PERFORMANCE IMPROVEMENT OF LIQUID FLOW CALIBRATORS BY APPLYING SPECIAL MEASUREMENT AND CONTROL STRATEGIES

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Abstract:
PTB's new 'Hydrodynamic Test Field', which represents a high-accuracy water flow calibration facility, will serve as the national primary standard for flow measurands: volumetric and mass flow rate, respectively, and total flow measurement, i.e. the quantity of fluid (volume or mass) passing a flowmeter. Owing to this application aspect, the main design goal was to realize a total expanded measurement uncertainty as low as 0,02 % for total volumetric flow-rate measurement. To meet this decisive requirement, low-uncertainty components were combined with state-of-the-art measurement and control strategies.

Introduction

In order to meet the requirements dedicated to the 'Hydrodynamic Test Field' as the national flow standard: expanded measurement uncertainty of total flow as low as 0,02 %, all accuracy determining component parts of the test field, like gravimetric references (special-design weighing system with integrated calibration capabilities [1][2][5]), flow diverters, volumetric reference (compact pipe prover) [6], density metering device and temperature sensing devices, were designed and constructed to meet individual uncertainty specifications that were verified by individual specifying test measurements. During the calibration facility's measurement operation the main process quantities (water flow rate, pressure and temperature), are stabilized by a computer-based *Supervisory Control and Data Acquisition* (SCADA) system, with numerous other relevant process parameters like fluid density, diverter actuation, balance readout and ambient-air conditions, being monitored. This is an essential prerequisite to provide reproducible conditions that are necessary to achieve a high degree of reproducibility in the measurement and calibration processes. This aspect of measurement uncertainty minimization is subject of this paper.

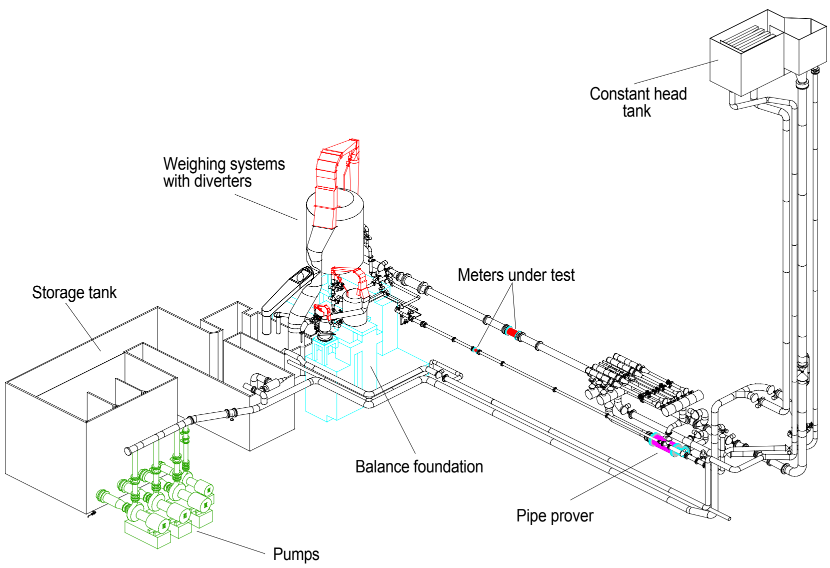


***Figure 1**. Cutaway view of PTB's water flow calibration plant (constant-head tank is located on 9th floor of Willy Wien Tower, at a height of 35 m)*

Plant design goals resulting from uncertainty requirements

General plant setup

The principle setup of PTB's new water flow calibration plant and its main component parts have been described in several conference papers or research reports ([1] through [6]). **Fig. 1** as a cutaway view and **Fig. 2**, presenting a view of the calibration hall, are to give a certain imagination about the plant's realistic dimensions that can be derived by comparing the 30-tons weighing tank in 3-dimensional drawing and photographic view of this tank in the background of **Fig. 2**. In **Tab. 1** there is presented a summarized overview of the calibration and measurement capabilities of the facility.

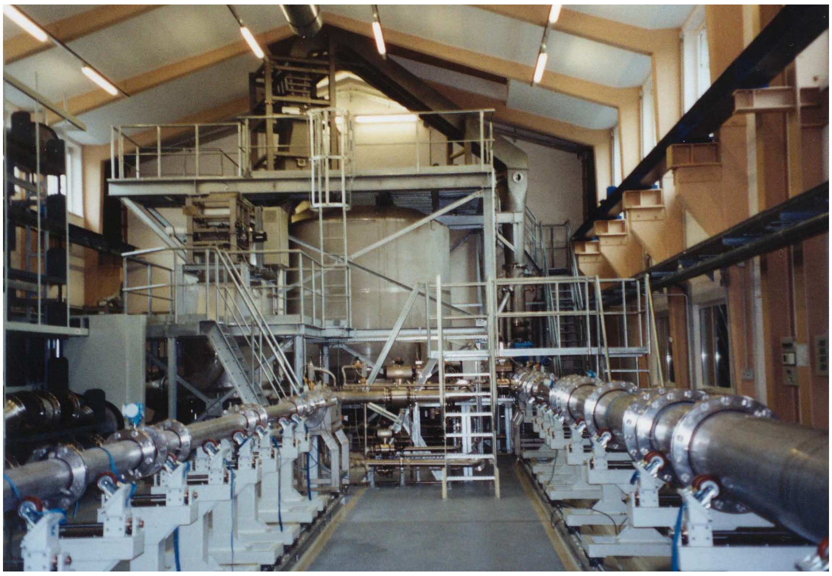


Figure 2*.* *View of calibration hall along the fluid's flow direction (calibration lines with the weighing system in the background)*

