THE ASFM MONITOR: A COST-EFFECTIVE TOOL FOR REAL-TIME MEASUREMENT OF TURBINE DISCHARGE

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Abstract

There is increasing need for optimizing hydroelectric generation operations at the plant and system levels, particularly on large river systems such as the Columbia and Tennessee. Real-time flow data for individual turbines is an essential component of the information required to do that. Such information may also be used for demonstrating compliance with environmental regulations or water-sharing agreements. To meet these requirements, absolute flow measurement is necessary for each turbine to allow comparisons among units and plants or to compute total flows. To date, making such flow measurements in low-head plants has been difficult and expensive.

The ASFM Monitor is a simplified version of the Acoustic Scintillation Flow Meter (ASFM Advantage), designed to provide continuous, real-time flow data in low-head plants at reasonable cost. Analysis of data drawn from use of the ASFM Advantage in more than 25 different low-head intakes over the past 8 years has shown that the flow velocity profiles are sufficiently consistent in most intakes, and that calibration measurements on installation allow accurate, repeatable real-time flow monitoring from a small number of sampling paths. Examples using the data from a number of plants on the Columbia River system are presented. The elements of the Monitor installation and operation are described, and examples are given of its potential application for different plant configurations. Issues are addressed that determine the optimal number and arrangement of acoustic paths, in terms of performance accuracy and repeatability. Examples of procurement and calibration costs are provided for general information. The maintenance requirements and operating costs of a Monitor system are projected to be minimal, in comparison, for example, to Winter-Kennedy taps.

Introduction: short-intake flow measurement dilemma

Obtaining accurate and repeatable flow measurements in short-intake plants is challenging due in large part to the uneven, or even unstable, velocity distribution often encountered in the short, rapidly converging intakes of low-head plants. It is so difficult, in fact, that as of today, “no existing standard deals with discharge measurements in short penstocks or intakes, especially for low-head plants” (*1*).

Does this mean that flow measurements are not required or are not being performed at low-head plants? Of course they are, and with increasing importance, as dictated by a variety of economic and environmental pressures. Flow measurements, either direct (using field-testing methods) or indirect (using model-derived values) are often made for special purposes, such as acceptance testing of a new or upgraded turbine, or installation of some new equipment in the intake (e.g. fish diversion devices). Such measurements typically occur over a period of 1-2 weeks under reasonably stringent test conditions, including operation of the turbine unit under a full suite of operational parameters in terms of gate openings and, where applicable, blade angles.

In this paper we address a related but even more demanding requirement for short-intake flow measurements: accurate and repeatable measurements of flows with real-time outputs that continue on a quasi-permanent basis, i.e. for periods of years. The advantages of real-time absolute flow measurement and monitoring for individual turbines are to support operation optimization at a plant or system level *(2, 3)*, and to demonstrate compliance with regulations and/or agreements. While a great deal of work has been done on developing methods for plant and system optimization, and on developing related software to support this, real-time inputs of the key data parameters is lagging behind, particularly the direct flow measurement input. Perhaps the most commonly used field flow measurement technique is Winter-Kennedy differential pressure taps. However, these do not measure absolute flows, being "index" measurements, and they suffer from upstream obstructions such as fish diversion devices *(4)* and are prone to instrument re-calibration issues (e.g. air developing in manometer lines).

Arrays of current meters are not feasible for permanent installations because of their intrusive nature. The acoustic time-of-travel method is suitable for permanent installations. However, it requires a certain minimal conduit length to accommodate the 45 to 65 degree path angles, often not available in short intakes *(5)*. Furthermore, because the acoustic time-of-travel integration techniques prescribe the exact path locations in a given conduit, excessive – and expensive - numbers of measurement paths have to be installed in order to achieve acceptable accuracy when the velocity distributions exhibit localized anomalies resulting from upstream obstructions, such as unusual intake roof convergence, major trashrack supports or fish diversion devices.

The ASFM Advantage, developed over the last 10 years by ASL AQFlow Inc., Sidney, British Columbia, Canada specifically for one-time absolute flow measurements in short intakes, is now being offered in a new configuration that addresses the need for permanent real-time flow monitoring in such short intakes. This new version of the product, the ASFM Monitor, offers the following, previously unavailable, features:

- measurement paths oriented directly across the intake, hence even the shortest intake can be addressed (6);
- no obstructions in the flow path (unlike current meter arrays), hence permitting permanent installations with virtually zero head loss and vulnerability to debris impact;
- no moving parts, hence very little mechanical maintenance and calibration;
- wall mounting in the lower part of the intake, hence easily accessible and with unrestricted flexibility in choosing the most effective path locations; where an existing little used slot is available, frame mounting may be preferred, allowing installation in and portability between intakes without dewatering;

- acceptable accuracy (systematic uncertainty defined prior to the measurement and linked to the characteristics of the intake) and outstanding repeatability (random uncertainty typically less than ±0.5% or better) (*7*), even with fish screens installed; and
- significant savings in the cost of equipment, and in the time and cost of installation and calibration (particularly important when no storage is available and inflows must be spilled) (*8*).

