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Handbook Of Uncertainty Calculations – Ultrasonic Fiscal Oil Metering Stations

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ABSTRACT

A "*Handbook of uncertainty calculations - Ultrasonic fiscal oil metering stations"* [1] is being developed in a cooperation between NFOGM, NPD, Tekna and CMR, addressing fiscal metering of oil using multipath ultrasonic transit time flow meters (USM). The many different approaches to calculating the uncertainty of ultrasonic oil metering stations have been a source of confusion; - varying practice in this respect has definitely been experienced. The intention of the present initiative has been that a handbook together with a spreadsheet program *EMU - USM Fiscal Oil Metering Stations*, based upon the principles laid down in the "*Guide to the expression of uncertainty in measurement (GUM)"* [2] and ISO 5168:2005 [3], would satisfy the need for a modern method of uncertainty evaluation in the field of ultrasonic fiscal oil measurement.

Three different metering station scenarios are being addressed in [1]: (a) Scenario A, a USM ”duty meter” which is *in-situ* calibrated using a prover; (b) Scenario B, a USM ”duty meter” which is operated together with a USM ”master meter”, which is *in-situ* calibrated using a prover; and (c) Scenario C, a USM ”duty meter” which is operated together with a turbine (TM) ”master meter”, which is *in-situ* calibrated using a prover.

The present paper gives a description of Scenario A. Calculation of the expanded uncertainties of the following three metering station measurands are addressed: the actual volumetric flow rate, the standard volumetric flow rate and the mass flow rate. The analytical uncertainty model accounts for metering station instrumentation such as pressure transmitter, temperature element and transmitter, density measurement (vibrating element densitometer), prover and a multipath ultrasonic gas flow meter (USM). The expanded uncertainty of each of these measurands and instruments can be calculated and analyzed, isolated and combined (for the metering station). The basis for the *Handbook* and the program is described, together with an illustration example of a metering station uncertainty evaluation.

1 INTRODUCTION

1.1 Uncertainty evaluation of ultrasonic fiscal metering stations

Regulations relating to fiscal measurement of oil and gas [4-6] require that the overall measurement uncertainty is documented to be within defined limits. However, the different methods used have given different results. Consistent and standardised methods of uncertainty evaluation have been required, so that different measurement systems could be directly and reliably compared.

On this background, a series of handbooks on uncertainty calculation of fiscal metering stations for oil and gas is being developed in a cooperation between the Norwegian Society for Oil and Gas Measurement (NFOGM), the Norwegian Petroleum Directorate (NPD), Tekna and Christian Michelsen Research (CMR). This series includes handbooks of uncertainty calculations for ultrasonic fiscal gas metering stations [8,9] and for fiscal orifice gas and turbine oil metering stations [10]. The series is being extended by a handbook of uncertainty calculations for ultrasonic fiscal oil metering stations [1]. These handbooks are developed in conformity with the ISO "*Guide to the expression of uncertainty in measurement"* (commonly referred to as the *"Guide"* or the "*GUM"*) [2], which provides general rules for evaluating and expressing uncertainty in measurement, intended for a broad scope of measurement areas.

1.2 The *Handbook*

The *Handbook of uncertainty calculations - USM fiscal oil metering stations* [1] (for convenience here referred to as the *"Handbook")* consists of the *Handbook* itself and the Microsoft Excel program *EMU - USM Fiscal Oil Metering Stations* for performing uncertainty calculations of fiscal oil metering stations based on multipath ultrasonic transit time flow meters (USM), and individual instruments of such stations (cf. Section 2).

The USM fiscal oil metering stations addressed in the *Handbook* are primarily taken to be built and operated according to NPD regulations [4]. For USM fiscal metering of oil, the NPD regulations refer to e.g. the NORSOK I-105 national standard [5] and the API standard on ultrasonic liquid hydrocarbon meters [6] as recognised standards ("accepted norms"). The NPD regulations require hydrocarbon metering stations to be in conformity with the requirements stated by the European Union's "measurement instrument directive" (MID) [7]. Both the NPD regulations and the NORSOK I-105 standard refer to the *GUM* [2] as the "accepted norm" with respect to uncertainty analysis.

The *Handbook* and the accompanying computer program *EMU - USM Fiscal Oil Metering Stations* are based primarily on the recommended procedures in the *GUM*, in conformity with ISO 5168:2005 [3] (also based on the *GUM*).

With respect to uncertainty evaluation and documentation, refs. [3,4] state that the expanded uncertainty of the metering station shall be specified at a 95 % confidence level, using a coverage factor k = 2. Consequently, for output expanded uncertainties k = 2 is set as a fixed value in the program. For input expanded uncertainties, however, k is set by the user for each input uncertainty value (depending on the confidence level of the input uncertainty in question).