Table 1. *Global plant parameters of PTB's new 'Hydrodynamic Test Field'*

Plant features	Item(s)	Characteristics
Measurands	Volumetric flow rate Mass flow rate ***Volume*** (totalized) Mass (totalized)	Flow-rate meters *and* volume and mass flow totalizing meters
Calibration modes	a) flying START / FINISH b) standing START / FINISH	*Operation control via:* ***Diverter*** ON/OFF valve
Reference standards	***Gravimetric calibration*** (static weighing) Volumetric calibration	***Balances:*** 30 t 3 t 0,3 t Pipe prover
Operation modes	**Via constant-head tank** Pump direct operation	Constant pressure in calibration line (approx. 0,35 MPa) Variable pressure in calibration line (Max., approx. 0,6 MPa)
Meter / pipe sizes	Line A Line B	DN 200 ... DN 400 DN 20 ... DN 150
Ranges of flow rate	Line A Line B	3 m³/h ... 2100 m³/h 0,3 m³/h ... 320 m³/h
Expanded measurement uncertainty	**0,02 %**	(Operation via constant-head tank)

Referring to the expanded measurement uncertainty of 0,02 % that was claimed as one of the most important goal parameters, it must be mentioned that it will attained under following conditions and plant operations, respectively: totalized volume as the measurand (volume passed through the flowmeter under test, **FUT**), gravimetric calibration (flying START and FINISH operation with flow diverter) and stable flow-rate conditions by utilizing constant-head with auxiliary active level control. This calibration mode is the most frequent task in flowmeter calibration applications.
From this point of view, following questions arise:
- What process quantities, what plant devices and what environmental conditions (or parameters and conditions that have not been recognized as a potential factor of influence) have an impact on measurement uncertainty of the measurement process?

Table 2. *Measurement deviation ΔV_{Meas} of flowmeter calibration (factors of influence)*

$$\Delta V_{Meas} = V_{FUT} + \Delta V_{IP} - m_{REF} / \rho_{Water} \qquad \textbf{(1)}$$

A) **Fluid density**
- **Density measurement**
- **Temperature measurement in/nearby FUT**
- Calibration fluid sampling

B) **Gravimetric reference** (weighing system)
- **Mass of water** (collected in weighing tank)
- **Balance parameters/calibration**
- **Density of** environmental **air** (buoyancy)
- Density of water
- Diverter operation
- Evapuration of collected water
- Condensing moisture on weighing tank's outside

C) **Change in volume contents of interconnecting piping**
- **Temperature change** during a calibration run
- **Compressibility of water** (test fluid)
- Pressure change during a calibration run
- Leakage flow from/to neighboring pipe system(s)

D) **FUT's reading**
- **Density of water** (test fluid)
- **Time measurement** of divertion (flow diverter)
- **Temperature change** during a calibration run
- **Compressibility of water** (test fluid)
- **Change in flow rate** [3]
- Pressure change during a calibration run
- Meter readability
- Velocity profile of test fluid flowing through flowmeter
- and others

In **Tab. 2** we are presented an overview of the plant, the process and the environmental quantities that make contributions to the measurement deviation ΔV_{Meas} as a result of the measurement and calibration process. In order to achieve a low measurement uncertainty in this measurement and calibration process, there is the necessity for process quantities to be stabilized by active control loops (fluid flow rate, temperature, and pressure), others have to be metered and monitored in case that they are not controllable (e.g. fluid density, air contents in the fluid, ambient conditions like ambient-air temperature, barometric pressure, and ambient-air humidity).
Additionally there are process quantities whose magnitudes are not directly quantifiable by measurement, but the absence of which is a necessary prerequisite for a reliable measurement and calibration process. Such process parameters are air bubbles in the fluid or a leakage flow across closed valves that are to isolate the calibration line from neighboring pipe work which is not in use for the specific calibration task.
Above all, the stabilization of the fluid flow rate during a calibration run, is a necessary measure for precision flow calibration. It is obvious that a stable steady-state flow rate is an essential factor of uncertainty in the measurement of flow rate. But even in total flow (the mass or volume passing a

flowmeter) calibration a varying flow rate, i.e. imprecision in flow rate adjustment and stabilization, has an impact to measurement uncertainty [7].
In order to achieve a measurement uncertainty as low as 0,02 % for the calibration plant's operation, special provisions were made for precision control capabilities of fluid flow rate, fluid temperature, and pressure in the calibration line.

