Comparison of Turbine Discharge Measured by Current Meters and Acoustic Scintillation Flow Meter at Fort Patrick Henry Power Plant

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ABSTRACT

Performance tests were conducted on Unit 1 at the Tennessee Valley Authority's Fort Patrick Henry Plant on September 24 – 25, 1997. These tests included measurements of the discharge through the turbine using current meters and the Acoustic Scintillation Flowmeter (ASFM). Fort Patrick Henry is a low-head, short intake plant typical of the type for which current meters have been the traditional and only effective method for measuring discharge. Unit 1 is rated at 21 megawatts and is equipped with a Kaplan turbine. The intake to the turbine consists of two bays, each 21.65 ft high and 17.67 ft wide. The net head for the plant is approximately 65 ft. Measurements of the discharge through the turbine were made at two power levels: the Most Efficient Load (MEL) and the Maximum Sustainable Load (MSL). The ASFM is a new instrument which offers some unique advantages for measuring intake flows in plants of this type. It is non-intrusive, and its deployment in intake gate slots is straightforward, allowing data to be collected with a minimum of plant down-time. The measurements described here were taken to assess the ASFM's accuracy under operational conditions. Flow measurements at the same unit settings were made using current meters operated by the Norris Engineering Laboratory, for comparison with the ASFM results. The ASFM and current meter measurements were made sequentially. Immediately following data collection discharges were computed independently and then compared. These results for both techniques agreed to within 1%, after correction for small head differences between the measurements.

Introduction

Acoustic scintillation drift is a technique for measuring flows in a turbulent medium, such as water or air, by analyzing the variations (with position and time) of sound which has passed through it. Scintillation in this context refers to random variations in the intensity of the sound caused by the variations in the refractive index of the water produced by the turbulence which is always present in any natural flow. The ASFM measures the speed of the current from the transverse drift of the acoustic scintillations observed across two relatively closely-spaced propagation paths. The method has been used for many years to measure winds in the atmosphere and ionosphere (Ishimaru, 1978; Lawrence, Ochs & Clifford, 1972; Wang, Ochs & Lawrence, 1981), more recently for measuring currents and turbulence in ocean channels (Clifford & Farmer, 1983; Farmer & Clifford, 1986; Farmer, Clifford & Verrall, 1987; Lemon & Farmer, 1990) and in hydroelectric plants (Birch & Lemon, 1993; Lemon, 1995; Lemon & Bell, 1996); its derivation is well-established.

The ASFM measures the lateral (i.e. along-path) average of the component of the flow perpendicular to the acoustic path. It is therefore well-suited for collecting data for discharge measurements, since the product of the path length with the lateral average of the normal component of flow gives the element of discharge at the depth of the path. Sampling at several levels in the vertical and integrating then gives the discharge.

Application in Hydroelectric Plants

Measurement of the discharge for a turbine requires that a location in the intake be chosen as the measurement plane, and a number of sampling paths be established across it. The transducers can either be fixed to the intake walls, for a permanent installation, or attached to a frame deployed into a gate slot, if one is available. Using a frame in a gate slot allows the ASFM to be moved from one unit to another relatively quickly and easily, if the slots are all the same size. The number of paths required to sample in the vertical is achieved either by placing transducers at every desired height on the frame, or by using fewer transducers and moving the frame to the required elevations. In either case, the discharge is computed by integrating the horizontal component of the laterally-averaged velocity over the height of the intake.

The ASFM measurements at Fort Patrick Henry were planned to coincide with discharge measurements using current meters, to be carried out by the Norris Engineering Laboratory after installation of an upgraded turbine in Unit 1. Discharge would thus be measured by both methods, under the same circumstances, which would afford an opportunity to make a direct comparison of the two, and assess the accuracy of the ASFM in measuring discharge under operational conditions. Measurements of the discharge were planned for two operating points, and were to be made sequentially by the two methods, as the same support frame was to be used by the current meters and the ASFM, in order to keep the measurement conditions as close as practically possible to being identical.

Fort Patrick Henry is a 40MW low head plant equipped with two Kaplan turbines. Each turbine is configured with a two-bay intake and a single gate slot for each bay. Unit 1 has two rectangular intake bays, each 21.65 feet high and 17.67 feet wide. The unit operates at a net head of approximately 65 feet with a maximum rated output of 21 MW. The distance from the deck to the bottom of the gate slot is 76 feet.

