at the position in the intake where the measurement was made. The length of the vector gives the magnitude of the velocity, scaled by the legend in the diagram, and its direction shows the inclination. The notations at the top of the figure detail the conditions under which the data were collected.

Computing the discharge, for both the current meters and the acoustic scintillation data, requires an estimation of the flow in the boundary regions next to the floor and the roof, since neither method can measure right to the boundary. In both cases, the following forms were used:

For the floor region, a curve of the form:

$$\left[\frac{z}{T}\right]^{\frac{1}{X}} \qquad \ldots\ldots \; (1)$$

was fitted for the measured profiles between the floor (z = 0.0 m) and the boundary thickness (T = 0.3 m) using a curve with the form X = 7.

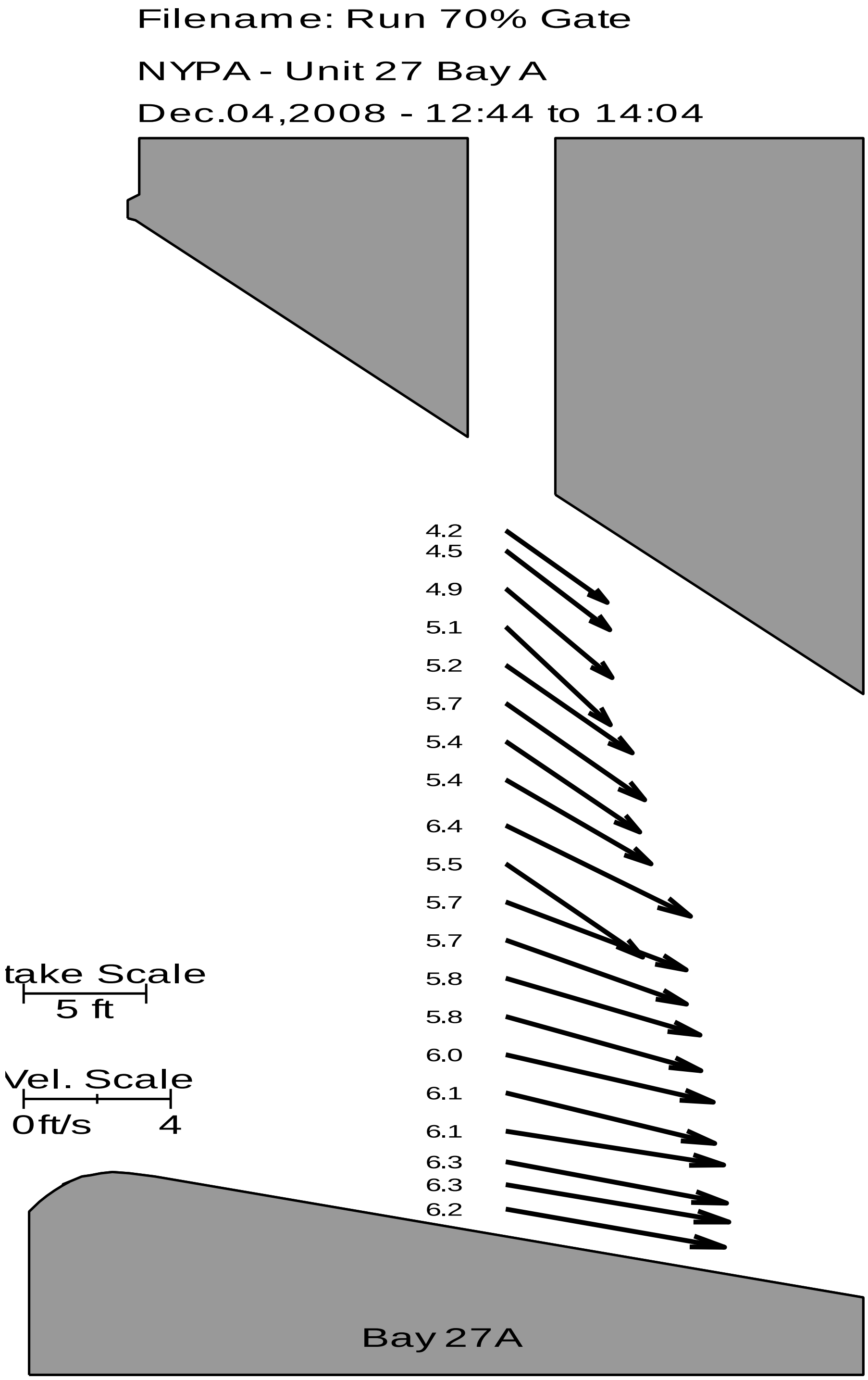

Figure 5a: Velocity vectors from ASFM measurements, 70% gate.