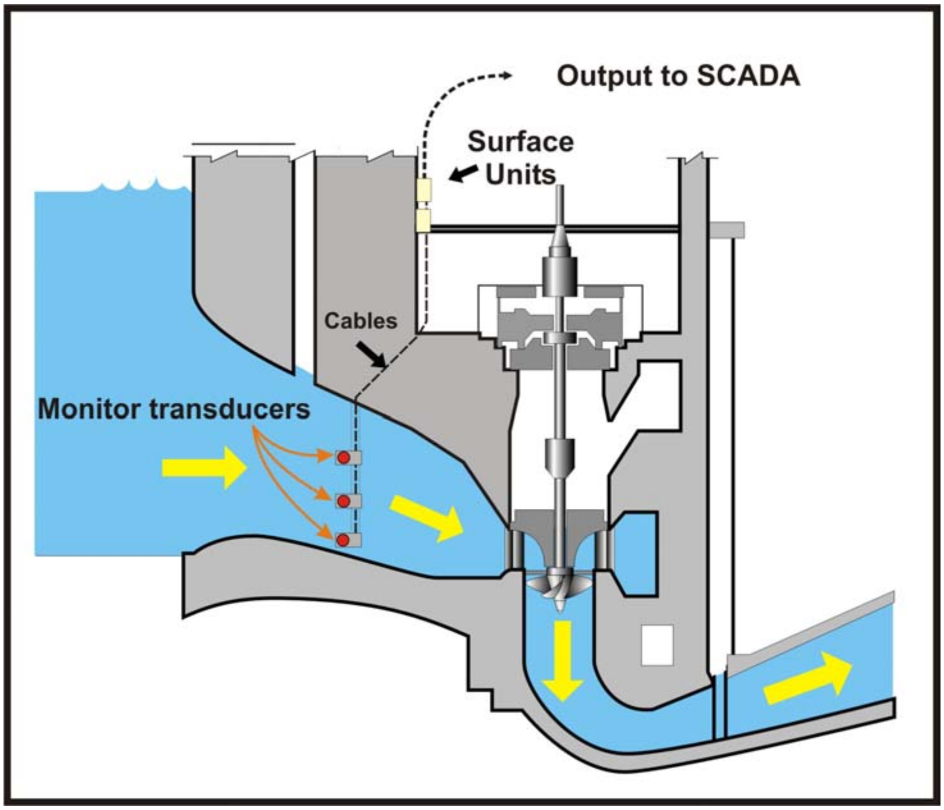

Fig. 1: ASFM Monitor – schematic arrangement

The ASFM Monitor (Fig. 1) uses fewer acoustic measurement levels than the ASFM Advantage product used for one-time field-testing applications. The fewer acoustic paths reduce costs to the point where it is feasible to outfit a large multi-unit plant with flow monitoring in all of the plant's intakes. The ASFM Monitor is designed to be highly configurable for virtually any hydroelectric plant configuration.

Once calibrated with an ASFM Advantage (or with an array of current meters), the ASFM Monitor offers accurate and highly repeatable flow monitoring for as long as the inflow/intake characteristics remain unchanged.

The remainder of this paper considers the configuration issues of the ASFM Monitor sensors and how they are optimized to provide the most reliable total flow measurements, as derived from previously conducted extensive studies; information on the functionality and performance issues, including installation, calibration and operation; and some typical costs of the whole system from installation through long-term routine maintenance requirements.

Analysis of previous measurements

The expected performance of the Monitor may be simulated by comparing the results obtained using subsets of sampling levels from ASFM Advantage measurements. We consider a selection of the data collected in a number of low-head intakes over the past eight years the ASFM Advantage has been in use. Most of this work has been done in plants on the Columbia River system, and the examples discussed here are all drawn from those plants. The basis for the Monitor design is the observation that in most intakes, the shape of the laterally averaged velocity profile is nearly invariant with discharge. Figure 2 shows an example from the USACE's John Day plant on the Columbia River. The plot shows the velocity at each level, in each of the three bays in the intake, for 9 separate discharges. The velocities have been normalized by the discharge and, as may be seen, variation in the form of the profile with discharge is very small. (The low-velocity zone near the floor is caused by the cross-pipe at the bottom of the ASFM frame.)