Measurements

Discharge measurements were planned for two test points: 1 (MEL: Most Efficient Load) and 2 (MSL: Maximum Sustainable Load), corresponding to the expected maximum efficiency and maximum power output, respectively. Data were first collected with the current meters at test point 1. The meters were then removed, the ASFM transducers were mounted and data was collected by the ASFM system at test points 1 and 2. The ASFM transducers were then removed and replaced with current meters for measurement at test point 2. The current meter data for test point 1 were collected September 24; all the remaining data were collected September 25.

ASFM Data Collection

The components of the ASFM are shown in Figure 1. The instrument was set up with one pair of transducers for each intake bay, mounted on the same frames used for the current meters. Cables from the transducers ran to a transmitter canister and receiver/switching canister, mounted on the deck between the two gate slots. A set of surface cables connected the canisters to the data acquisition and control module, set up under a protective cover on the deck.

Measurements were taken at 13 separate elevations in each intake bay (Table 1). The frames were first lowered to level 1, and held there. Flow data were collected for 120 seconds in Bay 1, then for 120 seconds in Bay 2. The frames were then lowered to level 2 and the process was repeated down to, and including, level 13.

Table 1: Measurement Levels

Level	Elevation (ft)	Level	Elevation (ft)	Level	Elevation (ft)
Roof	53.92	5	59.77	10	71.95
1	54.25	6	62.24	11	73.66
2	54.61	7	64.74	12	74.86
3	55.81	8	67.23	13	75.27
4	57.54	9	69.70	Floor	75.60

Current Meter Data Collection

The principle of current meter-based flow determination is to measure the flow velocities at a number of points across a section of the intake, and then to numerically integrate these point flow velocities over the intake area to determine the total flow. The current meters used in these tests are horizontal-axis propeller meters which are specially designed to respond only to the horizontal component of the flow velocity vector. The flow velocity at a given current meter location is determined by counting the number of revolutions of the propeller over a fixed period of time, and then applying calibration curves to convert the average rotational speed to velocity. At Fort Patrick Henry, the current meters were mounted in a horizontal line on the same two frames (one for each intake bay) as were used for the ASFM measurements. Eight current meters were mounted on each frame, arranged so that the spacing between the current meters was closer near the wall and further apart near the center of the frame. Full coverage of the intake was achieved by successively lowering the frame to each of the thirteen vertical elevations given in Table 1. At each vertical location, the revolutions of the current meter propellers were counted for a period of three minutes using automatic data acquisition, and the average velocity at each current metering point was determined from these counts. More detail on the current metering method can be found in the IEC test code for hydraulic turbines (IEC, 1991) and the ISO code for current meter flow measurement (ISO, 1988).

