Field Trial of an ASFM Monitor at Lower Granite, December 2004 – January, 2005

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ABSTRACT

In December, 2004, an acoustic scintillation Monitor was installed and tested in one of the three intake bays of Unit 4 at Lower Granite Dam, as part of a larger index testing and flow measurement program involving a standard 20-path Acoustic Scintillation Flow Meter (ASFM Advantage), an acoustic time-of-flight system and Winter-Kennedy pressure taps. The Monitor's five acoustic paths were installed in the lower (free-stream) region of the intake passage in Bay A, downstream of the gate slot where the ASFM Advantage was installed. The Monitor was operated continuously for the duration of the testing program and for a full month afterwards, unattended and recording data internally.

The testing was performed both with and without Extended Submerged Bar Screens (ESBS) installed. In each case, the Monitor was calibrated against the ASFM Advantage during the on-cam test series. The discharges subsequently computed by the Monitor for each of the off-cam runs were recorded and compared to the discharge data collected by the ASFM Advantage. The Monitor recorded discharges within ±1.5% of the ASFM Advantage values throughout all of the off-cam runs made with ESBS in place, with the largest deviations occurring when the operation of neighbouring units differed from that in effect when the calibration runs were made. Without the ESBS in place, larger deviations, up to 5%, were observed during the off-cam runs.

Simulations of other configurations, using velocities from subsets of the ASFM Advantage paths, showed that for the Monitor to attain discharge measurement accuracy of ±1.5% or better, under most plant configurations (including ESBS in or out) and neighbouring unit operating patterns, requires installations covering the full height of the intake and a minimum of 5 paths in at least each end bay. These results are consistent with simulations carried out at other projects in the recent past, and indicate that the Monitor is capable of cost-effective, reliable long-term real-time monitoring of turbine flows in low-head intakes.

Introduction

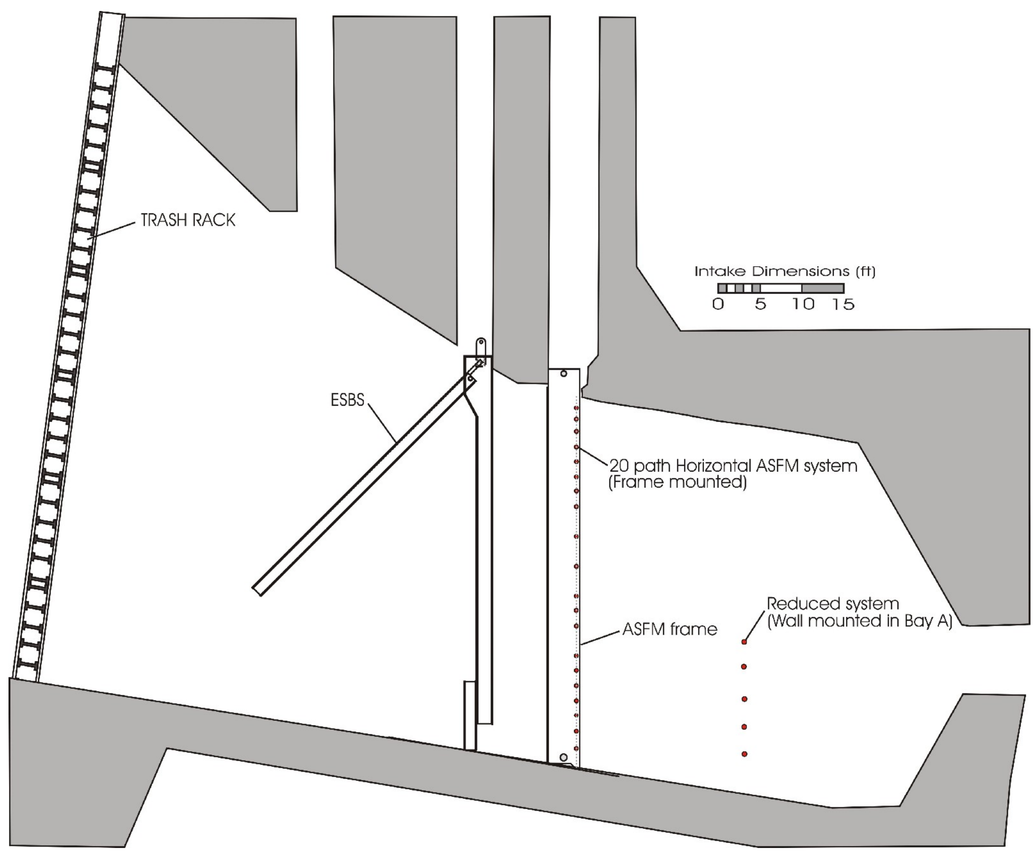
ASL Environmental Sciences Inc. (ASL) was contracted by the Portland District, US Army Corps of Engineers to install and operate a reduced-path version of the Acoustic Scintillation Flow Meter (the Monitor) at Lower Granite Dam during efficiency testing of Unit 4 in December 2004. Intake flow measurements for the testing program were made using three simultaneous methods: acoustic scintillation, using an ASFM Advantage, a time of travel acoustic flowmeter and Winter-Kennedy pressure taps [**1**]. The purpose of the Monitor measurements was to test the conclusions reached in [**2**] by the Hydroelectric Design Center (HDC), that relative flow data could be obtained with a greatly reduced number of acoustic paths compared to the number used in a standard ASFM Advantage. At the same time, it was also possible to test the hypothesis put forward in [**3**], that by calibrating the Monitor output with data from a reference discharge measurement, accurate absolute discharges could be obtained from the Monitor.