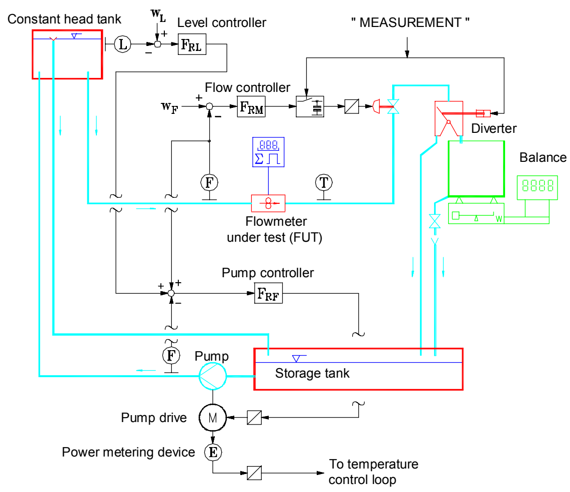


Figure 3. *Water flow calibration facility: flow control loops*

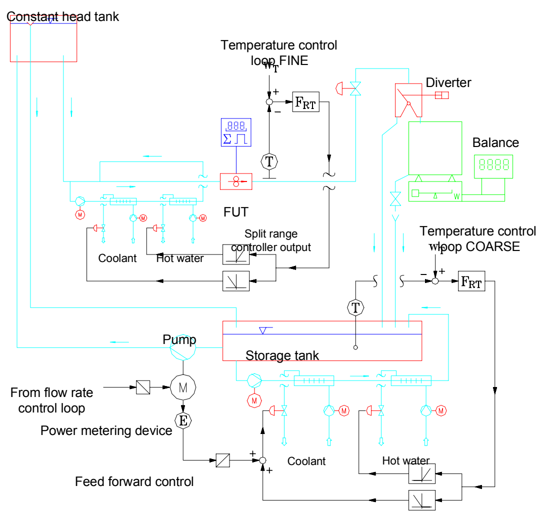


Figure 4. *Temperature control loops*

Control loop structures

- *Flow control*

The accuracy of flow rate stabilization is guaranteed by a cascaded control loop structure that comprises variable-speed pump drives (**Fig. 3**: Pump controller), upper-level tank with overflow weir and active level control (**Fig. 3**: Level controller), and, finally, a control loop for flow rate regulation in the calibration line (**Fig. 3**: Flow controller). This flow rate control structure is supported by an adaptive controller parameter adjustment strategy. Thus, an accurate and stable flow rate is guaranteed over a range from 0.3 m^3/h through 2,100 m^3/h.

- *Temperature control*

Another significant process variable is the water temperature in the calibration line and in the flowmeter under test (FUT), respectively. To meet the requirements of a low measurement uncertainty, the function of temperature control was dedicated to two separate control loops (see **Fig. 4**): *temperature coarse* (water temperature in the storage tank) and *fine controls* (water temperature in the calibration line). These two control loops were superseded by a distributed observer-based multivariable control strategy [8].
This sophisticated control loop structure and strategy was implemented on a specialized dedicated computer, which runs a real-time operation system. Adaptive parameter adjustment of the temperature controller is provided by the calibration plant's supervising process control system (a SCADA system based upon standard PC technology) via fieldbus-based communication devices, which incorporates the 'intelligent' fieldbus-based sensor and actuating devices (ON/OFF and regulating valves) in the plant's process area.
The magnitude of the process quantity temperature as a parameter of calibration can be adjusted by simply varying the respective setpoint value of the temperature controller in the SCADA system, what can be managed via interactive input to the SCADA system. Rangeability of temperature setpoint is from 20 °C through 26 °C. Widening this range will result in an increase of measurement uncertainty.

- Multi-variable control: Flow-pressure controls
The versatility of this calibration facility was expanded by the provision of capabilities to modify the flow-rate control loop structure. So it is possible to choose an operation mode in which the pumps directly feed the test fluid into the calibration line. Thus, water flow rate and pressure in the calibration line can be set independently, e.g., in order to investigate the influence of a varying fluid pressure on flowmeter accuracy (pressure rangeability: 2 bars through 6 bars).

Measurement procedures, data acquisition and processing

Real-time process data base system – "raw" measurement data gathering

The calibration plant in its entirety comprises approximately 570 process communication input and output points, i.e. sensors and actuating devices. Plant and process visualization and operating capabilities are provided by a distributed process control system: industrial programmable logic controllers in the process area, PC-based operator consoles and a SQL-based process-data archiving system at control room level. This data acquisition and data base computer system realizes a fully automated system startup, flowmeter calibration with, if wanted or necessary, interactive operator intervention capabilities for program modification, and finally automatic system shutdown. Automatic computer-based supervision of all plant devices, e.g. the leakage-prove operation of on/off valves, guarantees to provide reliable calibration results.

Measurement data correction

As a standard, all data acquired from sensing and actuating devices are stored in the SCADA system's real-time data base as so-called "raw" values, i.e. no corrective functions or signal filtering operations have been applied to these process values at the moment they are being stored.
Corrective functions are applied to acquired and stored measurement data to utilize the "raw" measurement data for visualization and data analysis purposes how it is necessary, e.g., to compute the accuracy characteristics of the flowmeter under test (error curve) based upon measurement data acquired during the meter's calibration.
Thus, there is the opportunity to modify or improve (e.g. the increase in the polynomial degree of an approximation function) corrective measures at any time it might be found to be necessary. It is also possible to simulate the effect of different types of corrective measures.
Individual corrective functions are applied to:

- Pt100 resistance temperature transducers (linearization of the sensors' steady-state response characteristics);
- Computation of the ambient air's density, utilizing measurement data of air temperature, pressure, and humidity;
- Buoyancy correction with the weighing systems (during calibration and during measurement);
- Linearization of balance readout (of both strain-gauge transducer and electromagnetic force-compensation load cells);
- Computation of the actual water density in the flowmeter under test (FUT) due to measured water density and process temperature;
- Process signal (measurement data) filtering to avoid erroneous effects due to signal noise (e.g. flowmeter signal output utilized for closed-loop flow-rate control);
- any further measurement and data processing application that will be found to be necessary.

This modular approach of after-measurement corrective measures avoids any loss of measurement data in case the corrective function is to be modified.