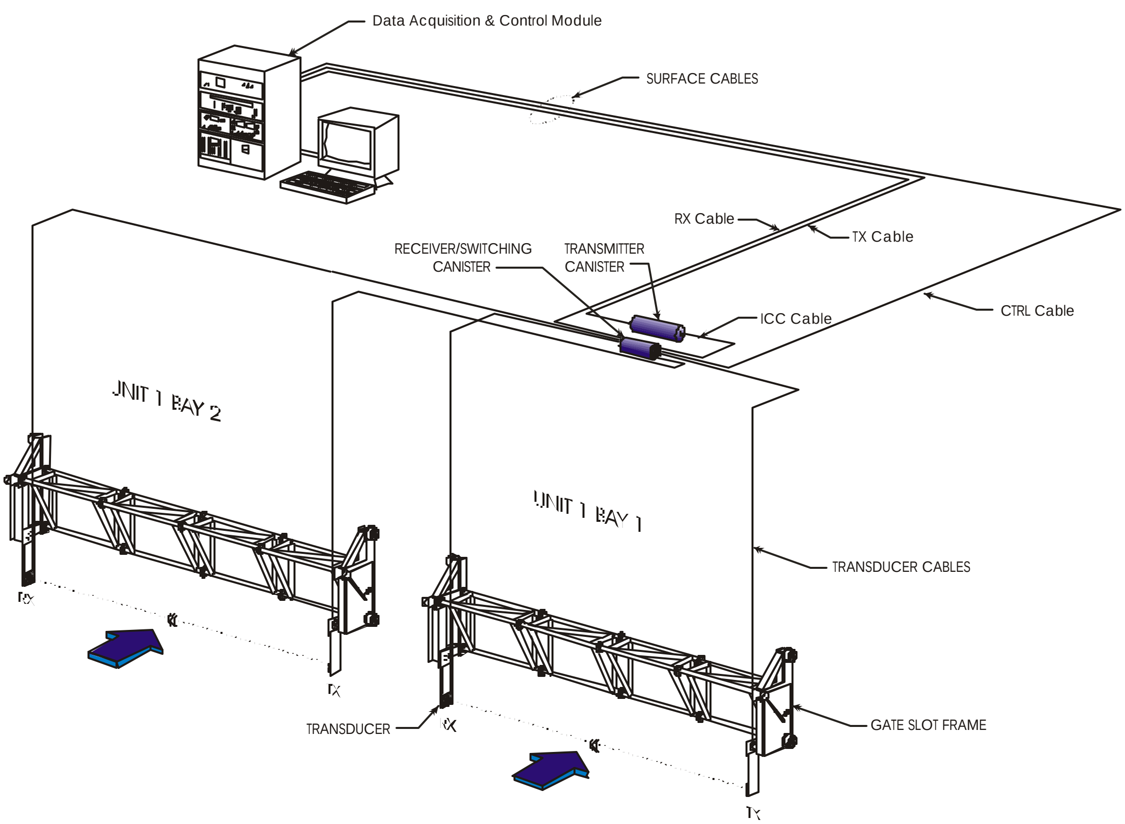

Figure 1: Major ASFM system components.

Results

ASFM Velocity Distribution

The ASFM measured a laterally-averaged value of the flow speed and inclination for each of the frame positions in each intake. That value is also an average over the sampling time at each frame level, which in this case was 120 seconds. They are shown graphically in Figure 2 as scaled vectors on a cross-sectional view of the intake. The number at the base of each arrow is the flow speed in feet/second. The sharp variation in the velocity of the flow in the lower five feet of the intake is likely due to a partial blockage of the trash rack.

Discharge Computation: ASFM

The roof and floor of the intake tunnel, and the path followed by the sides of the frame holding the ASFM transducers define a plane surface, *S*, through which the flow into the intake bay must pass.

If *z* is the vertical coordinate, then the discharge, *Q*, in terms of the laterally-averaged velocity **v** is:

$$Q = \int_0^H v(z) \cos[q(z)] L \, dz \qquad (1)$$

where $v(z)$ is the magnitude of the laterally averaged flow at elevation *z*, $q(z)$ is the

