A Measurement Assurance Program for Calibration by the Static Weigh Method – CS5000

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This document outlines the Measurement Assurance Program (MAP) for *SeaMetrics* CS5000 flow measurement system – a liquid flow measurement system used to calibrate liquid flow meters. It consists of four elements: 1) calibration of measurement devices, 2) statistical process control of measurement devices, 3) a measurement uncertainty analysis, and 4) a proficiency test. This MAP is responsible for process control, maintaining quality of measurements, and traceability to National Institute of Standards and Technology (NIST) standards.

MAP's are necessary to maintain quality assurance and ties to national standards [1]. They assure quality of all measurement devices and test procedures and assure a state of statistical control of the measurement process. Upon establishing traceability to national standards a MAP may be implemented to maintain it over time.

This document outlines the MAP used to evaluate and manage *SeaMetrics* liquid flow calibration system. Law of propagation of error is used to predict measurement uncertainty [2]. A proficiency test is used to validate the system's measurements. Process control is maintained by Statistical Process Control (SPC) [3]. Under this MAP liquid flow rate measurements are traced to NIST and measurement quality is maintained.

Methods

Liquid flow meter calibrations are performed by driving liquid water at constant flow rate through a system of closed conduit and referencing a primary flow meter (meter under test) to a secondary flow reference (flow standard). The flow references are gravimetric static weigh systems. Each reference consists of a collection tank resting on load cells, temperature probes, a fishtail for flow profile control, and a flow diverter. All components are connected by steel pipe. Upstream of the primary meters are sections of straight pipe that are sufficient in length to fully develop flow.

Prior to collecting measurements a thermal steady state, hydrodynamic steady state, and test meter output steady state are obtained. After all steady states are obtained, the scale is tarred and the diverter is actuated causing the flow to change course from returning to the storage tank to the collection tank. The motion of the diverter synchronously starts a collection timer. After a predetermined volume has been collected, the diverter is deactivated; causing the flow to divert back to the storage tank and synchronously stopping the collection timer. At this point the weight and temperature of the water inside the collection tank, the duration of the test triggered by the diverter motion, and the primary meter output is collected and used to calculate volumetric flow rate.

Flow rate measurements are traced to NIST through an unbroken chain of comparisons. Comparisons are created annually by calibrating all measurement devices at an accredited laboratory. Traceability is maintained through SPC. Measurement uncertainty was evaluated by an uncertainty analysis. The entire system was validated by a proficiency test.

Statistical Process Control

Statistical control of the calibration system is assessed using SPC. The system is calibrated regularly against a check standard. Check standard calibrations include two flow rates. Measurements are grouped and plotted using control charts. Control limits are calculated from Shewhart's control limit factors [3; Table A.5].

A proficiency test is performed annually using an accredited laboratory, and establishes measurement traceability at that point in time. For all other points in time, SPC maintains confidence in the measurement processes.

Uncertainty Analysis

Law of Propagation of Uncertainty [2] was used to determine uncertainty in flow rate, volume, and K-factor measurements. The result was second order accurate (Eq. 1).

$$w_R = \left[\left(\frac{\partial S}{\partial \eta_1} w_1 \right)^2 + \left(\frac{\partial S}{\partial \eta_2} w_2 \right)^2 + \dots + \left(\frac{\partial S}{\partial \eta_n} w_n \right)^2 \right]^{\frac{1}{2}} \qquad (1)$$

Where ∂ was partial differential operator, η was component of measurement process, w was uncertainty of η, S was measurand, and w_n was measurement uncertainty.

Conservation of mass was used to derive a function for flow rate (the method is similar to that given by T. T, Yeh *et. al* [4]). The calibration system was modeled as a completely closed system (no leaks) and was broken into three components: 1) storage mass, 2) primary mass and 3) secondary mass. Storage mass was mass contained between the secondary and primary meters, secondary mass was total mass seen by the flow reference and primary mass was total mass seen by the primary meter (meter under test). Assuming that mass was conserved, the difference in mass passing through the primary meter from test start to test end was obtained by equating the total mass at each time.

$$\Delta M_{\mathrm{Pri}} = \Delta M_{\mathrm{S}} + \Delta M_{\mathrm{Sec}} \tag{2}$$

where Δ was the difference operator. Subscripts *S*, *Sec*, and *Pri* refer to Storage volume, Secondary flow reference, and Primary flow meter respectively.