Man-machine interface and data presentation

With the 'Hydrodynamic Test Field', the calibration of the FUT can be run fully automatically, with the capabilities of the computer-based Supervisory Control and Data Acquisition (SCADA) system being utilized for automatic process control and operator interaction. The operator that initiates and supervises FUT calibration has full access to all process variables of the calibration plant. The so-called man-machine interface as the operator's view of the plant was realized with PC monitors presenting color graphics displays.

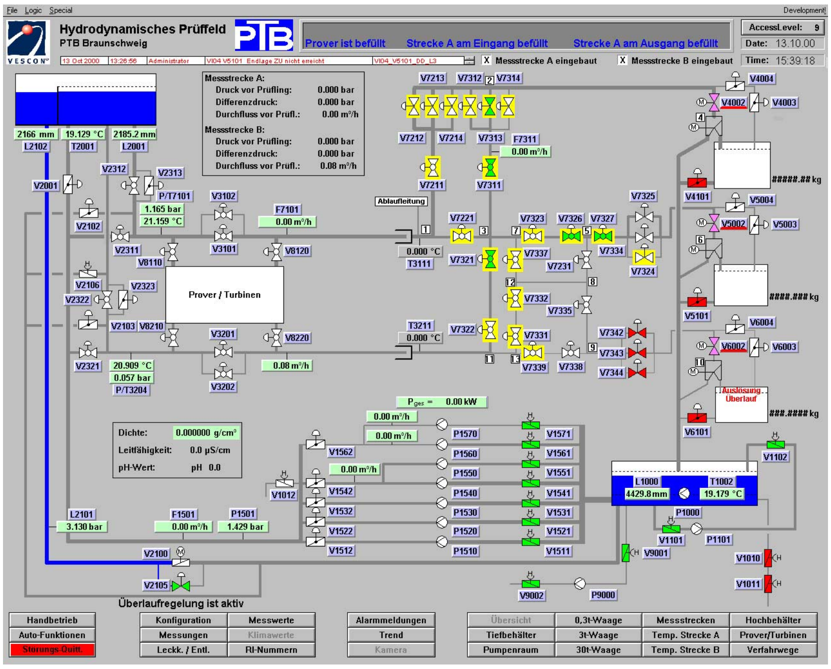


***Figure 5**. Video graphics display: PLANT OVERVIEW*

Fig. 5 depicts, as an example, the on-screen PLANT OVERVIEW display, which shows the most relevant plant items: sensing and actuating devices, their status and the actual measurement values. Virtual on-screen buttons are the "entry points" to start calibration or to dial zoomed views of certain plant areas presenting more detailed information.
Another essential feature of the calibration plant's SCADA system is the availability of oscilloscope-like real-time trend displays (**Fig. 6**) to present information to the operator what the stability of the process quantities is like, i.e. what the quality of the FUT's calibration will be like. In order to guarantee that the results of low-uncertainty calibrations are reliable, it is an absolute necessity to monitor the leakage-proof operation of ON/OFF valves that disconnect neighboring piping not in use from the calibration line (see **Tab. 2**: item **c**). **Fig. 7** shows such a leakage detecting device with an optical drop sensor.

<u>Advanced process measurement applications</u>

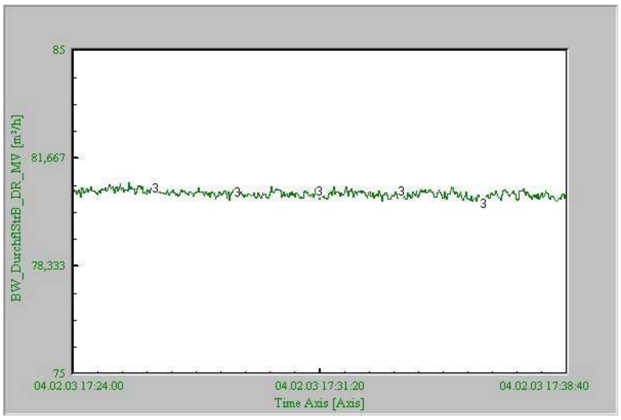
<u>In-process density metering</u>

In case that a volumetric flowmeter is subject of calibration in a gravimetric-reference system, it is evident that the measurement of the exact value of water density in the FUT is an accuracy-determining factor of meter calibration (see **Tab. 2**: **Equ. 1**). As water density is a function of temperature, the exact measurement of water density at the temperature that occurs within FUT during a calibration run has to be performed. According to [9] the temperature dependence of water density (air-free water) can be described by a fifth-order polynomial approximation in the temperature range from 0 °C up to 40 °C (**Equ. 2**).

$$\rho = \sum_{n=0}^{5} c_n \, t_{90}^{n} \qquad (2)$$

Investigations revealed that water density which has been measured by a high-accuracy density meter (described below) in temperature steps of 1 °C within the temperature range from 18 °C up to 30 °C can be described by a third-order polynomial approximation function (**Equ. 3**), with a numerical approximation error less than $2 \cdot 10^{-6}$ (see **Fig. 9a**).

$$\rho_{\text{Approx}} = \sum_{m=0}^{3} b_n \, t^m \qquad (3)$$



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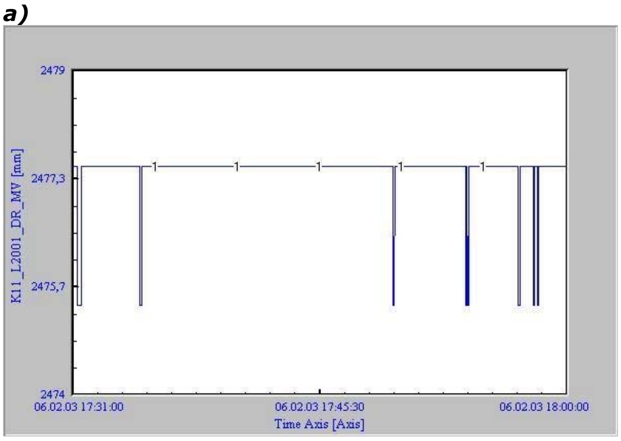