The Monitor was installed in Bay A of Unit 4. The location of the sensors was specified by HDC. Five acoustic paths were installed in the lower region of the intake passage, downstream of the gate slot where the ASFM Advantage was installed. The measurements made with the ASFM Advantage are described in [**4**], where a description of the operating principles of the acoustic scintillation method may also be found. **Figure 1** shows a cross section of the intake illustrating the location of the measurement systems. The Monitor was operated throughout the entire measurement program, which was performed both with and without Extended Submerged Bar Screens (ESBS) installed. The measurements done for the two configurations were:

1. One on-cam and seven off-cam series with ESBS in place. One off-cam series was repeated with varying combinations of neighbouring unit operation.

2. One on-cam and six off-cam series with ESBS removed. Selected off-cam measurements at two blade angles were repeated with varying combinations of neighbouring units in operation.

Figure 1: A cross section of the intake showing the trash rack, ESBS and both ASFM systems.



Installation

The Monitor transducer arrays and their cabling were installed in Bay A of the intake at Unit 4 during September, 2004, while the unit was dewatered. The five paths were installed immediately upstream of the pier nose at the end of the bay, in the lower part of the intake. **Figure 2** shows the intake during the installation. The transducer arrays were bolted directly to the intake wall, and covered with a metal fairing (**Figures 3 & 4**). Cables from the arrays were attached to the intake walls, and run back to the operating gate slot, up and through an air vent into the breaker gallery. The exposed cable runs were covered with semicircular plastic pipe sections, to form a continuous conduit from the arrays to the entrance of the air vent (**Figure 5**).

The cables were terminated inside the breaker gallery until the surface equipment was installed in December, before the beginning of the tests. **Figure 6** shows the surface equipment (consisting of two switching boxes and one control unit) in place in the breaker gallery. The control unit was connected by an Ethernet cable to the computer on the generator floor, for control and data transmission during the tests. Data were also recorded internally in the control unit.

Figure 2: Interior of Bay A, Unit 4, during installation of the arrays and cabling.

Figure 3: Monitor transducer attachment and fairing.

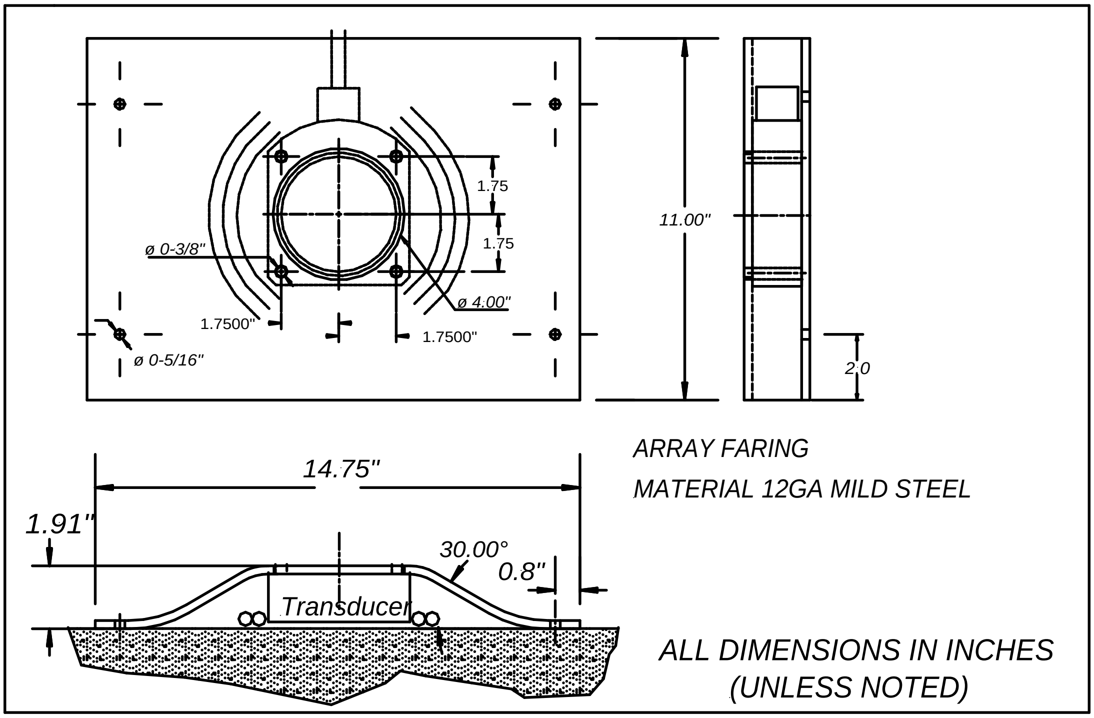


Figure 4: Monitor arrays in place on the intake wall.