The change in Storage Mass, ΔM_{Sec}, depended on its physical volume (V_S) and the density of water (ρ_w) at the test start and test stop times. Subscripts 1 and 2 refer to start and stop time respectively. $V_{S2} = V_{S1} + \Delta V_S$ and $\rho_{w2} = \rho_{w1} + \Delta\rho_w$, and second order terms were dropped.

$$\begin{aligned} \Delta M_{\mathrm{Sec}} &= M_{\mathrm{Sec2}} - M_{\mathrm{Sec1}} \\ &= V_{S2}\rho_{w2} - V_{S1}\rho_{w1} \\ &= (V_{S1} + \Delta V_S)(\rho_{w1} + \Delta\rho_w) - V_{S1}\rho_{w1} \\ &= (V_{S1}\rho_{w1} + V_{S1}\Delta\rho_w + \Delta V_S\rho_{w1} + \Delta V_S\Delta\rho_w - V_{S1}\rho_{w1} \\ \Delta M_{\mathrm{Sec}} &\cong V_{S1}\Delta\rho_w + \Delta V_S\rho_{w1} \end{aligned} \tag{3}$$

Volume and density were assumed to change with temperature according to Eqn. (4-5).

$$\Delta V = 3\cdot\alpha_s\cdot\Delta T\cdot V \tag{4}$$

$$\Delta\rho = -\rho\cdot\alpha_w\cdot\Delta T \tag{5}$$

Where α_s and α_w are the coefficients of thermal expansion for steel (linear) and water (volumetric), and ΔT is the change in temperature from test start to stop.

$$\begin{aligned} \Delta M_{\mathrm{Sec}} &= -V_S\alpha_w\cdot\Delta T\cdot\rho_w + \rho_w 3\cdot\alpha_s\cdot\Delta T\cdot V_S \\ &= V_S\rho_w\Delta T(3\alpha_s - \alpha_w) \end{aligned} \tag{6}$$

ΔM_{Sec} is the mass collected in the weigh tank and was calculated by measuring the difference in mass contained in the weigh tank from test start to test end. A buoyancy correction was made to account for buoyant force exerted on the water in the collection tank by the surrounding atmosphere.

$$\Delta M_{\mathrm{Sec}} = \Delta M_M \,/\left(1 - \frac{\rho_a}{\rho_w}\right) \tag{7}$$

Where ΔM_M the change in mass as is measured by the weigh scale, ρ_a was the density of air, and ρ_w was the density of water in the weigh tank. The density of water was assumed to be a function of temperature and the data shown in Table (2) was used to determine water density from temperature. The density of air was assumed to depend on temperature and the following equation was used to determine air density from temperature.

$$\rho_a = \frac{101.325\mathrm{kPa}}{287.058\frac{\mathrm{J}}{\mathrm{Kg\cdot K}}(T + 273.15)} \tag{8}$$

Where T was temperature in degrees Celsius.
Eqns (6) and (7) were then inserted into Eqn (2) to generate the change in Primary mass.

$$\Delta M_{\mathrm{Pri}} = V_S\rho_w\Delta T(3\alpha_s - \alpha_w) + \frac{\Delta M_M}{\left(1 - \rho_a/\rho_w\right)} \tag{9}$$

The mass flow *rate* seen by the meter under test was

$$\frac{\Delta M_{\mathrm{Pri}}}{\Delta t} = \frac{V_S\rho_w\Delta T(3\alpha_s - \alpha_w)}{\Delta t} + \frac{\Delta M_M}{\left(1 - \rho_a/\rho_w\right)\Delta t} \tag{10}$$

Where Δt was the adjusted test time. The test time was measured by the use of a photo-eye attached to the diverter. As the diverter passed through the stream of fluid exiting the fish tale, the photo-eye is trigged which simultaneously enabled the pulse counters for the MUT and a high precision frequency generator used to measure time. Adjustment of this photo-eye location was critical for accurate flow measurement. To account for diverter triggering asymmetries, the test time was adjusted as a function of flow rate using a 5th order polynomial fit of the data acquired following the procedure outlined in *Method 1 of Annex: A of ISO 4185* [8].

$$\Delta t = \Delta t' + \Delta t_{ISO}(Q_{set}) \tag{11}$$

Δt was the adjusted test time, $\Delta t'$ was the measured test time, $\Delta t_{ISO}(Q_{set})$ was the test time adjustment according to the ISO 4185 procedure as a function of Q_{set}, the set point flow rate. See Figs (1-2).