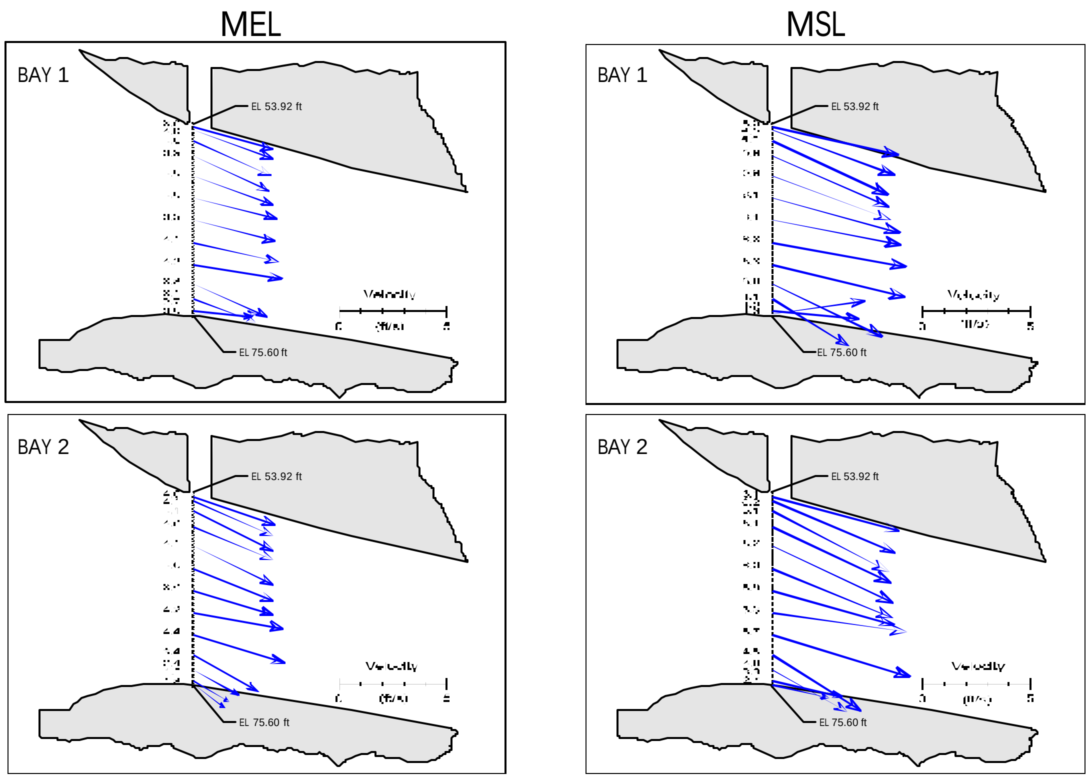

Figure 2: Laterally-averaged ASFM velocity vectors.

corresponding inclination angle, *L* is the width between the transducer faces (17.58 feet for Bay 1; 17.60 feet for Bay 2) and *H* is the height of the tunnel roof above the floor. The lateral averaging performed by the ASFM is continuous, while the sampling in the vertical was at thirteen discrete points. Calculating *Q* then requires estimation of the integral in equation 1 when the integrand is known at a finite number of points. The integral was evaluated numerically using an adaptive Romberg integration, with a cubic spline interpolation in the integrand between the measured points. The horizontal component of the velocity is forced to zero at the floor of the tunnel, along a boundary layer curve of the form:

$$[z/z_0]^{1/n} \qquad (2)$$

between the floor and the first measured point, z_0, where n takes a value between 7 and 10, depending on the thickness of the boundary layer expected above the tunnel floor. Because of the proximity of the entrance, n was set to 10. At the roof, because of the open boundary at the gate slot, the horizontal component of the velocity was not forced to zero, but was extrapolated to the roof elevation H along the cubic spline fitted to the measured points with the second derivative forced to zero at the endpoint.

Figure 3 shows the horizontal component of velocity, v_h, for both intake bays for both conditions 1 and 2. The boundary layer assumption at the floor is shown as a dotted line.

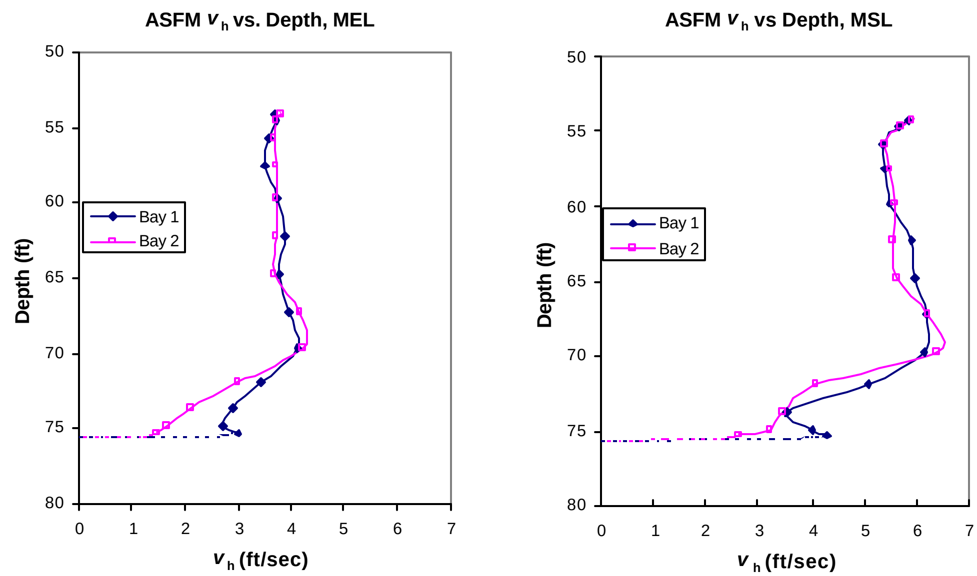

Figure 3: Horizontal component of velocity vs. depth measured by the ASFM. The dotted lines show the assumed boundary layer.

The area between each of these curves and the depth axis is the discharge for the corresponding bay and condition. Because the current meter and ASFM measurements were taken sequentially, rather than simultaneously, corrections for head differences between the measurement times had to be applied before comparing the results of the two methods. The head differences measured by the TVA test team resulted in correction factors of 0.99870 and 0.99751 for the MEL and MSL measurements, respectively, to be applied to the ASFM discharge values. Table 2 lists the discharges (before and after correcting for head differences) measured by the ASFM in each bay as well as the total for both operation conditions.