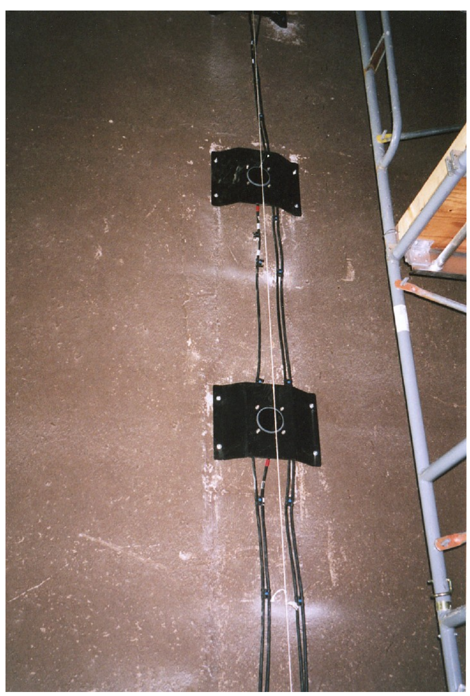


Figure 5: Monitor cable run and splice protection.

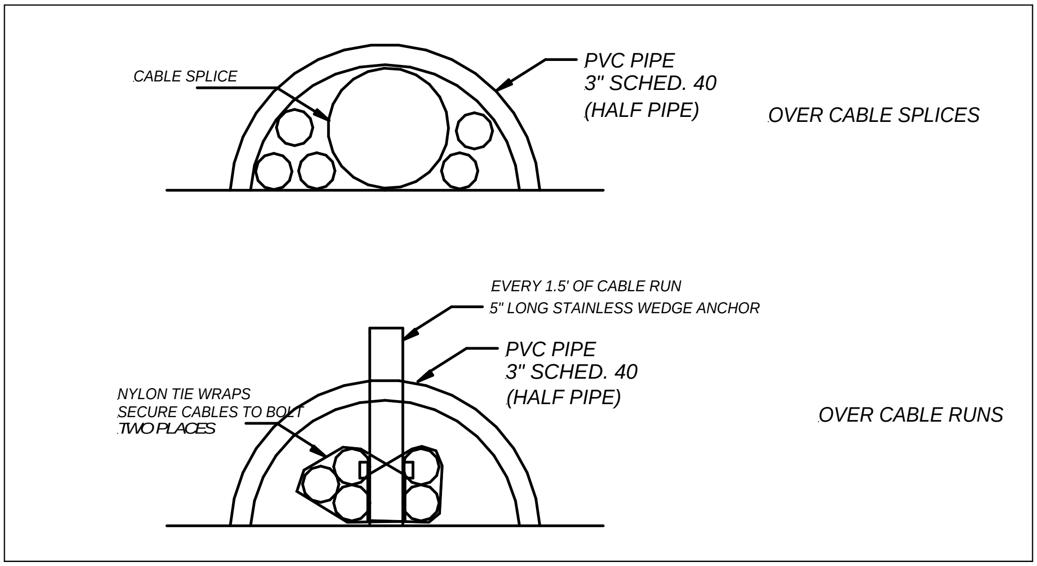


Figure 6: Monitor control unit and one switching box.

Data Collection and Results

The Monitor data collection with ESBS installed began at 10:30 December 10, simultaneously with the other flow measuring information. Previously-run mutual interference tests showed no effect on operation among all the instruments installed in Unit 4 intake. In all cases, the Monitor collected 32-second acoustic data series at each of its five levels consecutively, cycling through them continuously until the ASFM Advantage data collection was complete. Nine complete Monitor cycles were usually obtained for each flow condition during the time required for the ASFM Advantage data collection to be completed. The magnitude and inclination of the flow velocity at each level was then computed by averaging the repeats.