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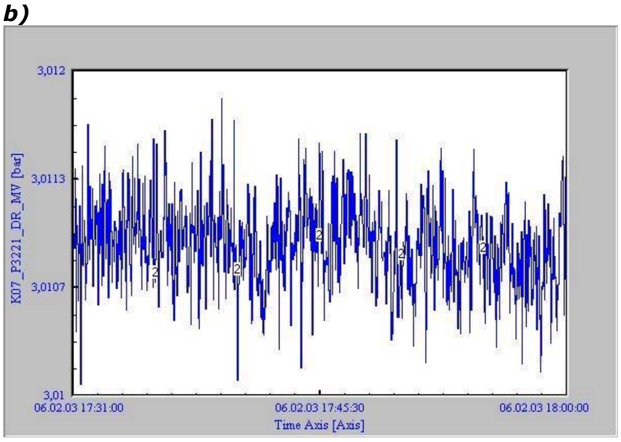


c)

Figure 6. *Oscilloscope-like real-time trend display of plant's process variables via SCADA system*
a) *Fluid flow rate through FUT*
b) *Level gauge at constant-head tank*
c) *Fluid pressure in FUT*

In the 'Hydrodynamic Test Field' in-process water density metering capabilities were provided to determine water density during calibration by means of a laboratory-type density meter with built-in sampling pump. A low-flowrate bypass flux is tapped from the calibration line and directed through a sampling vessel (see **Fig. 8**).
Measurements and observations of water density in the test field over several months (**Fig. 9b**) have shown that the requirements of measurement uncertainty (standard deviation [1]) in practical density measurement can be met by the density metering equipment in use.

Avoiding the presence of air in the calibration line
The presence of air (bubbles or solved air) in the calibration line will cause erroneous calibration results. To avoid this abnormal plant operation at several locations of the test field's pipe system air eliminating facilities were installed. The setup of such a air eliminator can be seen in **Fig. 10**. It comprises inlet and outlet solenoid valves to connect and disconnect, respectively, the facility to or from the calibration line and a vessel, in which air is accumulated and which is equipped with water level gauges. Accumulated air causes the water level in the vessel to fall. Conductive level gauges in the vessel detect three discrete water levels and are readout by the SCADA system. Reduced water level indicates the presence of air in the system and will cause an interruption of the regular calibration procedure until the accumulated air has been fully released via the upper solenoid valve.

A special automated operation mode of the air eliminators at system's startup supports the filling of the pipe system and the air elimination.
It should be mentioned that the presence of air in the test fluid can also be recognized or detected due to abnormal deviations of the computed approximation coefficients in **Equ. 3** as result of density measurement.

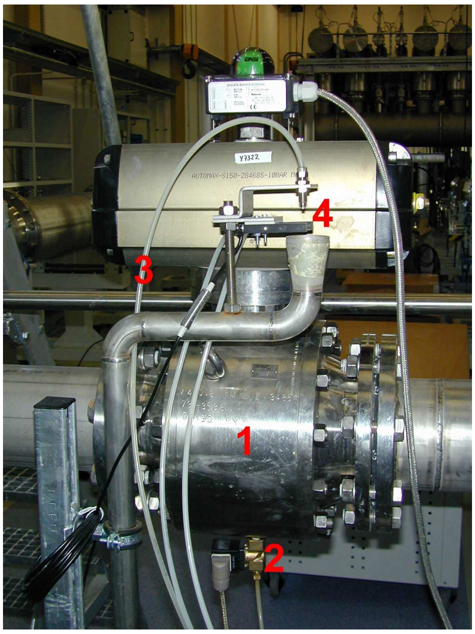


Figure 7. *Valve leakage-proof operation monitoring*
1) *Ball valve to be monitored*
2) *Solenoid drain valve*
3) *Connecting hose-pipe*
4) *Optical "drop" sensor*