Volumetric flow rate, Q, was expressed as Eqn (10) divided by the fluid density, ρ_w.

$$Q = \frac{V_S \Delta T(3\alpha_s - \alpha_w)}{\Delta t} + \frac{\Delta M_M}{(\rho_w - \rho_a)\Delta t} \tag{12}$$

By measuring the uncertainties of each variable in Eqn (12), and using the law of propagation of uncertainty, Eqn (1), the uncertainty in flow rate were calculated.

References

[1] B. Belanger, "Measurement Assurance Programs Part I: General Introduction," NBS Special Publication 676-I, *U.S. Government Printing Office*, Washington, May 1984.

[2] S. J. Kline and F. A. McClintock, "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering*, January, 1953.

[3] D. J. Wheeler and D. S. Chambers, "Understanding Statistical Process Control," *SPC Press*, Knoxville TN, May 1984.

[4] T. T. Yeh *et. al*., "An Uncertainty Analysis of a NIST Hydrocarbon Flow Calibration Facility," *Proceedings of the 2004 Heat Transfer/Fluids Engineering Summer conference*, ASME 2004.

[5] ANSI/ASTM, "Measurement Uncertainty for Fluid Flow in Closed conduits" *American Society of Mechanical Engineers*, 2001.

[6] F. P. Incropera and D. P. Dewitt, "Introduction to Heat Transfer" John Wiley & Sons, Inc., 1996.

[7] Norman E. Dowling, "Mechanical Behavior of Materials." *Prentice Hall*, 1999.

[8] Iosif I. Shinder, "NIST Calibration Services for Water Flow Meters." NIST Special Publication 250, August 2006

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TABLE 1
THIS TABLE LISTS THE UNCERTAINTY BUDGET FOR FLOW RATE MEASUREMENTS.

	Value	Standard Uncertainty (%)	Standard Uncertainty (%)
1. Mass Uncertainty		Large Tank (2000 Gallon)	Small Tank (300 Gallon)
Small Scale Indication	0.5 lbs	N/A	0.02
Large Scale Indication	2 lbs	0.0125	N/A
Scale Drift		0.01	0.01
Scale Calibration	Class F	0.01	0.01
Storage Mass		0.002	0.014
Total Mass Uncertainty		0.019	0.028
2. Collection Time Uncertainty	100 (s)		
Timer Calibration	10 kHz	0.0002	0.0002
Diverter Actuation Small	0.031 (s)	N/A	0.031
Diverter Actuation Large	0.051 (s)	0.051	N/A
Total Time Uncertainty		0.051	0.031
3. Water Density Uncertainty			
Temperature Uncertainty	0.5 (C)	N/A	N/A
Total Water Density Uncertainty		0.01	0.01
Combined Uncertainty for Q		0.055	0.043
Expanded Uncertainty for Q (k=2)		0.111	0.086

Combined Standard Uncertainty: Values were calculated using the law of propagation of uncertainty (Fig 3). Uncertainty values were calculated under the assumption of a 100 (s) test where the tank was filled completely. Overall uncertainty depends on test time and amount of fluid collected in tank. In general, low flow rates and longer test times yield smaller system uncertainty.

TABLE 2
THIS TABLE LISTS THE WATER DENSITY AS A FUNCTION OF TEMPERATURE.

Temperature C	Density Kg/m^3
32.22	994.95
26.67	996.60
21.11	997.97
20.56	998.09
20.00	998.20
19.44	998.32
18.89	998.43
18.33	998.53
17.78	998.63
17.22	998.73
16.67	998.83
16.11	998.92
15.56	999.01
11.67	999.53

To determine the uncertainty in density, a polynomial fit of (Table 2) was made and the uncertainty was determined by the use of the law of propagation of uncertainty.