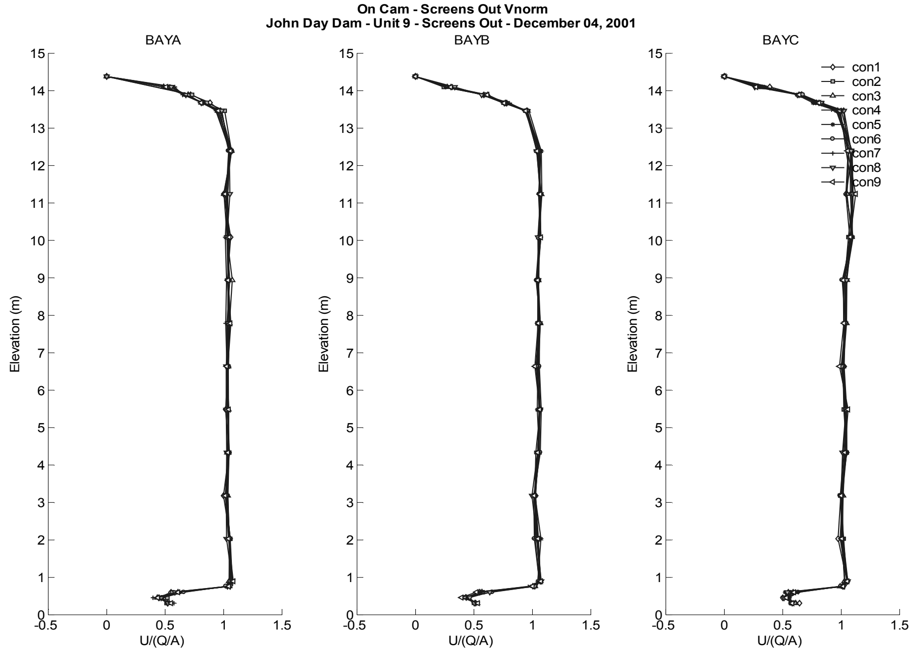
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Figure 2: Profiles of the horizontal component of velocity, John Day Dam

The profiles from the John Day plant are very regular; in this case, the discharge in any of the bays could be computed as a constant times the velocity at any of the levels

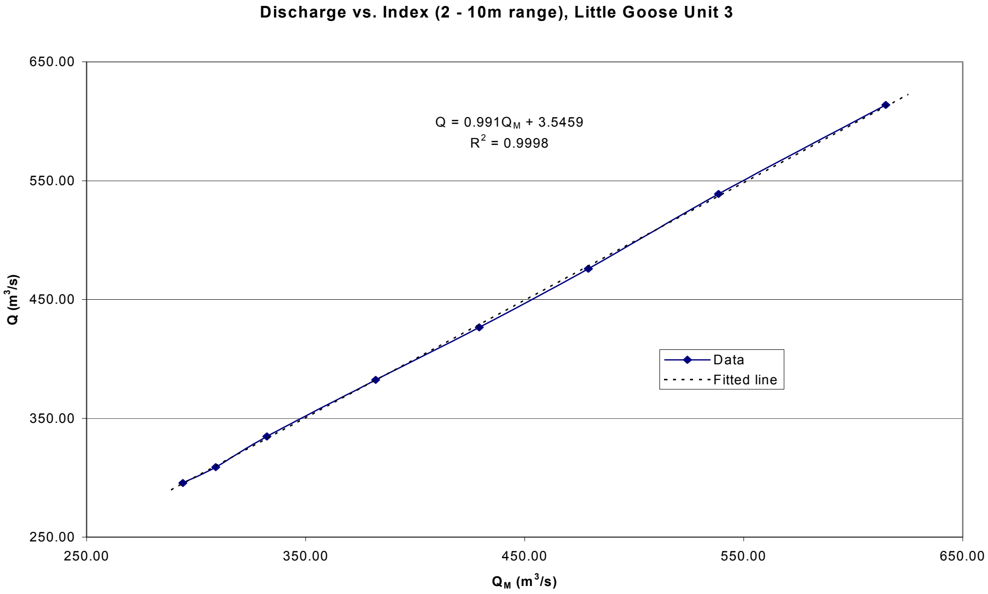

Figure 3: Measured discharge vs. discharge computed from four paths per bay index, Little Goose U3