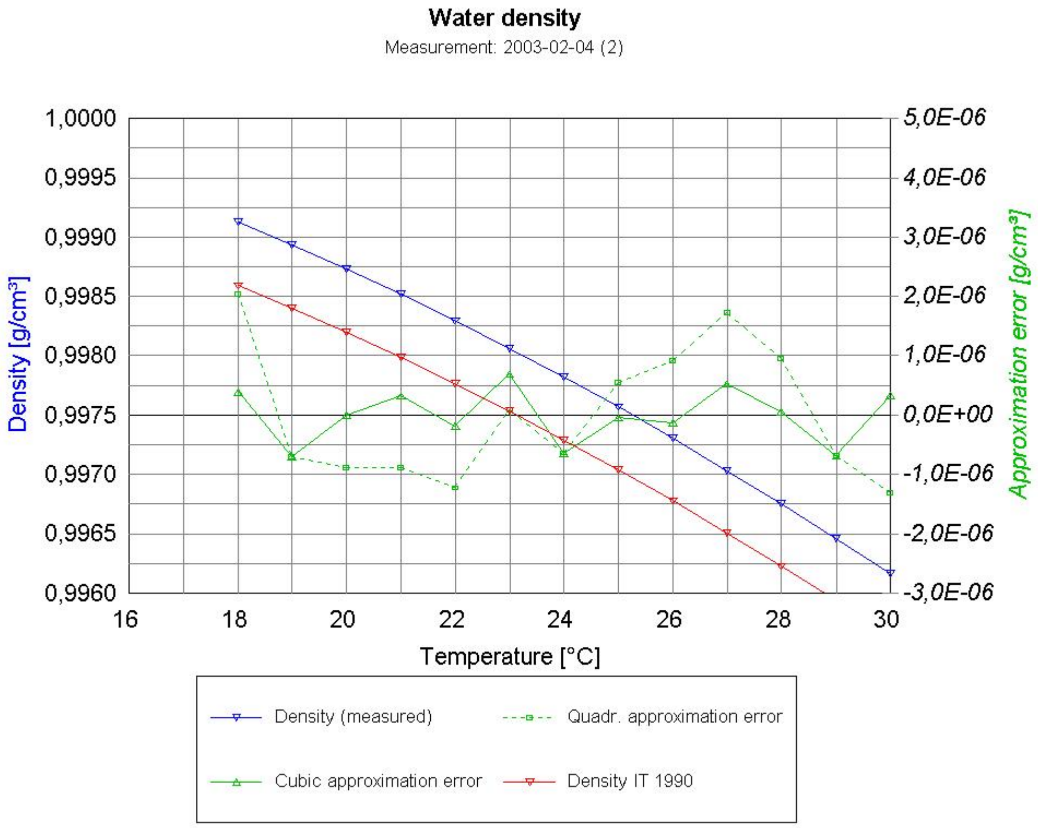
a)

b)

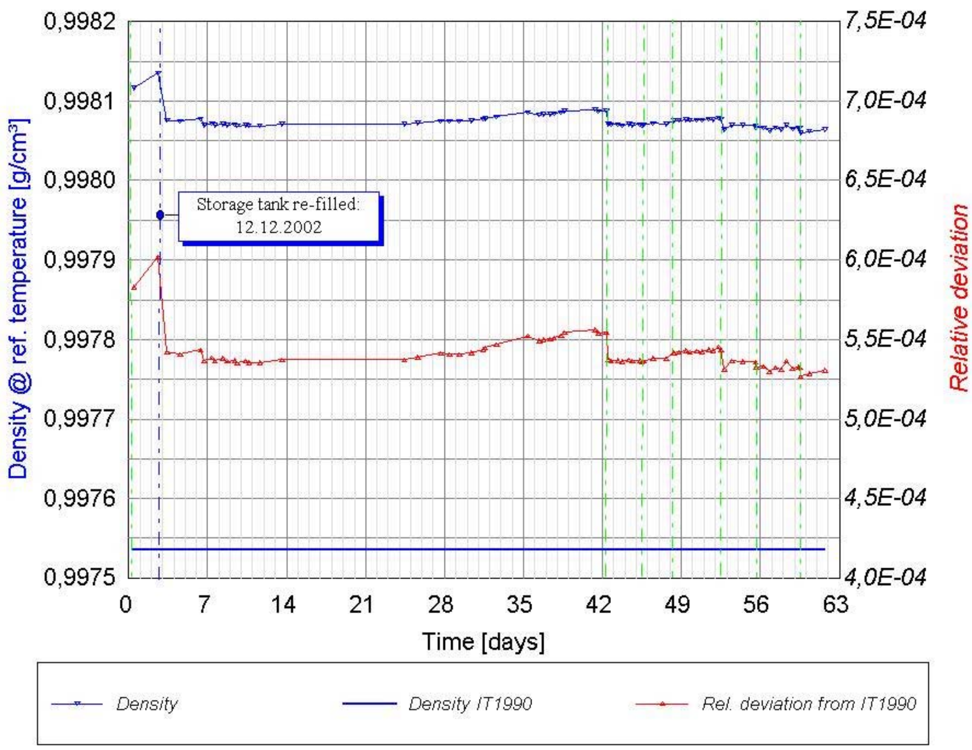
Figure 8. *In-process density metering facility*
a) *Laboratory-type density meter with automatic sampling pump (principle only)*
b) *Water sampling vessel that is flown through by water flow tapped from calibration line*

Weighing systems

The gravimetric-reference system comprises 3 weighing systems (30 tons, 3 tons, and 300 kg) with integrated calibration capabilities. Each of the 3 weighing systems consists of a dual-balance facility, combining strain-gauge transducer and electromagnetic force-compensation load cells [5]. **Fig. 11** presents the steady-state characteristics (calibration curve) of the 30-tons weighing system obtained from verification measurements.
Calibration data and measurement data readout is performed under supervisory control of the SCADA system and so all characteristics data are available in the central real-time data base for automated data processing purposes, e.g. function monitoring and correction of the balances' non-linear static characteristics.
The dual-balance weighing systems of the 'Hydrodynamic Test Field' represent extremely sensitive force-metering devices, e.g. the discrimination threshold of the 30-tons balance amounts to 10 grams.



a)



b)

Figure 9. *Water density measurement*
a) *Density measurement and approximation*
b) *Density (at reference temperature 23°C) vs. time (green dash-dot lines: density meter re-adjustments)*