The Monitor control unit was equipped with ASL AQFlow's dedicated software. This software uses the velocity data to compute turbine discharge in real time, so that it can provide continuous input to a plant operation management system. An initial calibration against an absolute flow measurement instrument is required for the Monitor to produce absolute flow values; otherwise its output is relative flow only. The on-cam test sequence was used to provide the calibration, using the horizontal-path ASFM Advantage as the reference instrument. Separate calibrations were made with the ESBS in and out. An elevation-weighted average of the horizontal component of velocity at each level is computed for each of the calibration conditions. The weighting for any given level reflects the fraction of the free-velocity zone that the path represents, and is the half the sum of the distance to the paths above and below, divided by the total height of the free-velocity zone. A table is constructed to match the weighted averages to the reference discharges, and subsequently-measured weighted averages are interpolated in the table to calculate the corresponding discharge.

After the calibration tables had been constructed, the Monitor was run throughout all the subsequent off-cam tests, and the repeat test performed to assess the effect of neighbouring unit operation on the measured flow. A discharge value was computed from the elevation-averaged velocity and the calibration tables for each flow condition.

Figure 7 plots the total discharge derived from the Monitor against the discharge measured by the ASFM Advantage (horizontal path system), along with the fractional difference between them. Flow measurement accuracy of ±1.5% is usually desired for turbine performance tests [**5**]; differences between two simultaneous measurements should therefore be randomly distributed about zero and usually less than ±1.5% if they are consistent. The difference between the two discharge values remains within ±1%, except for the 12th through the 17th points, where the difference consistently exceeds –1%. Those points correspond to the runs for which Unit 6 was in operation at generation levels close to those of Unit 4. (The discharge difference for point 30 is 1.02%, and in that case Unit 2 was the only other unit operating. However, for the runs immediately before and after that, in which the operating levels of Units 4 and 2 were nearly the same, the discharge differences were 0.33% and –0.05%, respectively.)

Figure 8 shows the same quantities from the measurements made with no ESBS in place. The differences between the Monitor and ASFM Advantage discharges are much greater than they were when the ESBS were in place (nearly 5% in some cases). The Monitor discharge consistently exceeds the ASFM Advantage value, except for the 4 conditions at blade angle 30 (points 21 – 24) and six of the repeat runs at 19.75 blade angle (points 25 – 35) made during the neighbouring unit load variation tests. With one exception (Unit 2 operating at 129 MW and Unit 6 at 120 MW) those conditions were the only ones for which no other units in the plant were operating. During the calibration run, Unit 6 was always in operation, and units 2 and 3 were operating for the first three flow conditions.

Figure 7: Discharge from Monitor and ASFM, ESBS In, Unit 4.

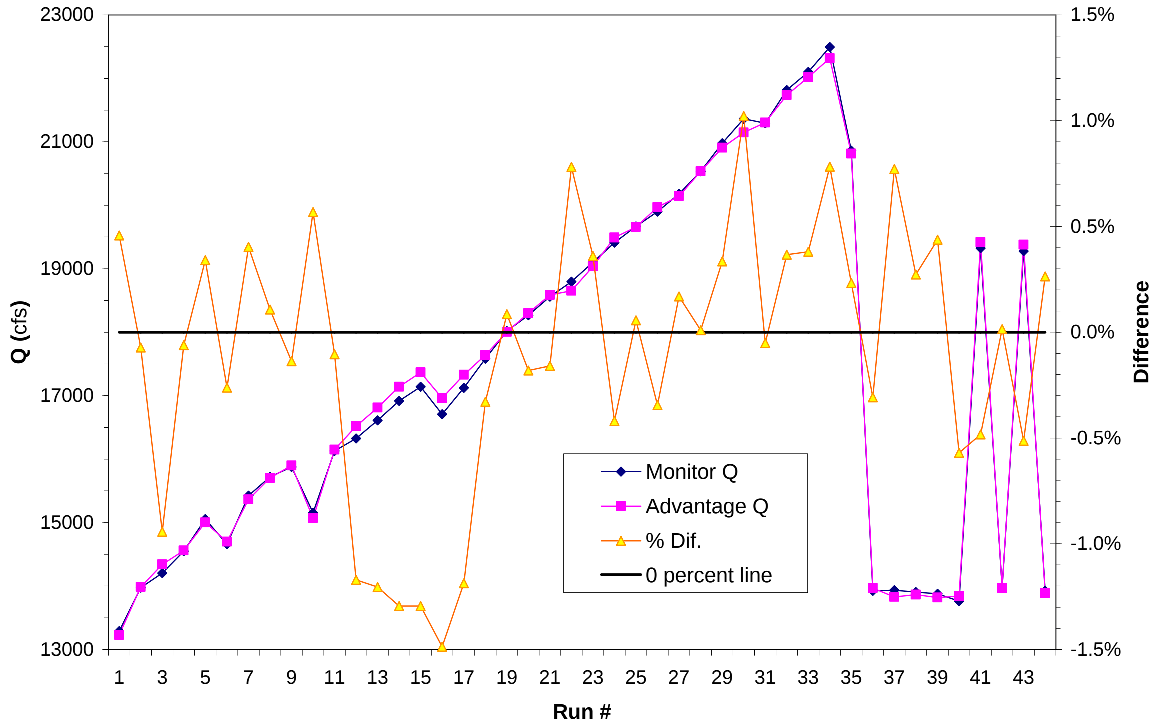
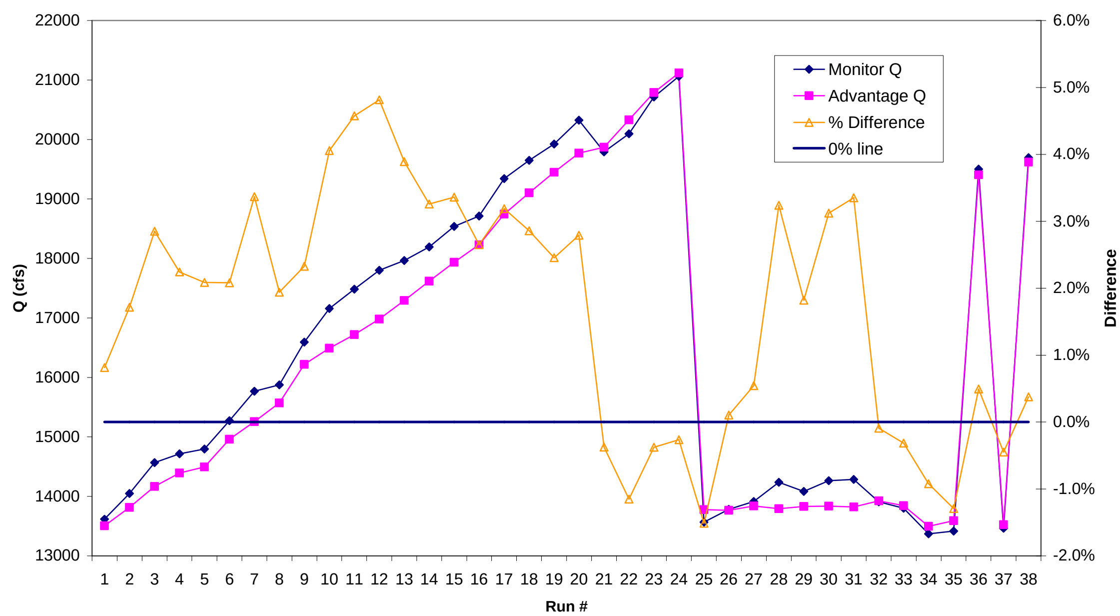


