Cost-effective turbine flow measurements in short intakes with acoustic scintillation

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Introduction

Flow measurement in short, rapidly converging intakes of low-head hydroelectric plants with uneven or even unstable velocity distributions has traditionally been very difficult – often impractical, always exceedingly laborious and expensive.

The acoustic scintillation technique offers portable (frame mounted), unobtrusive (no instruments in the flow path), cost-effective (no intake dewatering, little maintenance and calibration required) flow measurement in even the shortest intakes (measurement plane perpendicular to the flow). From its beginnings, the acoustic scintillation technique has produced consistently repeatable index testing results, such that the relative efficiency improvements gained on double regulated units (typically up to 2%) quickly paid for the testing costs. The acoustic scintillation technique, when properly applied, allows operational optimization of units using relative flow measurement and has the potential of producing reliable absolute flow measurements. Absolute flow measurements are necessary for operational optimization of entire plants and systems and for calibration of unit flow measurement systems. An abbreviated form of the acoustic scintillation technique offers permanent, long-term real-time relative flow monitoring and, with proper calibration, real-time absolute flow monitoring.

1. Acoustic Scintillation - History and Principles of Operation

By utilizing the natural turbulence embedded in the flow, the acoustic scintillation technique has successfully reduced the traditionally excessive costs of flow measurement in short intakes of low-head plants such that the resulting relative efficiency improvements quickly pay for the testing costs. While relatively new in hydroelectric applications, the technique has been well proven in measuring solar winds for more than half a century, and ocean currents for almost a quarter century.

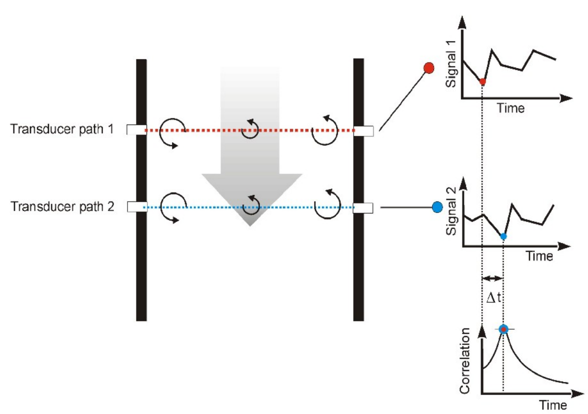

Fig. 1 – Acoustic scintillation operating schematics

In its simplest form, an array of two transmitters is placed at one side of the intake, and an array of two receivers is placed at the other. The signal amplitude at the receivers varies randomly in time as the distribution of turbulence along the propagation path changes with time and flow. If the two paths are sufficiently close, the turbulence remains ‘embedded’ in the flow and the pattern of the signal variations (scintillations) at the downstream receiver will be nearly identical to those at the upstream receiver, except for a time delay. The mean flow velocity is then the transducer separation distance divided by the time delay. With the use of an additional, vertically-separated element in each of the arrays, the average magnitude and average inclination of the velocity are measured at several levels. The discharge is then calculated by integrating the horizontal component of the velocity at each level over the total cross-section of the intake, providing results in real time.

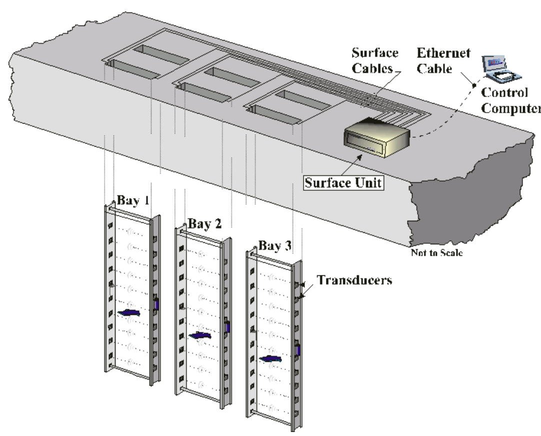

Fig. 2 – Typical arrangement

Acoustic transducers are mounted on opposite sides of a fixed or movable frame, which is then lowered to the existing intake stoplog or gate slot. Thus the technique can be used in very short intakes and without dewatering for installation and removal. In multiple unit plants, a fully instrumented frame can be simply moved from intake to intake, again saving plant downtime. Furthermore, no instruments are exposed to debris damage or interfere with the measured flow, and there are no moving parts requiring maintenance and frequent calibration.