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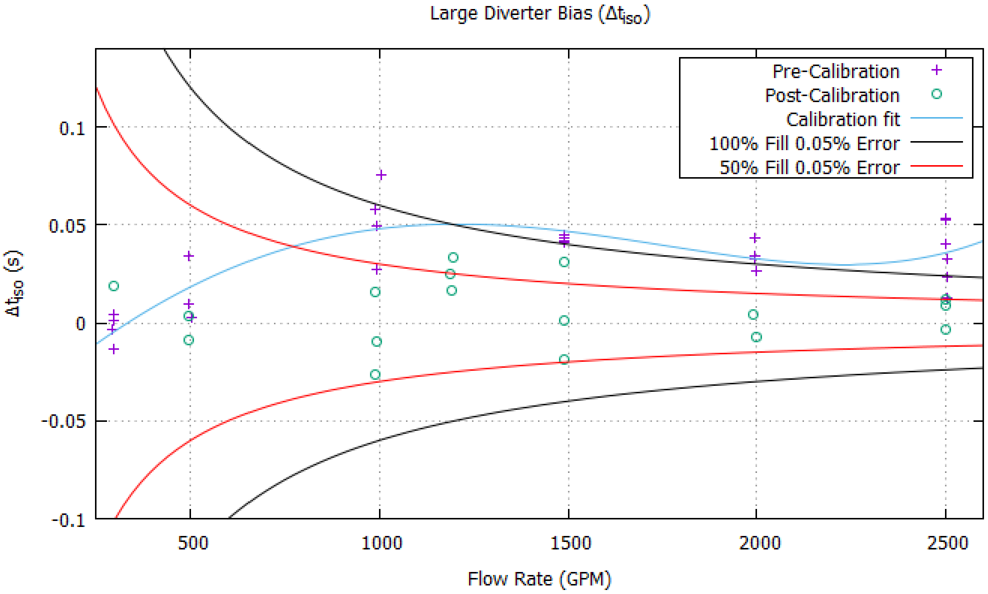

Figure 1: Large Diverter bias measurement results according to Method 1 Annex: A of ISO 4185.

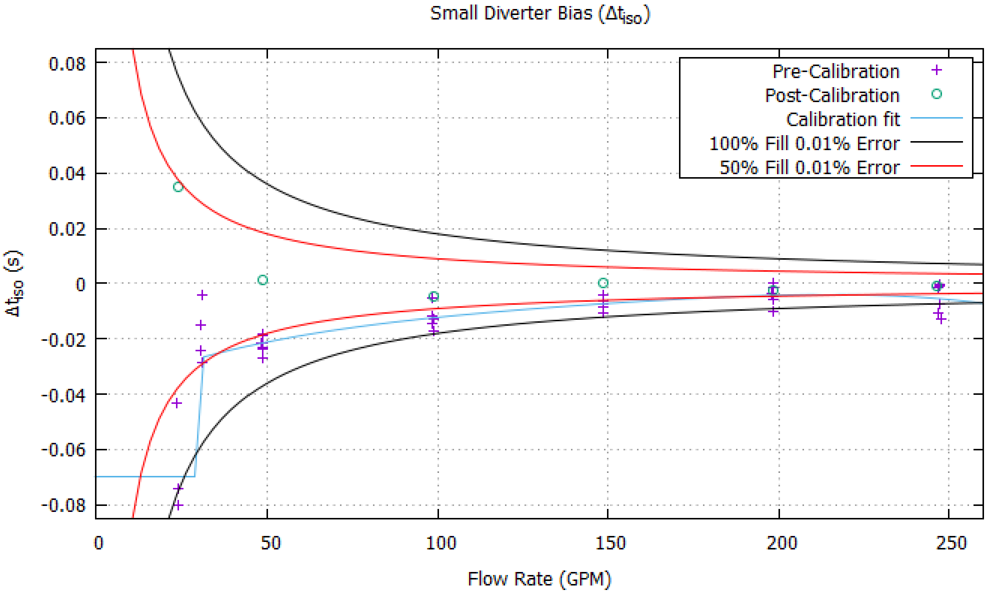

Figure 2: Small Diverter bias measurement results according to Method 1 Annex: A of ISO 4185.