Figure 8*:* Discharge from Monitor and ASFM Advantage, ESBS Out, Unit 4.

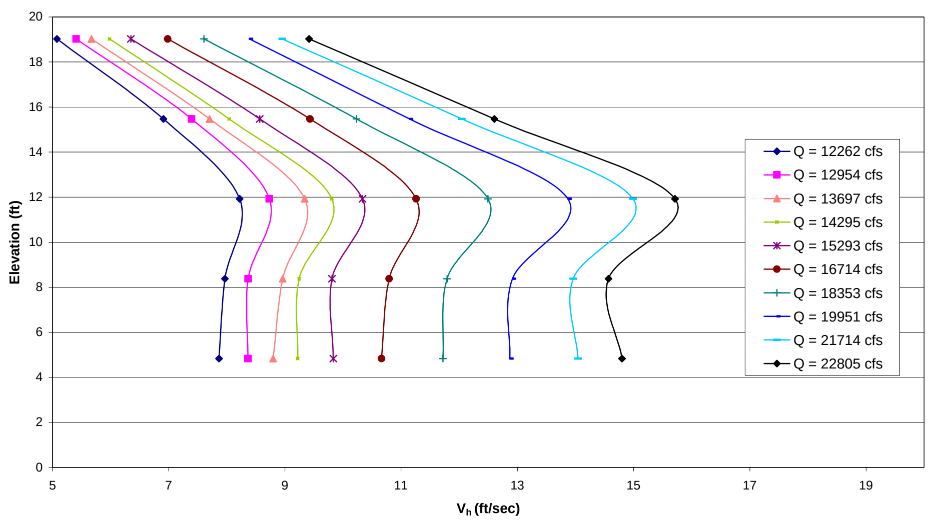


Analysis

The results summarized in **Figure 8** indicate that the Monitor used in this test (5 paths in the lower part of Bay A) does not provide a sufficiently accurate estimate of the total discharge to be used for either absolute or relative flow measurements. The analysis of the repeat runs done with the standard ASFM Advantage data, gives no indication of any error in that data (an interpretation supported by the results of HDC's efficiency calculations [**1**]), and leads to the conclusion that the Monitor values are in error.