During the last 10 years, the acoustic scintillation technique has been used effectively in more than 25 plants, mostly in North America.

2. Cost Effective Index Testing of Individual Units

The key requirement for index testing is the repeatability of the measurements. As reported previously (*1*), equipment based on acoustic scintillation technology consistently produced repeatable measurement results with acceptable random uncertainty (better than ±0.5%) at Lower Monumental Unit # 2 and #6 and at Little Goose Unit #3 (Snake River, Washington State), and at McNary Unit #5, at John Day Unit #9 and at Wells Unit #3 (Columbia River, Washington and Oregon). Interestingly, the acoustic scintillation technique appears to produce repeatable results even in the presence of various fish diversion devices. In contrast, Winter Kennedy piezometers require computation of a different calibration constant once a fish diversion device is introduced.

Potential performance improvements obtained near peak efficiency from revised cams for the double-regulated units listed above ranged from 0.75 to 1.25% per unit at Lower Monumental, 0.75 to 1.25% per unit at Little Goose and 2% per unit at John Day with fish diversion screens installed (*2*). Considering the size of these units, this represents a net gain of up to US$1,300 for each 24 hours of operation.

The acoustic scintillation frame fabrication and transducer installation and removal are all done in the yard, without interference with the operation of the unit. With the right equipment, the frame installation and removal are relatively quick operations, allowing one owner to state "[acoustic scintillation] results are the key for other Hydro plant owners considering using [it] for index testing: efficiency increases pay for the test itself " *(3)*. Another owner, who has used both current meters and acoustic scintillation techniques, estimates his equipment cost savings to be in the order of US$22,500/unit, when using acoustic scintillation rather than current meter equipment in the gate slot. Furthermore, the same owner estimates that 2 days of lost generation can be avoided by using acoustic scintillation rather than current meters (a potential saving of over US$60,000 for a 50MW unit) *(4).*

3. Cost-Effective Optimization of Operation of Multiple Units

Optimization of the operation of multiple units within a plant, and of a number of plants within a hydro system is attracting increasing interest. Advances in software and control automation have made it possible to coordinate and optimize the operation both of units within a plant, and plants along a river system to achieve goals such as maximizing revenue or efficiency, minimizing water use or meeting specific water management objectives *(4,5)*. The plant and system optimization requires using absolute efficiency curves for each of the generating units in the system, which in turn requires absolute rather than relative (or index) measurements of the flow. Although at present there are no methods accepted by the IEC or ASME performance test codes for making absolute discharge measurements in short intakes, current meters have been used for that purpose for many years, but are time-consuming, labour-intensive, and hence relatively costly. Acoustic scintillation measurements are less costly, but in some intakes, despite good repeatability and precision, have been subject to systematic error. Recent work has led to the conclusion that such biases are largely due to the effect of upstream structures, such as trashracks with large structural members, on the distribution of velocity and turbulence in the intake *(6)*. In the minority of intakes where these effects extend as far as the location of the acoustic scintillation measurement, significant biases can be produced, but otherwise systematic errors have been negligible. Understanding the causes for bias therefore allows intake configurations to be selected where accurate absolute flow measurements by acoustic scintillation technique may be obtained (directly or by application of corrections), which in turn allows cost-effective optimization of multiple units.

Significant gains in plant or system efficiency, in some cases as much as 2 or 3%, are possible using operational management software, without measured flow data. In many cases, the unit operating characteristics are derived from nominal values, assumed to apply to all members of a family of turbines. Using measured values for each of the turbines in a system may reasonably be expected to further increase the gains from plant and system optimization programs, given the improvement in individual unit operation gained from index testing. As an example, at one six-unit, 240 MW plant, an efficiency increase of 1% was achieved by operating the individual units at their best efficiency points, and a further 0.3% gain in plant efficiency by preferentially operating the most efficient units (*4*). The cost of the testing (US$150,000) was more than offset by the estimated annual revenue gain (US$490,000).