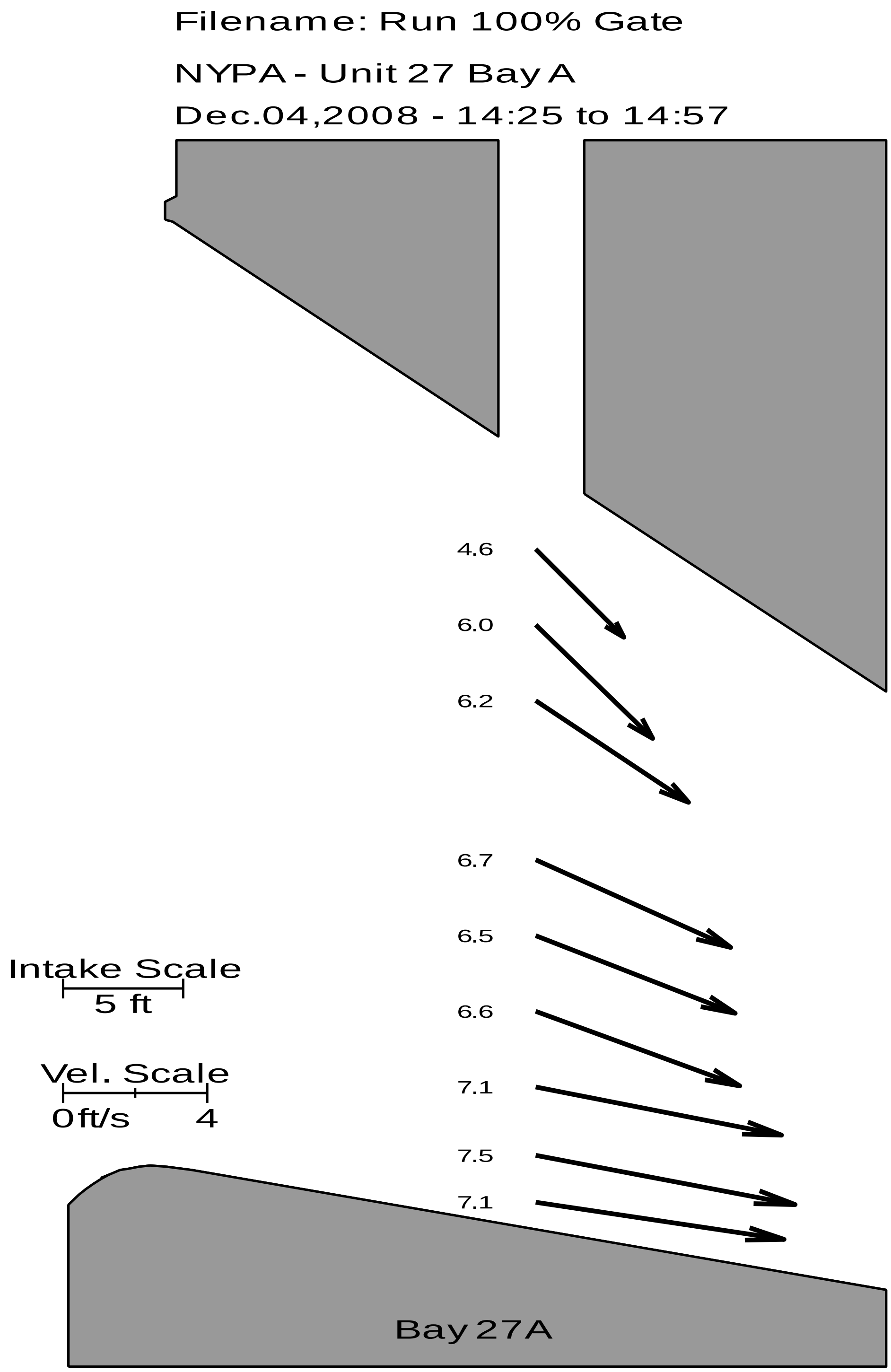

Figure 5b: Velocity vectors from ASFM measurements, 100% gate.