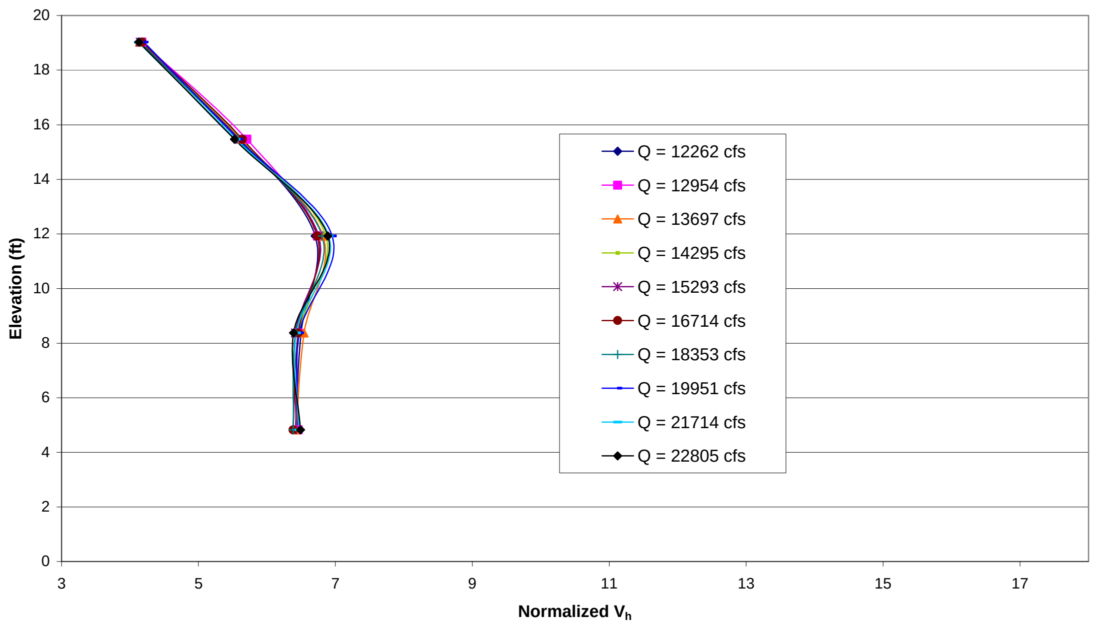
Successful discharge measurement by the Monitor requires that the shape of velocity profile in the region where the acoustic paths are placed be invariant with discharge [**2,3**]. A plot of the horizontal component of the velocity with elevation as the discharge is increased should form a family of parallel curves. Scaling each profile by the discharge should cause them to collapse to a single curve. **Figure 9** shows an example of the reduced-path system profiles taken with ESBS in place, spanning the full range of flows.

Figure 9: Monitor horizontal component of velocity curves, ESBS in.



The profiles form a nearly regular family of parallel curves; there is some evolution in the shape of the profile with increasing discharge, but the change is small and progressive with discharge. **Figure 10** shows the same profiles, scaled by discharge, and as may be seen, they form a tight distribution.

Figure 10: Monitor horizontal component of velocity curves, scaled by discharge, ESBS in.



With the ESBS removed, however, the profiles of the horizontal component of velocity no longer form as uniform a family of curves. The discharge-scaled profiles show proportionally more variation than was the case with ESBS in, consistent with the larger errors found in the calculated discharges for the off-cam runs. One possible cause considered was that the position of the reduced-system paths, near the end of the dividing pier in Bay A, may have contributed to the errors observed with no ESBS in place, through the flow being more variable at the end of the passage. This possibility was disproved, however, by an examination of the flow profile measured by the ASFM Advantage in the gate slot. Variability similar to that seen by the Monitor was apparent, indicating that the increased variability seen in the Monitor velocities is a property of the flow as a whole, and is not a consequence of the position of the paths near the end of the pier.

The effect of the flow profile variability was further tested by selecting 5 paths in Bay A from the ASFM Advantage (paths 2, 4, 6, 7 and 8), at elevations close to those used in the Monitor, and constructing an equivalent discharge calibration table from the on-cam runs. The velocities from those 5 paths were then used to calculate discharges for all of the off-cam runs. The differences with the reference discharge (shown in **Figure 11** [ESBS in] and **Figure 12** [ESBS out]) are comparable to those found with the Monitor system. The performance of the Monitor in other configurations may therefore be usefully simulated with selected combinations of paths from the ASFM Advantage.