The uncertainty model for the USM oil metering station used here is based on an analytical approach. That is, the uncertainty models involving the USM, prover, pressure transmitter, temperature element/transmitter, densitometer, etc., are fully analytical, with expressions given and documented for the model and the sensitivity coefficients. The model is treated at a sufficiently generic level so that all relevant USM types for oil measurement are covered (cf. e.g. [11-14]), irrespective of path configuration, including non-reflecting path as well as reflecting path USMs. The intention has been to meet as far as possible manufacturer data specified today with respect to instrument uncertainties, including the USM. The work builds on earlier developments in this field [15-19,8-10].

The *Handbook* [1] is intended to provide a practical approach to the field of uncertainty calculations of ultrasonic fiscal oil metering stations. It is primarily written for experienced users and operators of fiscal oil metering stations, manufacturers of ultrasonic oil flow meters, engineering personnel as well as others with interests within the field. It has been the intention that the Excel program may be run without needing to read much of the *Handbook*, such as the theory part. However, Chapter 5 in the *Handbook* which gives an overview of the program, as well as Chapter 4 which - through an uncertainty evaluation example - provides some guidelines for specifying input parameters and uncertainties to the program, may be useful to read together with running the program for the first time.

2 USM FISCAL OIL METERING STATIONS

The types of fiscal oil metering stations considered in the *Handbook* consist basically of a USM "duty meter" (q_v), a prover, in some applications a "master meter" (which may be a USM or a turbine meter (TM)), a flow computer, and instrumentation such as pressure transmitter (P), temperature element and transmitter (T), and vibrating element densitometer (ρ).

Table 1. Characteristics for the 3 scenarios A, B and C of the types of USM fiscal oil metering stations addressed in the *Handbook*.

Operational scenario	Instrumentation for flow calibration and proving
Scenario A	A USM "duty meter" which is *in-situ* calibrated using a prover, typically every 4th day.
Scenario B	A USM "duty meter" which is operated together with a USM "master meter". The USM "duty meter" is *in-situ* calibrated vs. the USM "master meter". The USM "master meter" is *in-situ* calibrated vs. a prover, typically once a year.
Scenario C	A USM "duty meter" which is operated together with a turbine (TM) "master meter". The USM "duty meter" is *in-situ* calibrated vs. the TM "master meter". The TM "master meter" is *in-situ* calibrated vs. a prover, typically once a year.

With respect to flow calibration and proving of the USM "duty meter" and the "master meter" (USM or TM), three different operational scenarios A, B and C are considered in the *Handbook* [1], cf. Table 1.

In the present paper, Scenario A only is addressed in the following. For this case, consider a fiscal oil metering station equipped with instrumentation as specified in Table 2.

Table 2. Equipment specified as default instrumentation for ***Scenario A*** of the USM fiscal oil metering station addressed in the *Handbook*. Included is also example instrumentation used for uncertainty evaluation of a fiscal oil metering station in Section 5.

Measurement	Instrument
Ultrasonic "duty meter" (USM)	Multipath ultrasonic transit time flow meter. Otherwise not specified. *In-situ* calibrated by use of prover, typically every 4th day.
Prover	Not specified (arbitrary).
Flow computer	Not specified (arbitrary).
Pressure (static), P	Not specified. Example: Rosemount 3051P Reference Class Pressure Transmitter [20].
Temperature, T	Not specified. Example: Pt 100 element: according to EN 60751 tolerance A [5]. Rosemount 3144 Smart Temperature Transmitter [21].
Density, ρ	On-line (by-pass) installed vibrating element densitometer. Otherwise not specified. Example: Solartron 7835 Liquid Density Transducer [22].

For fiscal oil metering stations, three flow rates are in question [5]:

- Actual volumetric flow rate (i.e. the axial volumetric flow rate at line conditions), q_v,
- Standard volumetric flow rate (i.e., the axial volumetric flow rate at standard reference conditions), Q_v, and
- Mass flow rate, q_m.