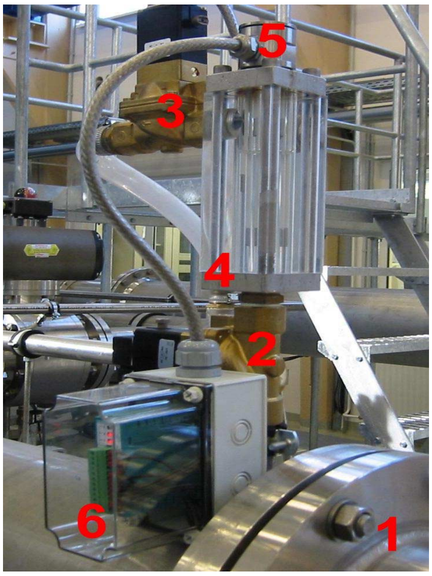


***Figure 10**. Plant air eliminating facility*
***1)** Calibration line piping*
***2)** Inlet solenoid valve*
***3)** Outlet solenoid valve*
***4)** Water level/air vessel*
***5)** Conductive level gauge*
***6)** Signal conditioning*

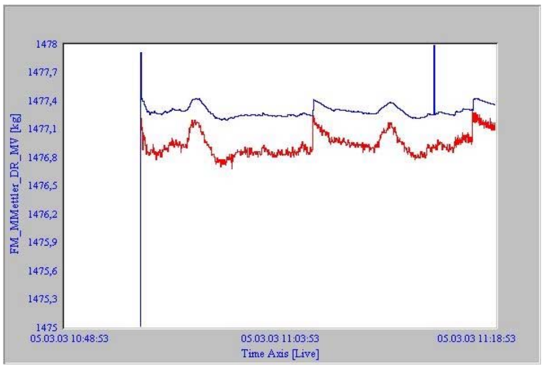


***Figure 12**. Readouts of dual-balance weighing system [5]: input step response and signal peaks due to external disturbances (Trend display of SCADA system)*
- upper/black curve: electromagnetic force-compensation load cell
- *lower/red curve: strain-gauge sensors*

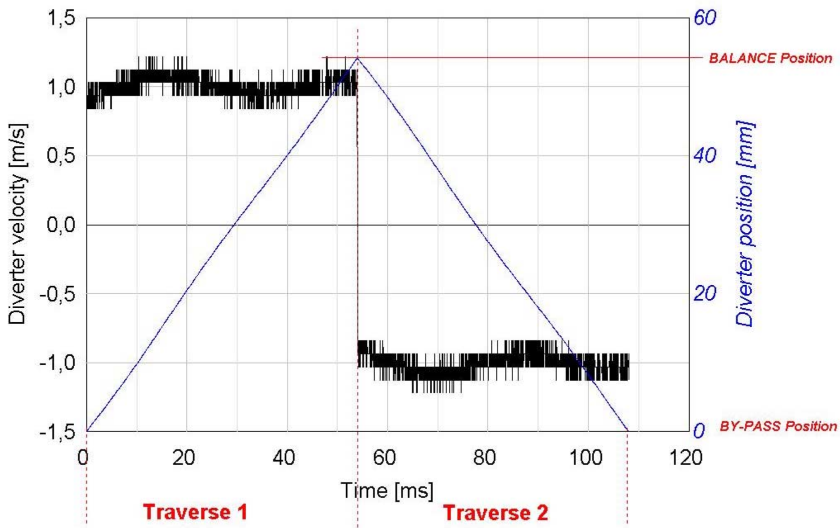
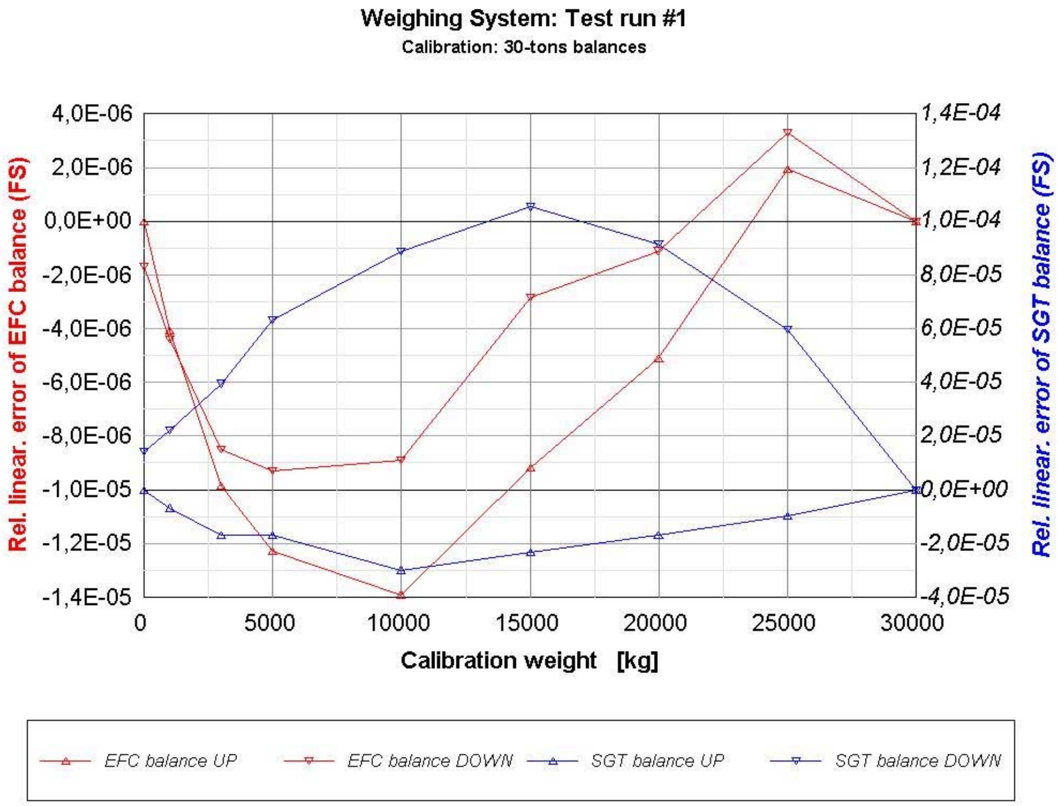
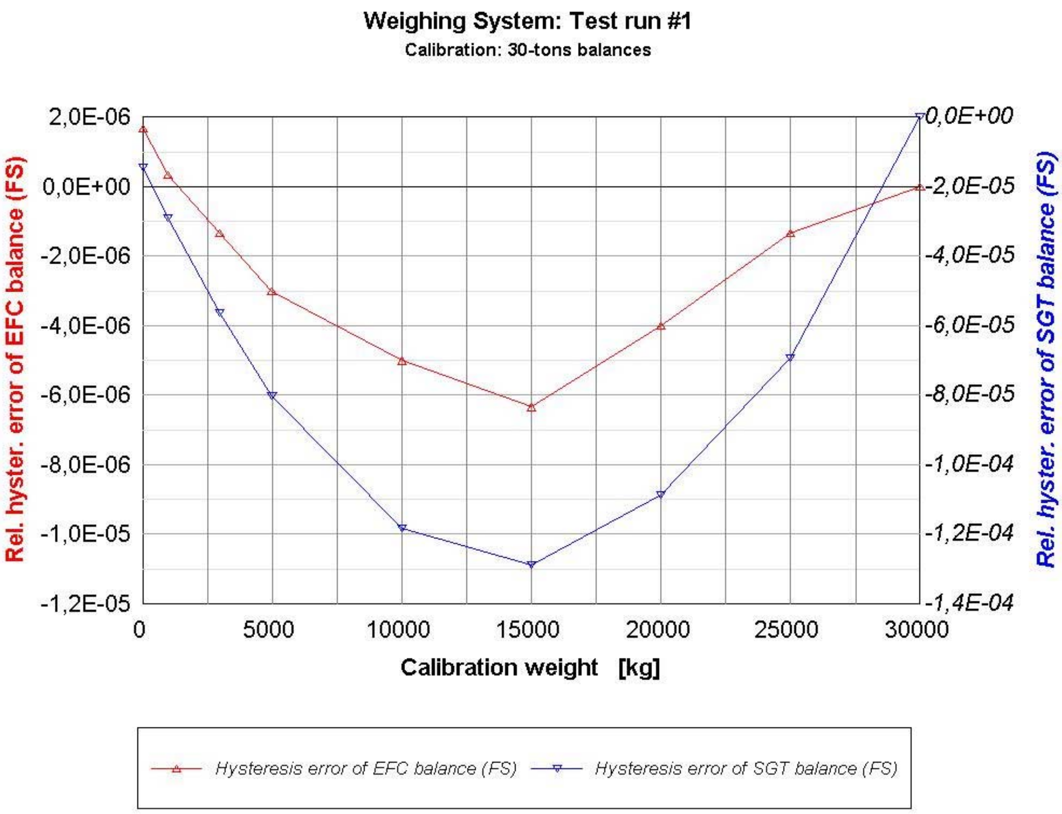