For the roof region, a curve of the form:

$$\left[\frac{z_r - z}{T}\right]^{\frac{1}{X}} \quad \ldots\ldots\ (2)$$

was used between z_r-z = 0.3 m (T = 0.3 m) and the roof (z_r = 15.53 m) using a curve with the form X = 7. A linear extrapolation was used between the top and bottom measurement points and the boundary thickness. The resulting discharges are shown in Table 2 below.

Table 2: Discharge results from both measurement methods

Wicket Gate Opening	ASFM Flow (cfs)	Current Meter Flow (cfs)	Difference (%) $(Q_{ASFM}-Q_{CM})/Q_{CM}$
70%	3797	3942	-3.7%
100%	4494	4687	-4.1%

Comparative plots of the horizontal component of velocity for both 70% and 100% gate settings are shown in Figure 6. Figure 6 shows that the horizontal components of the velocity measured by the two methods agree near the roof and floor of the intake, but the acoustic scintillation results are lower in the centre portion, accounting for the difference in the discharges. The centre region is where the quality of the ASFM data is lowest, and is also the zone where the refractive-index turbulence is lowest. Figure 7 shows the variance of the acoustic signal recorded by the ASFM (a measure of the refractive index turbulence intensity) and the difference in discharge between the ASFM and the current meters. As may be seen, the regions of lowest refractive-index turbulence correspond with the greatest discrepancy between the ASFM and current meter velocities.

Model Tests and Field Tests with Current Meters

As noted, a program to replace the two types of units at the New York Power Authority's St. Lawrence Project began in 2000. Model tests and field tests were conducted for both of the new designs. The results of these tests are reported in previous literature, and show acceptable correlation between the prototype predictions from the model tests (Loiseau et al, 2009, St-Hilaire et al, 2004), and the field tests based on the current meter method employed (Mikhail et al, 2001). When the current meter tests were conducted, current meters were simultaneously installed in all three bays on a travelling frame. The current meters were further laboratory calibrated including drag tests with the entire support system (Mikhail et al, 2001). The uniform and stable velocity profiles, high number of current meters used, calibration process and correlations between model and field tests provide reasonable confidence that the results of the current meter tests provide a sound basis to which to compare the scintillation measurements.