Several different configurations were simulated, with varying numbers of paths located in 1, 2 or all 3 bays. The results are summarized in **Table 1** below. Each simulated configuration was calibrated against the discharge measured by the horizontal-path ASFM Advantage using the on-cam runs, separately for ESBS in and out. The difference between the discharge calculated

Figure 11: Discharge from simulated Monitor and ASFM Advantage (paths 2,4,6,7 & 8 selected from Bay A) Unit 4, ESBS in

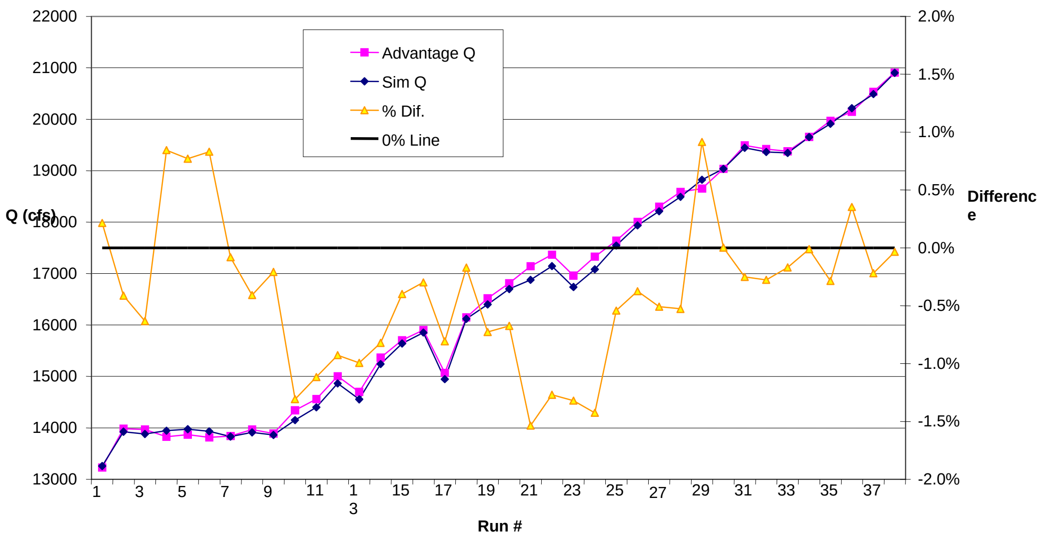
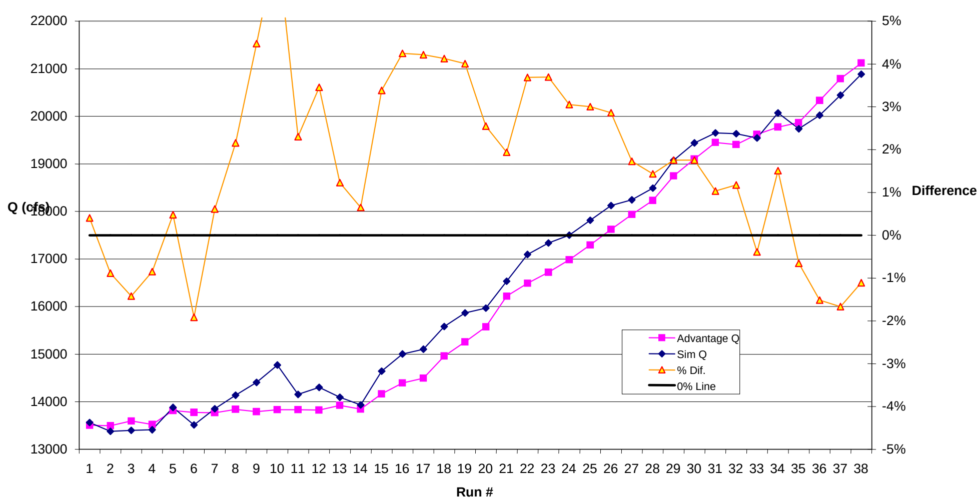


Figure 12: Discharge from simulated Monitor and ASFM Advantage (paths 2, 4, 6, 7, & 8 selected from Bay A) Unit 4, ESBS out.



by the simulated Monitor and by the ASFM Advantage was then computed for each off-cam run made as part of the index testing. The mean deviation (defined as the average of the absolute value of the differences [**6**]), standard deviation and the maximum of the absolute value of the differences are shown in the table. The combination that resulted in the overall best performance, i.e. both with and without screens in place required 5 paths in all three bays, spread over the full height of the bay. In that case, the maximum difference was less than 1.5%, and the mean deviation less than 0.6% in both configurations. By reducing the number of paths to three per bay, the best of the three cases considered (paths 2, 6 and 8, located in the lower mid-range of elevations) resulted in a maximum difference of 2.1%, and a mean deviation below 0.7% in both configurations. Using 5 paths in the two end bays (A & C, spread over the full elevation) gave comparable performance: a maximum difference of 1.8%, and the mean deviation less than 0.8% in both configurations. The best results that could be found for up to 5 paths in any one bay was a maximum difference of 2.5%, with the mean deviation below 0.8%, where the paths were distributed over the full height of the bay.

Table 1: Summary of Performance of Simulated Monitor, Unit 4.