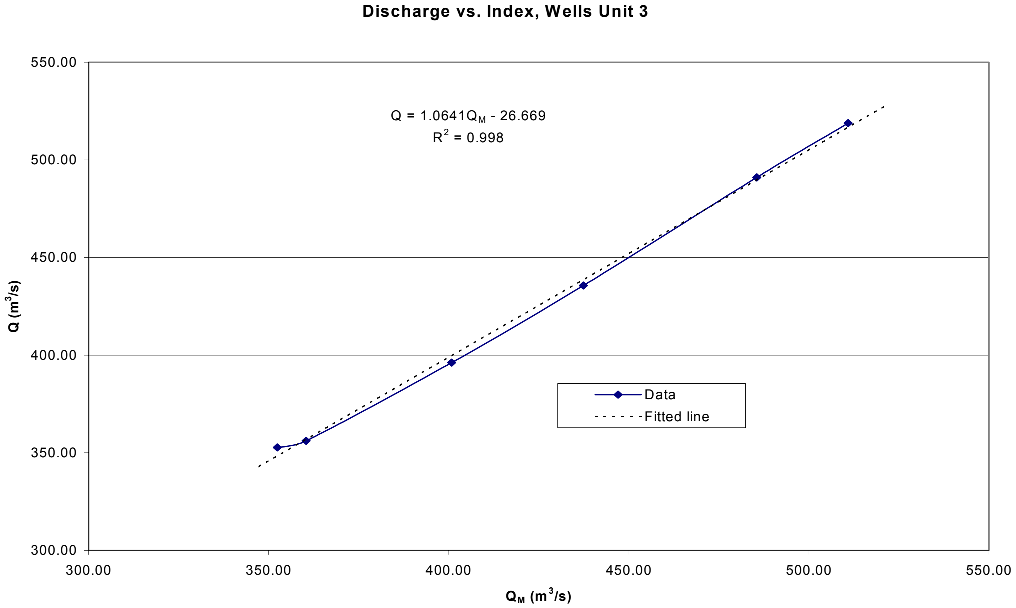

Figure 4: Measured discharge vs. discharge computed from four paths per bay index, Wells U3

between 3 and 6 metres elevation. The profiles in most plants are not so highly regular; a linear combination of the velocity from a number of paths is required to compute an index for the discharge, and the ratio between that and the total discharge varies with discharge. Figures 3 and 4 show plots of the discharge computed from four paths per bay at two different sites: Unit 3 at Little Goose Dam on the Snake River and Unit 3 at Wells Dam on the Columbia River.

In Figure 3, the four paths selected were spaced over the interval between 2 and 10 m elevation, while in Figure 4, the selected paths spanned the interval between 2 and 7 m elevation. In each case, the linear least-squares fit to the discharge as a function of the index is shown. Three other cases were examined: Little Goose Units 3 and 4, using paths between 1 and 5 m elevation, and Lower Monumental Dam (Columbia River), using paths between 0.8 and 3 m elevation. The fitted lines and maximum deviation of the discharge from the fit are summarized in Table 1. The greatest deviation is 1.5% and is a measure of the improvement in accuracy that may be obtained by calibrating the Monitor over the full range of discharges, rather than relying on a linear relationship between index and discharge.

Table 1: Summary of Linear Fit of Discharge to Index

Site	Fitted Line	R^2	Largest Deviation (%)
Little Goose U3 (2–10m)	$Q = 0.991Q_M + 3.5$	0.9998	0.6
Little Goose U3 (1–5m)	$Q = 1.008Q_M - 3.0$	0.9998	0.8
Little Goose U4 (1–5m)	$Q = 0.981Q_M + 8.4$	0.9989	1.5
Lower Monumental U6	$Q = 0.986Q_M + 5.9$	0.9999	0.4
Wells U3	$Q = 1.064Q_M - 26.7$	0.9980	1.3

The absolute accuracy of the Monitor is determined by the accuracy of the calibration measurements, but there will also be a random error in the discharge index arising from the random error in the individual velocity measurements. In three of the data sets shown above (Wells U3 and Little Goose U3 and U4), triplicate measurements were made at each discharge point. (The discharge points spanned the full operating range of the turbine, with between 6 and 9 points in each set.) These data sets may therefore be used to estimate the random error in the discharge derived from the Monitor index. Two different sets of four paths were chosen from the Little Goose Unit 3 data, one spanning 2 to 10 m elevation and the other spanning 1 to 5 m elevation, to test whether the positioning of the paths affects the magnitude of the error. In each case, the mean and standard deviation σ_M of the discharge, Q_M, calculated from the Monitor index ratio over the three replicate measurements, was computed. The same quantities were also computed for the reference discharges Q, since the random error in the reference discharge will contribute to the variability of the index. The results are summarized in Table 2, which shows the average and maximum of the ratio of the standard deviation to the mean over the range of measured discharges.