***Figure 13**. Diverter transition response: diverter position and velocity vs. time*



a)



b)

Figure 11. *Characteristics of the gravimetric reference system: 30-tons balances*
a) *Full scale (FS) related linearity errors of electromagnetic force-compensation (EFC) and strain-gauge transducer (SGT) balances*
a) *FS related hysteresis errors of EFC and SGT balances*

Though being supported by an active vibration isolation system, heavy mechanical excitation may "overcome" this disturbance avoiding system and, then, "blind" automated signal averaging techniques, as generally utilized, will deliver erroneous measurement results. The online trend-display capabilities of a SCADA system enable visual observations to be made in order to exclude time intervals from signal averaging when disturbing signals could be recognized.
Fig 12 shows an example of discontinuous signal response of the dual-balance weighing system in the presence of disturbing mechanical input excitation.

Monitoring the flow diverter operation
The flow diverter also represents a critical component part of a flow calibrator as it has a direct impact on measurement uncertainty [1].Thus the supervision of the diverter's reproducible operation is of essential importance. The new-design flow diverter [3] that incorporates novel approaches of actuating drive control and transition data measurement [4] is actuated and monitored by the SCADA system. In **Fig. 13** it can be observed that the diverter's transition movement is exactly controlled and held at the designed velocity of 1,0 m/s. The measured transition parameters are acquired by the supervisory control system and stored in the SCADA system's real-time data base. Thus the repeatability of the diverter operation can be monitored for quality assurance purpose.

Conclusions
The steady trend to improve the accuracy of measurement devices, including high-accuracy flow calibrators, is opposed by limiting factors and constraints, e.g. mechanical friction, components' inherent noise, instability or fluctuation of the quantity to be measured (measurand), as sources of uncertainty.
In designing the component parts of PTB's new 'Hydrodynamic Test Field' two accuracy determining goals were aimed at: the application of high-accuracy components ([1] through [6]) and the online monitoring of the system's performance characteristics to detect correlative interrelations that might occur between process variables or between process variables and ambient conditions.
The real-time data base as an inherent component of the SCADA system being applied for the automated operation of the test field provides capabilities to generate freely-programmable trend-curve diagrams (with a free choice from all process variables acquired and stored by the SCADA system). These special capabilities are a prerequisite for complex investigations that are necessary to uncover correlative relationships between process variables and to improve the system’s measurement uncertainty.

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