Table 2: ASFM Discharges

	MEL	MEL	MSL	MSL
	Q_{ASFM} (cfs)	Q_{ASFM}, scaled (cfs)	Q_{ASFM} (cfs)	Q_{ASFM}, scaled (cfs)
Bay 1	1393.6	1391.8	2089.8	2084.6
Bay 2	1345.2	1343.5	2025.5	2020.4
Total	2738.8	2735.3	4115.3	4105.0

Discharge Computation: Current Meters

The basic equation for computation of the flow from the point velocities measured in an intake bay is

$$Q = \int_0^H \int_0^L v_h(y,z)\,dy\,dz \qquad (3)$$

where $v_h(y,z)$ is the horizontal component of the flow velocity at horizontal location y and vertical location z, and L and H are the width and height of the intake bay at the current metering location. This is very similar to Equation 1 for integration of the ASFM data, except that an explicit integration of the data along the horizontal is required.

Equation 3 is evaluated numerically using a cubic spline integration technique described in detail in the ISO standard for current meter measurements (ISO, 1988). At the boundaries of the flow section, the boundary layer follows the equation presented in Equation 2. In addition, a small correction factor is included to account for the blockage effect of the current meter frame on the flow, which causes a slight increase in velocity at the current metering section (ISO, 1988).

Comparison of Discharge Results

The current meters recorded only the horizontal component of the velocity. Figure 4 shows the vertical profiles of the horizontal component of the laterally-averaged velocity measured by both methods for the MEL and MSL runs. The small differences between the profiles measured by

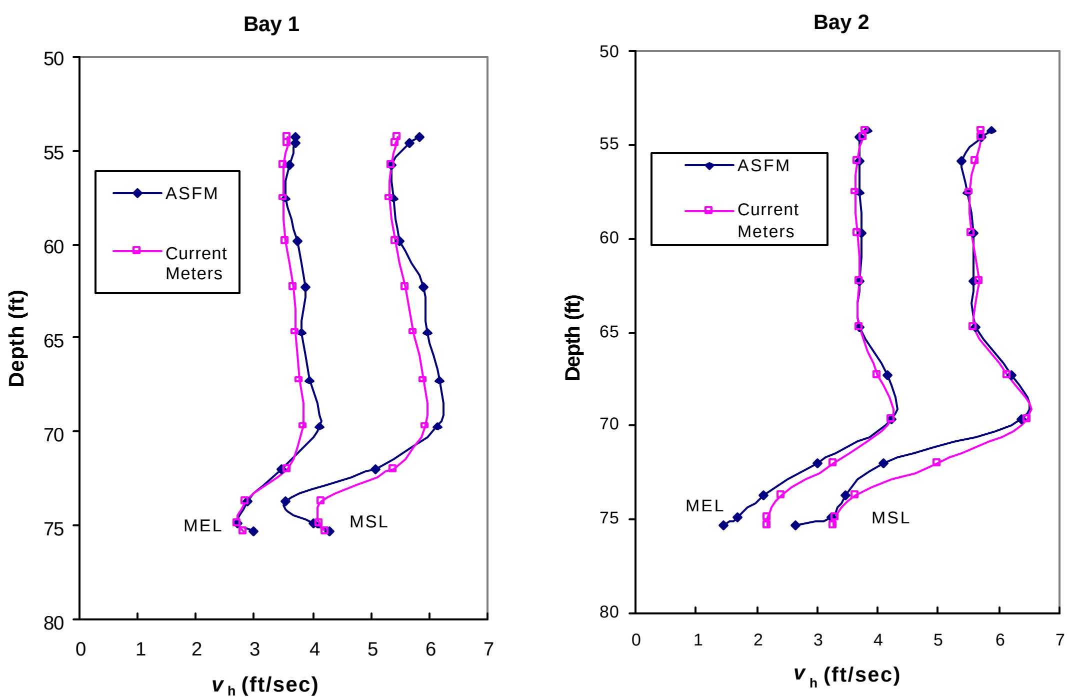

Figure 4: Comparison profiles of horizontal velocity, ASFM and current meters, both conditions.

the two methods are at least partly due to changes in the flow distribution which took place during the interval between the two measurements. No correction has been made in these plots for the changes in head which were applied to the discharge comparisons.