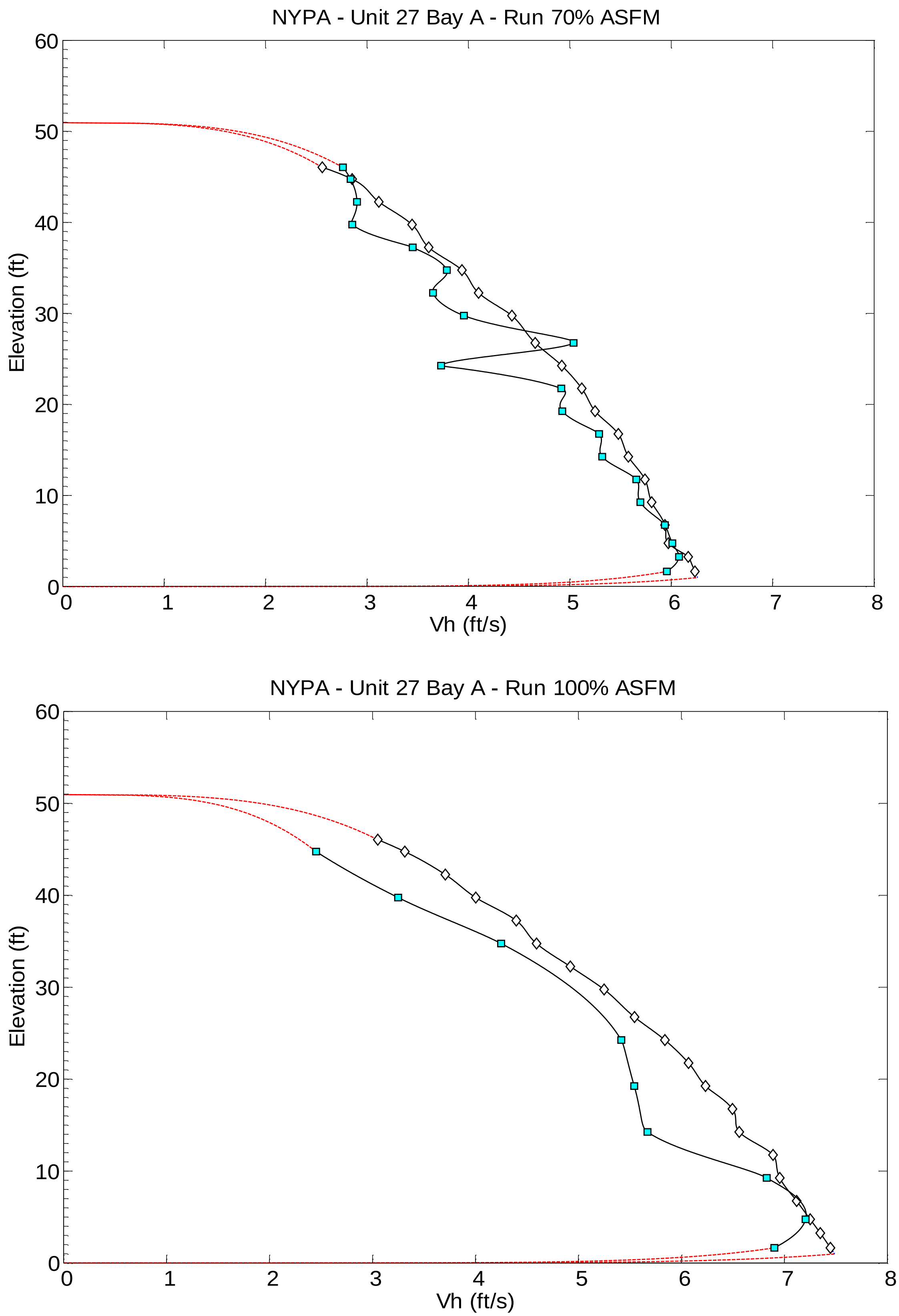

Figure 6 – Horizontal Component of Velocity – open Symbols are current meter data, filled symbols are ASFM data