		Screens In			Screens Out		
Bay	Paths	Mean Deviation	Std. Dev. of Diff.	Max. Abs. Difference	Mean Deviation	Std. Dev. of Diff.	Max. Abs. Difference
A	2,4,6,7,8	0.61%	0.43%	1.54%	2.03%	1.36%	4.82%
A	2,4,5,6,8	0.69%	0.42%	1.78%			
A	2,6,10,14,18	0.77%	0.57%	2.46%	0.56%	0.38%	1.68%
A	2,10,18	1.43%	1.18%	4.71%	1.15%	1.13%	4.62%
A	6,10,14	0.83%	0.71%	3.20%	0.61%	0.57%	2.12%
B	2,4,6,7,8				0.70%	0.60%	2.24%
B	2,4,5,6,8	0.45%	0.32%	1.19%			
B	2,6,10,14,18	0.99%	0.63%	2.34%	0.76%	0.71%	2.64%
B	2,10,18	1.36%	0.97%	3.88%	1.05%	0.67%	2.49%
B	6,10,14	1.29%	0.94%	3.24%	0.92%	0.89%	3.84%
C	2,4,6,7,8				1.32%	0.96%	3.24%
C	2,4,5,6,8	0.66%	0.47%	2.28%			
C	2,6,10,14,18	1.27%	0.99%	3.07%	0.87%	0.69%	3.21%
C	2,10,18	1.67%	0.81%	3.66%	1.17%	0.87%	3.53%
C	6,10,14	1.37%	1.00%	3.79%	1.15%	1.45%	6.50%
AC	2,4,6,7,8	0.32%	0.24%	1.04%	0.81%	0.63%	2.54%
AC	2,6,10,14,18	0.75%	0.50%	1.75%	0.42%	0.33%	1.48%
AC	2,10,18	0.97%	0.72%	3.44%	0.71%	0.59%	2.17%
AC	6,10,14	0.66%	0.54%	2.60%	0.65%	0.70%	2.97%
ABC	2,4,6,7,8				0.59%	0.41%	1.47%
ABC	2,4,5,6,8	0.35%	0.26%	1.35%			
ABC	2,6,10,14,18	0.55%	0.35%	1.41%	0.36%	0.30%	1.20%
ABC	2,6,8	0.35%	0.29%	1.30%	0.66%	0.52%	2.08%
ABC	2,10,18	0.90%	0.64%	2.95%	0.52%	0.38%	1.53%
ABC	6,10,14	0.54%	0.41%	1.61%	0.67%	0.58%	2.23%

(Blanks indicate combinations not used.)

Following completion of the turbine testing, the Monitor system was left in place, operating unattended and recording data internally. Since the ESBS had been removed, errors up to 5% were to be expected in the discharge data. The additional period of operation was intended to evaluate the reliability of the instrument; it operated successfully for a full month, through periods when the turbine was shut down and restarted, and through operation at varying levels of generation. The system functions proved over that period to be robust and capable of extended operation while unattended, and therefore with a suitable path configuration, the Monitor would be capable of supplying real-time, continuous discharge data for plant operational monitoring and control.

Conclusions

The Monitor configuration chosen for installation and testing at Lower Granite Dam, Unit 4, with 5 acoustic paths in the lower part of Bay A, gave more accurate discharge values with the ESBS in place than with ESBS out. When calibrated using the data from the horizontal-path ASFM Advantage installed in the gates slots collected during the on-cam runs, the Monitor recorded discharges within 1.5% of the reference ASFM Advantage values throughout all of the subsequent off-cam runs made with ESBS in place. The largest deviations were found when Unit 6 was operating; with no other units in operation, the differences were less than 1%.

Without ESBS in place, after calibration against the reference ASFM Advantage by the on-cam runs, the differences found during the off-cam runs ranged as high as 5%. The cause of these large differences was increased variability in the velocity profile, relative to that seen when the ESBS were in place. The increased variability was observed in the data from the Monitor and the reference ASFM Advantage. Changes in neighbouring unit operations appeared to influence the flow profiles, but no clear connection between the magnitude or sign of the differences in discharge between the Monitor and reference ASFM Advantage was found.

The performance of a simulated Monitor using other path configurations was constructed with data from selected paths in the ASFM Advantage. Using three paths per bay, the maximum difference between the ASFM Advantage and Monitor discharges, over all the off-cam runs, with or without ESBS in place, was 2.1%, with mean deviation (the average of the absolute values of the differences [**6**]) of less than 0.7%. Simulating 5 paths in each bay, the maximum difference found was 1.5%, and the mean deviation was less than 0.6%.

The simulations show that the Monitor can attain discharge measurement agreement with a full system of ±1.5% or better, but to do so under all plant configurations (ESBS in or out) and unit operating patterns requires an installation with 5 paths in each bay, spanning the full height of the intake. Agreement with the full system to within 2% could be achieved with 9 or 10 paths (either 3 bays with 3 per bay, or 5 paths in each of the end bays). Verification of the results of the simulation will require further field-testing.

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