Table 2: Average and Maximum Variability in Total Discharge, 4 Paths per Bay

Site	Average σ_M/Q_M (%)	Max σ_M/Q_M (%)	Average σ/Q (%)	Max σ/Q (%)
Little Goose 3 (2-10m)	0.42	0.71	0.28	0.78
Little Goose 3 (1-5m)	0.39	0.67	0.28	0.78
Little Goose 4 (1-5m)	0.80	1.95	0.43	0.88
Wells 3 (2-7m)	0.43	0.98	0.42	0.67

All of these plants have three bays per intake, so the same quantities may be calculated for each individual bay. The results are shown in Table 3.

Table 3: Average and Maximum Variability in Discharge per Bay, 4 Paths per Bay

Site	Average σ_M/Q_M (%)	Max σ_M/Q_M (%)	Average σ/Q (%)	Max σ/Q (%)
Little Goose 3 Bay A (2-10m)	0.69	1.11	0.62	0.94
Little Goose 3 Bay B (2-10m)	0.56	0.98	0.55	1.55
Little Goose 3 Bay C (2-10m)	1.23	2.14	0.60	1.06
Little Goose 3 Bay A (1-5m)	0.72	1.13	0.62	0.94
Little Goose 3 Bay B (1-5m)	0.44	1.16	0.55	1.55
Little Goose 3 Bay C (1-5m)	0.61	1.17	0.60	1.06
Little Goose 4 Bay A (1-5m)	0.85	2.86	0.48	0.93
Little Goose 4 Bay B (1-5m)	0.96	1.85	0.58	1.26
Little Goose 4 Bay C (1-5m)	1.32	3.42	0.89	2.10

Wells 3 (2-7m) Bay A	1.06	2.31	0.94	1.27
Wells 3 (2-7m) Bay B	0.31	0.57	0.61	0.78
Wells 3 (2-7m) Bay C	0.66	1.10	0.55	1.18

The average standard deviations in the total discharge index are all less than 1%, and exceed the standard deviations in the reference discharges by at most 0.4%. The largest maximum is 1.95% at Little Goose Unit 4, exceeding the reference discharge variability by 1.1%. This value corresponds to the minimum discharge measured at Little Goose U4; excluding it reduces the maximum index variability to 1.0%. As that discharge is at the lowest end of the operating curve, it is unlikely that it would frequently be used in normal operation, and therefore the variability to be expected under normal circumstances would be a lower figure. The average per-bay discharge index variability values are higher than for the total discharge (the same is true for the reference values), with the highest being 1.32%. Distributing the Monitor paths among all the bays of a multi-bay intake would therefore result in lower variability than would be the case if they were all in a single bay. Note that this increased variability does not necessarily reflect the performance in a single-bay intake, since the lower variability in the total discharge indicates that some fraction of the variability in each bay results from small changes in the distribution of the flow among the bays. That would not be the case in a single bay intake.

The effect of the number of paths installed was examined by calculating the random variability in total discharge index when the number of paths per bay was reduced to three and one (Table 4).

Table 4: Average and Maximum Variability in Total Discharge as a Function of Number of Paths per Bay

		Average σ_M/Q_M (%)			Max σ_M/Q_M (%)	
Site	4 paths	3 paths	1 path	4 paths	3 paths	1 path
Little Goose 3 (1-5m)	0.39	0.42	0.69	0.67	0.69	1.18
Little Goose 4 (1-5m)	0.80	0.77	0.99	1.95	1.93	2.11
Wells 3 (2-7m)	0.43	0.51	0.78	0.98	1.03	1.43

Reducing the number of paths increases the random variability, but even at one path per bay, the maximum variability calculated in the total discharge index remains below 2.5%.

Optimal configuration: number and placement of acoustic paths

The optimal configuration for any given Monitor installation depends upon balancing several factors: the accuracy desired, the cost of installation, the level of redundancy in the equipment, and the importance of detecting deviations from the reference flow profile which may arise, for example, from trashrack blockages. As may be seen from Table 4, the level of random variability in the discharge index increases slowly as the number of paths is reduced, so that for some applications, as few as 1 or 2 paths per bay could be deemed to produce an acceptable level of random variability. The discharge calibration will remain accurate, however, only if the shape of the flow profile does not vary. If it does, because of trash build-up or other causes, then the calibration relationship will not be correct. Detection of such deviations would require at least three paths, distributed over the majority of the height of the intake. The measured flow profile could then be compared with the reference as a means of detecting changes. Installing too few paths also does not provide redundancy, which would be required for the Monitor to continue operation should a level fail. Concentrating the levels in the lower part of the intake would reduce installation costs in most cases, without reducing accuracy, if the flow profile remains constant, but such a distribution would not be as effective in detecting changes in the profile as would one with the levels spread over a greater height. The installation cost savings therefore must be weighed against the requirement to detect flow profile changes.