4. Cost Effective Long-term Monitoring in Real Time

Real time flow data is an essential component of information required to optimize plant and system operation, and to demonstrate compliance with environmental regulations or water sharing agreements. In order for the comparisons between units and plants to be made, absolute flow information is required. In short intakes of low-head plants, this has not been possible.

The acoustic scintillation technique now offers precisely that. By building on the acoustic scintillation technique's capability for one time measurements described above, but in a significantly reduced format, cost effective real-time monitoring of flow in short intakes is possible.

In 2003, the Hydroelectric Design Center, U.S. Army Corps of Engineers (CoE) studied a simulated abbreviated acoustic scintillation technique (by abstracting selected measurement levels from the full set) at their John Day, The Dalles and Bonneville plants – all with short, 3-bay intakes and Kaplan turbines. These tests have yielded several interesting findings (*7*):

- measurement in only one bay appeared to produce satisfactory results, and it did not appear to matter which bay was used,
- acceptable results were obtained with the number of measurement paths reduced to four,
- measurement paths should be located in the free stream flow path (defined as a portion of the intake where path velocity is at least 80% of the maximum velocity, see example in Fig. 3).

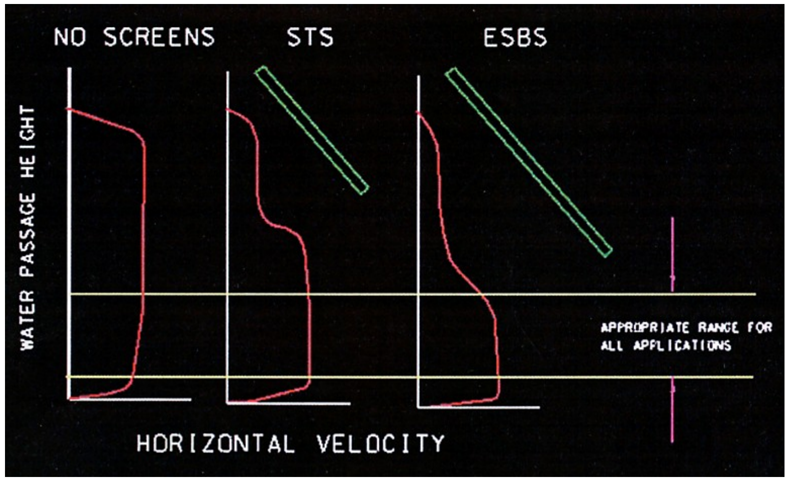

Fig. 3 - Example of the three conditions analyzed. STS – Standard Traveling Screen, ESBS – Extended Submersed Bar Screen (from 7)

Based on these findings, the CoE study concluded that for individual unit operation optimization, the equipment cost of a full acoustic scintillation installation for one-time measurement can be reduced by as much as 80 – 90%, while maintaining acceptable monitoring accuracy. Furthermore, by cutting the measurement cycle duration by at least 50% (and with a minor software adjustment by as much as 75%), a real-time, or very nearly real-time, monitoring can be provided.

It will be noted that the CoE study refers to relative flow testing, as at the time of their testing there was an unresolved problem of acoustic scintillation technique measurement bias. As covered in Section 3 above, significant progress has been made in resolving these measurement bias issues such that the abbreviated acoustic scintillation technique based real-time monitoring may be expected to produce reliable information on absolute flows.

As outlined in (*8*), the optimal configuration of abbreviated acoustic scintillation technique installation (i.e. the number and distribution of measurement paths among the intake bays) will depend on balancing the accuracy requirements against the cost of installation, the ability to detect trashrack blockages and the level of equipment redundancy.

The basis for the abbreviated acoustic scintillation technique installation is that the shape of the laterally averaged velocity profile in each bay is nearly invariant with discharge (Fig. 4).