Figure 5 shows the discharge measured by the ASFM plotted against the discharge measured by the current meters, for the individual bays and the total, for both conditions. The error bars shown on the points are ± 1% for both quantities. The dotted line is the line of perfect agreement; the solid line is the least-squares regression of the ASFM discharge on the current meter values. The slope is 0.9947, with an R^2 coefficient of 0.9988. The least squares line represents overall agreement between the discharges, over the measurement range, to within 0.5%. The largest single difference in total discharge is for the MSL case, where the difference is 1.0%. Those measurements were made consecutively, and some of the difference may be caused by real variations in the flow conditions.

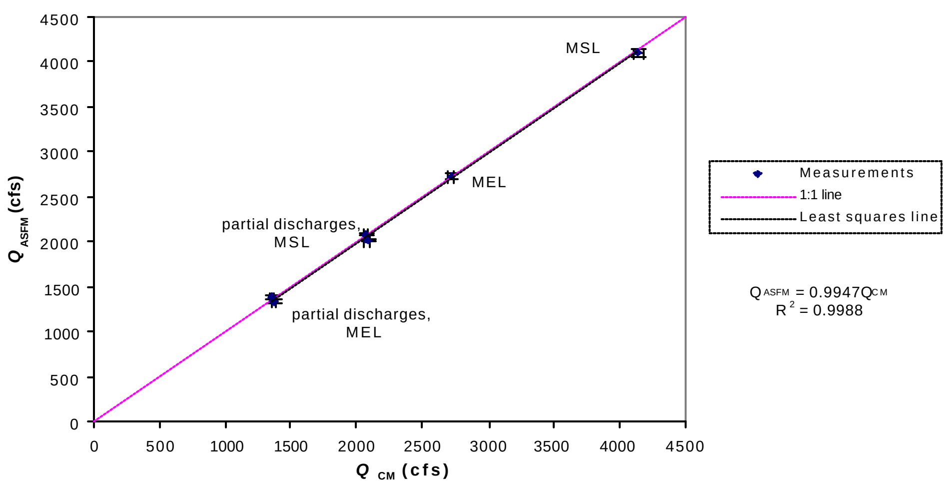

Figure 5: Discharge comparison, ASFM vs. current meters (by TVA method).

The laterally-averaged current meter velocities were then integrated using the same algorithm used for the ASFM data, to investigate the dependence of the discharge on the integration method. The results are listed in Table 3.

Table 3: ASFM and Current Meter Discharge (Meters by ASL Integration)

	MEL	MEL	MSL	MSL
	Q_{CM} (cfs)	Q_{ASFM}, scaled (cfs)	Q_{CM} (cfs)	Q_{ASFM}, scaled (cfs)
Bay 1	1347.5	1391.8	2060.2	2084.6
Bay 2	1360.0	1343.4	2071.9	2020.4
Total	2707.5	2735.3	4132.1	4105.0

In this case, the least squares fit line has a slope of 0.998, and an R^2 of 0.9985. The overall agreement as represented by the slope of the line has improved slightly to 0.2%, and the largest difference in total discharge remains at 1%, but for the MEL case rather than the MSL case. In both instances, the individual bay discharges differ by larger amounts, up to 3%, however the differences in the two bays are always of opposing sign, so that the difference in the total discharge is always 1% or less. That suggests that the discharge differences in individual bays are likely due to small changes in the flow distribution between the bays in the time between the two measurement runs, while the total discharge remained relatively unchanged.

Conclusions

Flow rate measurements were performed at TVA's Fort Patrick Henry plant using a traditional current metering method and using the relatively new acoustic scintillation technique. Each method was used to measure the flow at two different power outputs. The flow measurements were made in succession, with care being taken to keep the unit discharge constant between tests.

Both sets of measuring equipment were mounted on a moving frame installed in the intake gate slot which traversed the flow from top to bottom at 13 discrete elevations. The flow into the intake possessed a significant vertical component, so that the ability of each method to resolve the horizontal component required for the discharge computations was crucial.

Comparison of flow rate results showed good agreement between the two methods, demonstrating that the ASFM has the accuracy required to measure turbine discharge under operational conditions. Depending on the numerical integration procedure used, the overall agreement between the two methods ranged from 0.2% to 0.5%. The largest single difference in the total discharge was 1.0%. Comparison of the measured vertical profiles of the horizontal velocity component showed good general agreement, although there were differences in the details of the profiles. Also, there were differences in the individual bay flow computations, although these differences tended to be opposite in sign so that the agreement in total discharges was good. These differences may have been due to actual variability in the flow distributions over the two days that the tests were conducted, but there is no way to confirm this from the available data.

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