The Hydraulic Design Center of the US Army Corps of Engineers has recently concluded a study using an abbreviated form of the ASFM Advantage for flow measurement for Kaplan turbine operation optimization (*9*). Through analysis of the measurement results from their John Day, The Dalles and Bonneville plants, they established that using less than a full sensor array in only one of the three intake bays resulted in cam curves, similar to those derived from full-scale measurement tests. The full tests typically involved 20 measurement levels in each bay, for a total of 60 measurement levels. The analysis showed that acceptable results would be obtained from only 4 measurement levels in one of the three bays (for a total of 4 measurement levels instead of 60). This represents a 15-fold reduction in instrumentation, with the accompanying cost, manpower and time savings. It did not seem to matter which bay was selected for measurement. Furthermore, they were able to demonstrate that by locating the four measurement levels in the free-stream portion of the intake, the same Monitor configuration could be used with and without fish diversion devices in place. An additional benefit of installing the measurement levels in the lower third of the height of the intake is the relative ease of access for installation and maintenance.

Typical installation and calibration requirements

The Monitor consists of a Processing Module connected to a Switching Module, which in turn is connected to transducer pairs located in the turbine bays (Fig. 5). The Processing Module consists of digital and analog electronics for pulse transmission and data acquisition, data processing, data output and system control. The Processing Module can sample on three acoustical paths simultaneously, and selects the paths via the Switching Module that contains the switching electronics. The Processing Module and the Switching Module are connected by cabling of up to 80 meters in length. Both modules are housed in environmentally secure enclosures. The transducer arrays are connected to the Switching Module by cabling up to 90 meters in length.

A single Processing Module can control up to 30 paths with the following restrictions:

- a maximum of 15 turbines,
- a maximum of 10 paths for any bay, and
- a maximum of 3 bays for any turbine.