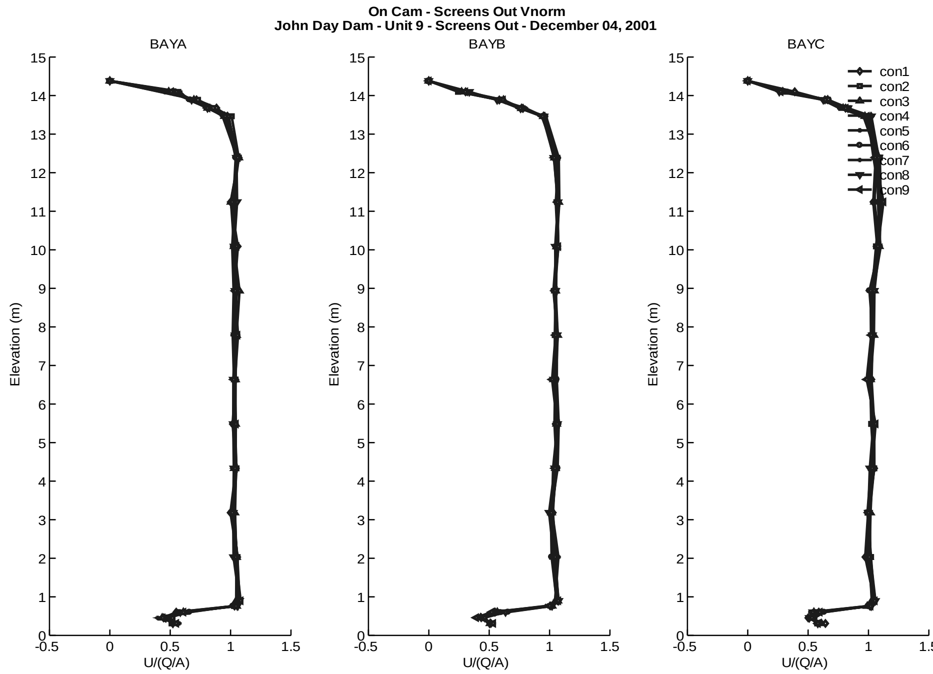

Fig. 4 – Normalized profiles of horizontal component of velocity, John Day

It has been found that even for plants with less regular profiles, the deviation between an index calculated from a linear combination of the velocity from 4 paths per bay and the total discharge was less than 1.5%. The deviation can be corrected by calibration of the index over the full range of discharges. It was also found that the random variability in the measured discharge increases relatively slowly as the number of measurement paths is reduced:

	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

Thus, in some applications, as few as 2 measurement paths may be judged acceptable, unless the abbreviated acoustic scintillation technique is being used to warn of trashrack debris blockage. In that application, the measured flow profile is compared with the reference profile; therefore, a minimum of 3, and preferably more, paths will be required in each bay.

The abbreviated acoustic scintillation technique equipment procurement costs will vary considerably depending on the above mentioned requirements:

Units/plant	# of measurement levels	# of bays utilized	US$/unit
1	2	1	33,900
1	4	1	40,600
1	3	3	59,000
5	2	1	13,100
5	4	1	20,900
5	3	3	45,000

The abbreviated acoustic scintillation technique installation costs will be highly site dependent, as the transducers will have to be attached to the intake walls and the cables routed to the readout location. With no equipment exposed to the damage from waterborne debris and with no moving mechanical parts, the operation and maintenance cost associated with abbreviated acoustic scintillation technique will be minimal.

5. Summary

The acoustic scintillation technique offers, for the first time in the history of hydroelectric industry, cost-effective flow measurement in the short intakes of low-head plants, both in relative and absolute terms, and – in most intakes - with acceptable precision and accuracy. This means that it now makes sense to measure the flow in short intakes, where it was not previously economic to do so, as the cost of testing is quickly recovered through improved efficiency of operation.

The number of successful applications of the technique is steadily increasing, thus demonstrating its capability to effectively facilitate optimization of operation of individual units and entire plants and river systems. Nevertheless, it is recognized that many more comparative measurements will have to be successfully carried out, and measurement errors for various intake types investigated and defined, before the technique is universally accepted by the industry and the relevant performance code committees. The potential benefits to the industry of the successful completion of these tests and investigations make it clear that they should be addressed as expeditiously as possible.

Acknowledgments

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