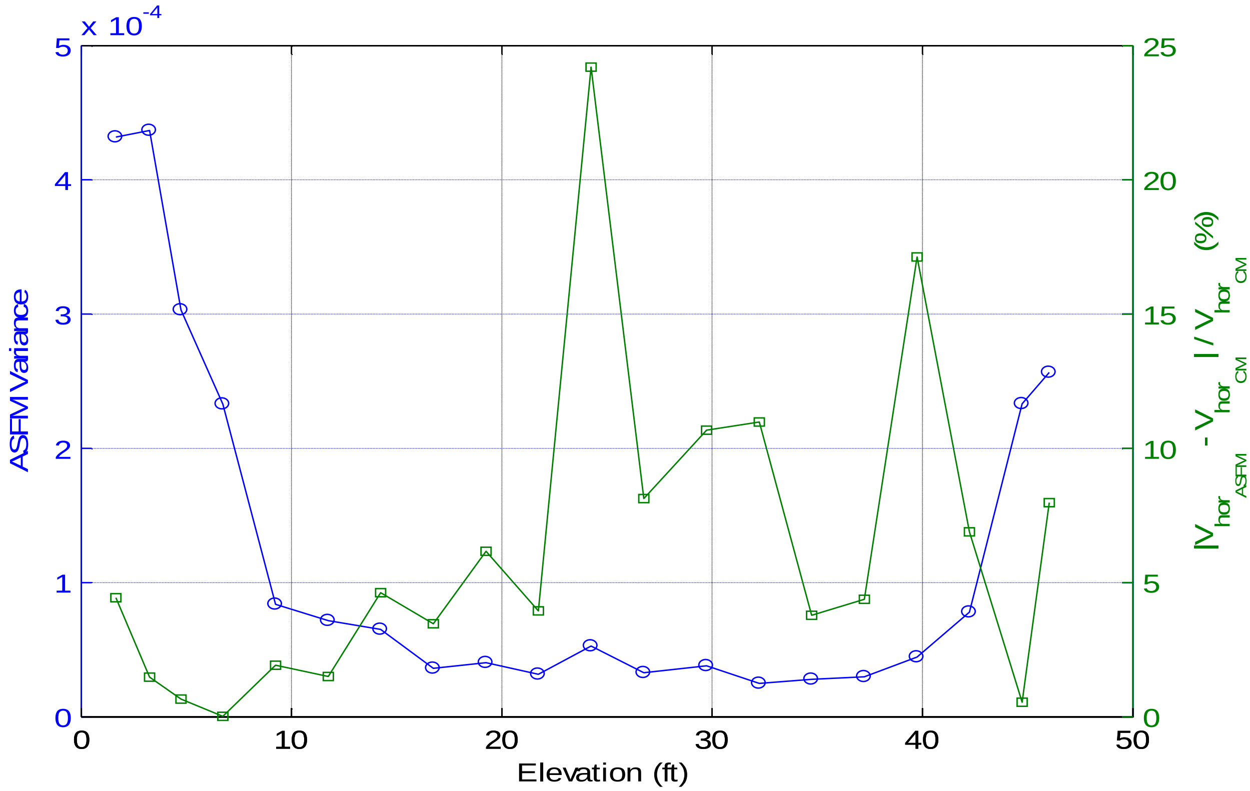

Figure 7: Variance profile at 70% gate and the fractional difference in horizontal velocity component from the ASFM and the current meters.

Conclusions

The flow and turbulence conditions were found to be more favorable for acoustic scintillation measurements made in 2008 further inside the intake at the stoplog slot than they were found to be in the 2007 tests where the sensors were located at the upstream trash rack slots. Although the turbulence levels in the center of the intake were still very low, ASFM data was collected successfully at two flow settings. Comparison with the current meter data showed that the ASFM discharge was between 3.5 and 4% lower than that measured by the current meters. The difference arose from the central portion of the intake, where the turbulence levels were 5 to 8 times lower than those observed near the roof and floor and 10 to 20 times lower than those found in similar intakes equipped with trash racks. The low turbulence levels forced the use of a less robust form of the ASFM velocity algorithm at these levels, and the resulting horizontal velocity components were approximately 10 % lower than those measured by the current meters.

Previous work on the correlation of the results of current meter tests and prototype predictions from the model tests, plus the general correspondence of output, head and gate expected from the model tests, suggests that the current meter tests provide a good indicator of actual unit flows.

It is therefore concluded that the lower velocities and flow rates measured by the ASFM system are in this case attributable to the low turbulence levels in the flows at this project. Since the effects of such low turbulence levels had not previously been identified at other projects, this was an unexpected finding and provides a reminder that the applicability of a test method for a particular site must be reviewed as part of the test development process.

Acknowledgements

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References

Clifford, S. F. and D. M. Farmer, 1983. Ocean Flow Measurements Using Acoustic Scintillation. J. Acoust. Soc. Amer., 74 (6), 1826-1832.

Lemon, D. D., C. W. Almquist, W. W. Cartier, 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, July, 1998.

Lemon, D. D., D. R. Topham and D. Billenness, 2010. Improvements to the accuracy of discharge measurements by acoustic scintillation resulting from revisions to data processing procedures. International Group for Hydraulic Efficiency Measurements, 8th International Conference, Roorkee, India, October 2010

Loiseau, F., P. Ludewig, M. Sabourin and F. Paquet, Rehabilitation of Propeller Turbines, the Example of St. Lawrence – FDR Project. Proc. Waterpower XVI, Spokane, Washington, July 2009.

Mikhail, A. and R. Knowlton, Performance Testing of the St. Lawrence Power Project using Current Meters, Proceedings of the Waterpower XII conference, Salt Lake City, 2001.

Mikhail, A. and R. Knowlton and R. Metcalfe, Intake Current Meter Calibration Program and Results, Proceedings of the Waterpower XII conference, Salt Lake City, 2001

St-Hilaire, A., P. Ludewig, F. Loiseau, J. Tadel, L. Bornard, M. Sabourin, Performance of the St.-Lawrence Rehabilitated Turbines – Step-up from Model to Prototype, Proc. HydroVision, Montreal, Quebec, 2004.

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