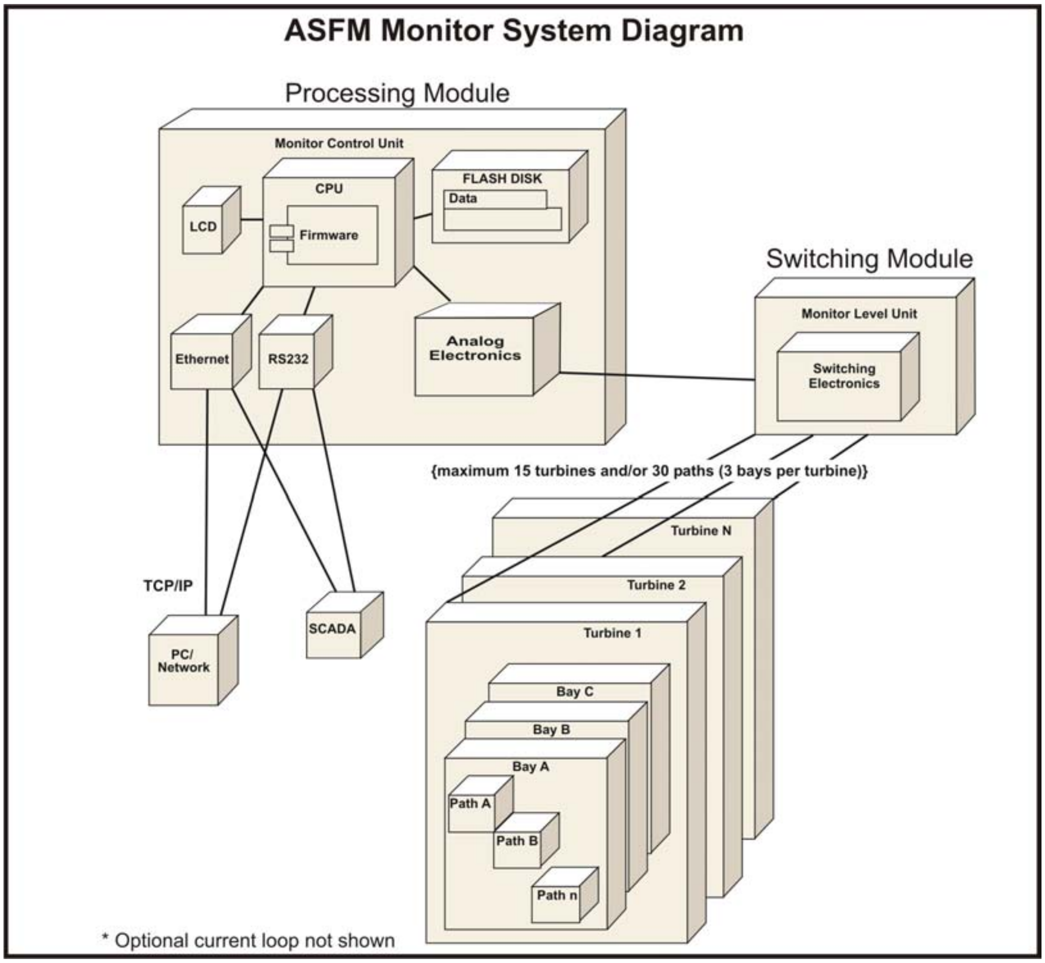

Fig. 5: Monitor system diagram

During installation, the Processing Module is configured using a computer connected to the onboard Ethernet port. During normal operation, the Processing Module collects acoustical data and computes velocities for each path. Using a lookup table, it computes the discharge values for each turbine and outputs the data to any or all the output ports (Ethernet or RS232). A history of the computed data is maintained for a period of time (up to one month or more) in local non-volatile memory. The Processing Module includes an LCD display, which provides system status information. The design of the Processing Module allows ASL AQFlow to provide inexpensive diagnostic services and support by connecting to the unit with a second computer through the Ethernet port, either on-site, or remotely through the internet, if network access can be provided by the customer.

The underwater components of the Monitor can be mounted in the wall of the intake in several ways. With the flush mount*,* each individual transducer is mounted to an aluminum channel and the channel is anchored into a 2” deep slot cut in the concrete such that the channel and the transducer faces are flush with the wall of the intake (Fig.6 – flush mount). No parts of the Monitor or channel extend into the flow. If a 2” slot cannot be cut without interference from the reinforcing steel, a shallower slot may be used, in which case a part of the channel will protrude from the wall of the intake. In some cases a surface mount may be preferred, in which case the channel, including transducers, is attached to the wall of the intake without the requirement for cutting into the concrete (Fig. 6 – surface mount). While the mounting channel will then protrude 2” from the walls, it can be streamlined as desired.

Alternatively, if there is an unused, or seldom used, slot in the intake, a frame mounted Monitor may be the preferred solution. In that case, the unused transducer openings in the frame should be blocked with blank covers.

The accuracy of the installation angles of the paths is not critical. Since paths are placed perpendicular to the flow, variations of a few degrees do not matter. Physical dimensions can be adequately measured using a tape measure after transducer installation.

The routing of the cables connecting the transducers with the surface unit is flexible. It will depend on the design of the intake and the desired location of the surface unit. Reliable watertight sealing of any necessary openings in the roof or the walls of the intake will be required. The routing of the digital output from the surface unit to a display and/or recording location is even more flexible, depending on whether a serial or Ethernet connection is used.

Placement of the Monitor acoustic paths is determined by the shape of the intake flow field, as defined either from model or field measurement data. As the Monitor calculates the discharge in real-time from a lookup table, the calibration of the Monitor must be carried out after installation, to define the lookup table. This is done by operating the Monitor simultaneously with a reference discharge measurement method (e.g. a full ASFM Advantage) over the full range of turbine discharges. As a specific calibration may be done for each configuration of the intake (e.g. with or without fish screens or surface collectors), no additional calibrations will be required unless an unforeseen modification of the intake becomes necessary.