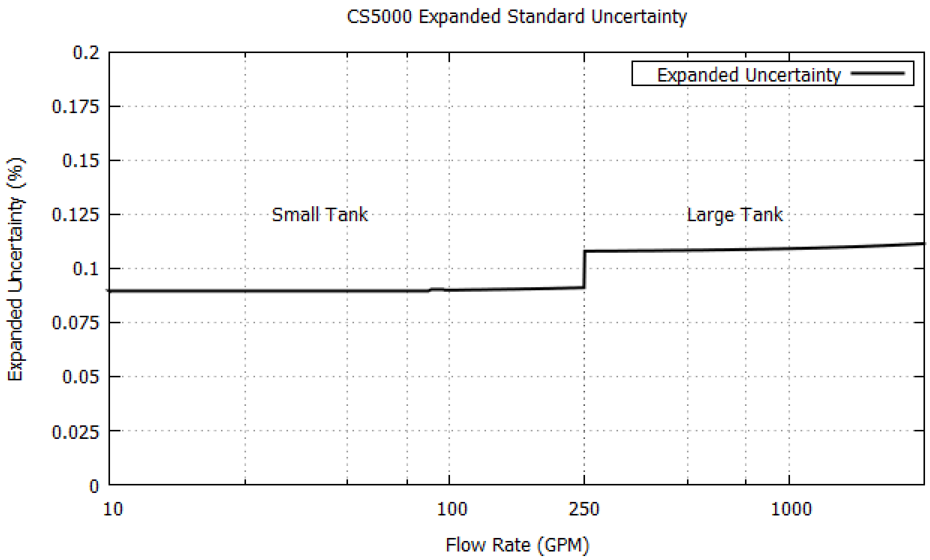

Figure 3: This figure illustrates combined expanded uncertainty of flow rate measurements versus flow rate. Coverage factor was two.

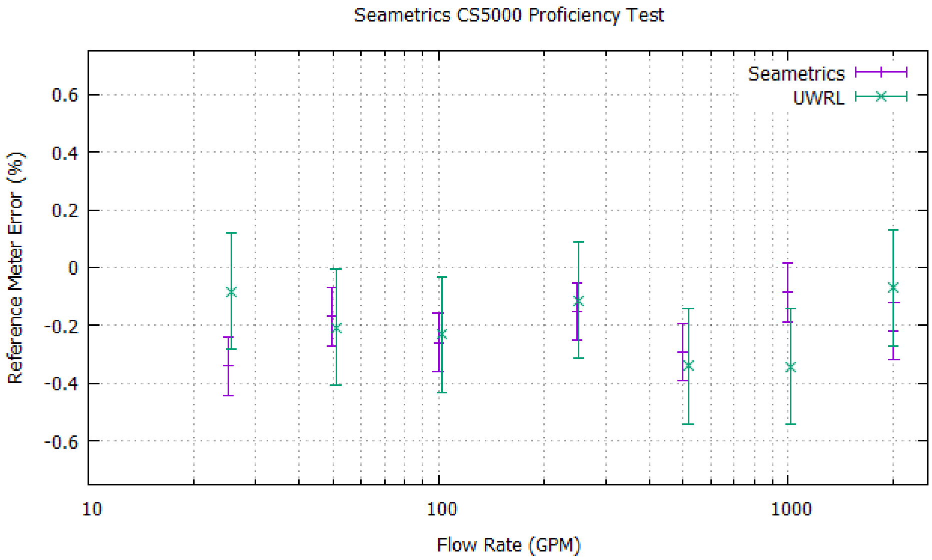

Figure 4: Proficiency Test results. Proficiency test was done by taking the mean of three readings from a 6" electromagnetic flow meter and using the standard deviation of the readings to reduce the random uncertainty contributed by the flow meter itself. Coverage factor was 2. Error bars for seametrics match those shown in **Table 1**, and uncertainty for UWRL was specified at 0.2% of Rate. Maximum difference of the mean was 0.27% at 25 GPM, average difference of the means over the full flow range was -0.018%.