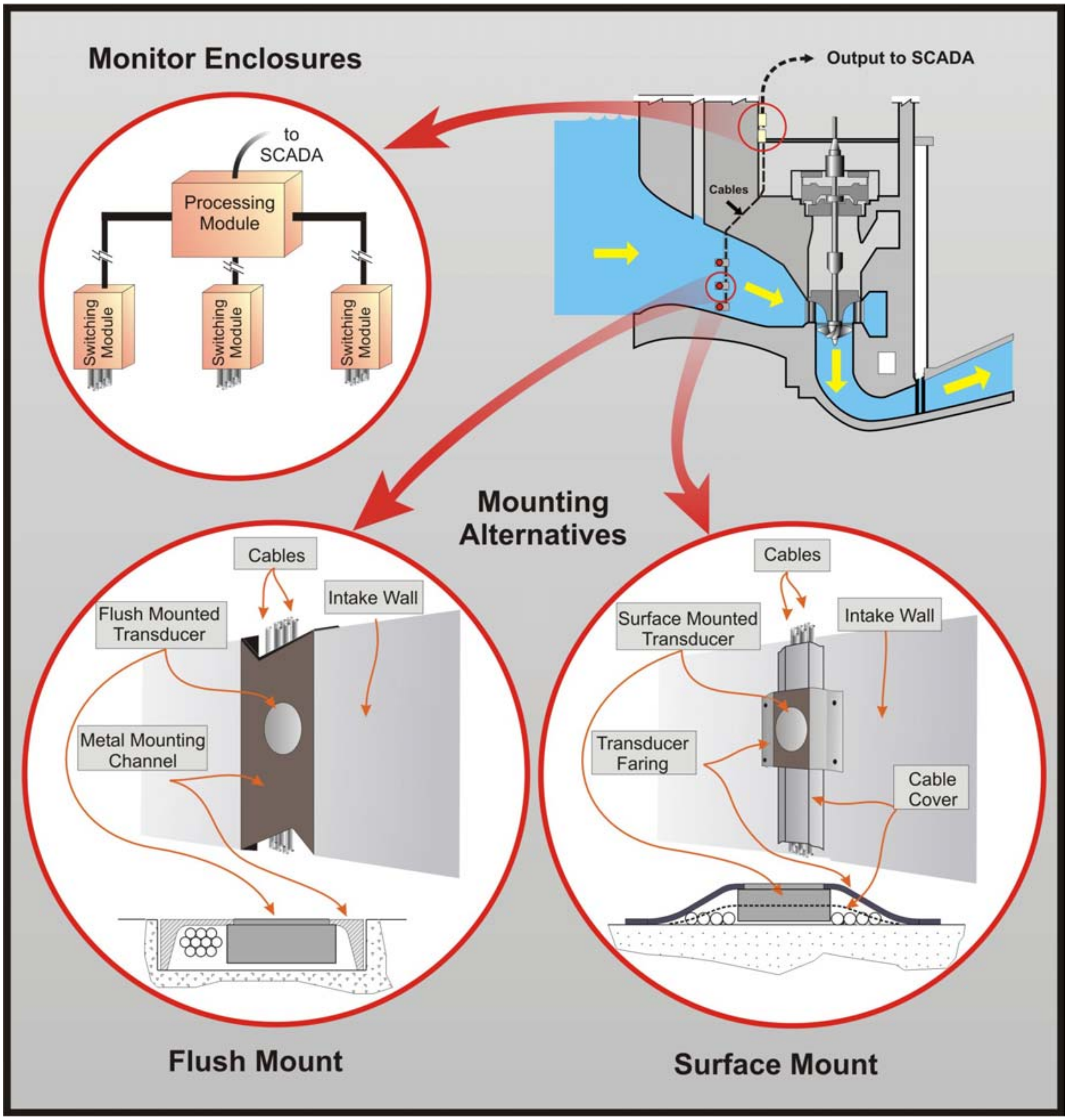

Figure 6: Monitor array mounting alternatives and above-water enclosures

For obvious reasons, the calibration must be performed with clean trashracks. For continued accurate operation of the Monitor, the trashracks must remain free from serious blockage. It is worth noting that because of its operating characteristics, the Monitor can, in fact, give useful information as to if and when the trashracks need cleaning.

Expected procurement, installation, calibration, operation and maintenance costs

The Monitor instrument procurement costs will depend on the number of acoustic paths used per bay, on the number of intake bays for each unit being monitored, and on the total number of units being monitored. To illustrate this range of procurement costs, for a two bay/turbine and three acoustic paths/bay, the Monitor procurement cost would be approx. US $50,000 for one unit, and US $30,000 per unit for five units.

Highly site dependent, installation costs depend on the installation arrangement selected, and whether or not Monitor specific intake dewatering(s) will be required. ASL AQFlow can provide installation recommendations, assistance and supervision. The exact needs of the client must be evaluated on a case-by-case basis.

The absolute calibration costs, including detailed ASFM Advantage field measurements and the Monitor site-specific configuration, will start at about US $50,000. We expect typical operation and maintenance costs of the Monitor to be low, much lower than, for example, Winter-Kennedy taps, and similar to other electronic equipment with an under-water component. There is no requirement for routine maintenance and repairs are likely limited to the replacement of parts that are damaged due to mishaps or electrical abnormalities. In the absence of any such abnormal occurrences, the lifetime of the system's under-water transducers and cabling components is estimated to be 10 – 20 years, and up to 10 years for the above-water electronics and computer components.

Summary

The ASFM Advantage represents a technological breakthrough in one-time turbine flow measurement in short intakes of low-head plants. By building on the ASFM Advantage's capability, but in a significantly reduced format, the ASFM Monitor brings the same performance into the arena of permanent real-time monitoring of turbine flows in short intakes of low-head plants.

The Monitor is suitable for even the shortest intakes, it has no vulnerable and head loss causing components in the flow path, it has no maintenance-requiring moving parts, it has acceptable accuracy (systematic uncertainty ±1.5% or better if calibrated) and outstanding repeatability (random uncertainty ±1.0% or better) at a price considerably lower than its competitors. Consequently, the Monitor makes possible – for the first time in the history of low-head hydro power plants - operation optimization of low-head turbines at the unit, plant and system levels, and demonstration of environmental compliance based on up-to-date field measured data, rather than on possibly outdated field or model tests, supplier data or even estimated values.

Acknowledgments

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