For Scenario A, these are given as[1] [1]

$$q_v = 3600 \cdot C_{prov} \cdot q_{USM} \qquad [\mathrm{m^3/h}] , \tag{1a}$$

$$Q_v = \frac{\rho}{\rho_{ref}} q_v = q_v \cdot C_{tlm} \cdot C_{plm} \qquad [\mathrm{Sm^3/h}] , \tag{1b}$$

$$q_m = \rho q_v = \rho_{ref} Q_v = \frac{\rho_d}{C_{tld} \cdot C_{pld}} Q_v \qquad [\mathrm{kg/h}] , \tag{1c}$$

respectively. The "proving correction factor"

$$C_{prov} \equiv f_{prov}(C_1^{prov}, C_2^{prov}, ..., C_M^{prov}) \tag{2}$$

is some function, f_{prov}, of the M meter factors,

[1] Symbols are defined at the end of the paper.

$$C_j^{prov} = \frac{K_{DFC}}{K_{prov,j}^{USM}}, \qquad j = 1, \ldots, M, \tag{3}$$

where the meter factors C_j^{prov} are calculated from the K-factors, $K_{prov,j}^{USM}$, j = 1, …, M, which are obtained by proving of the USM at M different nominal test flow rates (“proving points”) [1]. The DFC (digital-to-frequency converter) factor K_{DFC} is used to let the USM deliver pulses per second as its output quantity, and is specified by the USM manufacturer [1].

Typically, M is 4 to 6, and C_{prov} may be flow rate dependent. Methods for calculation of the correction factor C_{prov} from the M meter factors C_j^{prov} (cf. Eq. (2)) include various types of single-factor and multi-factor corrections[2]. The uncertainty model described here covers any of these methods. In fact, for use of the uncertainty program one does not need to know C_{prov} nor the method used for calculating C_{prov}. It is sufficient to know the corrected relative deviation after C_{prov} has been applied, $Dev_{C,j}$, defined by Eq. (9).

The functional relationships of the USM, pressure transmitter, temperature element/transmitter and liquid densitometer, which form the basis for the uncertainty model described in Section 3, are described in [1]. Due to space limitations these are not given here.

3 UNCERTAINTY MODEL OF THE OIL METERING STATION

For the three measurands given in Eqs. (1), the relative combined standard uncertainties are given as [1]

$$E_{q_v}^2 = E_{proving}^2 + E_{USM}^2 + E_{comm}^2 + E_{flocom}^2, \tag{4a}$$

$$E_{Q_v}^2 = E_{q_v}^2 + E_{C_{tlm}}^2 + E_{C_{plm}}^2 + correlation\ terms\ A, \tag{4b}$$

$$E_{q_m}^2 = E_{Q_v}^2 + E_{\rho_d}^2 + E_{C_{tld}}^2 + E_{C_{pld}}^2 + correlation\ terms\ B, \tag{4c}$$

respectively. In Eqs. (4), "correlation terms A" refer to correlations between the volume correction factors C_{tlm}, C_{plm} and the volume correction factors C_{tlp}, C_{plp}, C_{tsp} and C_{psp} appearing in Eqs. (1b) and (1a), respectively (cf. also Eq. (10)). Furthermore, "correlation terms B" refer to correlations between the volume correction factors C_{tld}, C_{pld} and the above mentioned volume correction factors. Such correlations are neglected in the simplified calculation example given here, cf. Section 5.

The corresponding relative expanded uncertainties at a 95 % confidence level are obtained by multiplying with the coverage factor k = 2 (assuming a normal probability distribution).

The derivation underlying the uncertainty model given by Eqs. (4) is rather comprehensive, and for details it is referred to [1]. The model has been obtained by a detailed analysis of correlated and uncorrelated effects in the USM, such as for the USM in duty operation vs. proving, between the various acoustic paths of the USM, between upstream and downstream signal propagation in a given acoustic path (correlated and uncorrelated transit time contributions), etc. Thus, elimination of systematic effects in the USM by proving is accounted for, so that these do not contribute to the metering station uncertainty. The analysis is made in compliance with the procedure for evaluating and expressing

[2] Single-factor correction methods for calculation of the "proving correction factor" C_{prov} include e.g. (a) the flow-weighted mean error (FWME) [23], (b) the weighted mean error (WME) [24], and average meter factor methods. Multi-factor correction methods include e.g. (a) piecewise linear interpolation [23], (b) multi-point (higher order) polynomial algorithms [23], and (c) regression analysis methods.

uncertainties recommended in [2][3]. The various terms involved in Eqs. (4) are further described in the following.

3.1 Pressure transmitter uncertainty

The relative combined standard uncertainty of the pressure measurement is given as $E_P \equiv u_c(\hat{P})/\hat{P}$, where [1,10]

$$u_c^2(\hat{P}) = u^2(\hat{P}_{transmitter}) + u^2(\hat{P}_{stability}) + u^2(\hat{P}_{RFI}) + u^2(\hat{P}_{temp}) + u^2(\hat{P}_{atm}) + u^2(\hat{P}_{vibration}) + u^2(\hat{P}_{power}) + u^2(\hat{P}_{misc}) \quad (5)$$

gives the combined standard uncertainty of the pressure measurement[4]. The eight terms at the right hand side of Eq. (5) account, respectively, for uncertainties related to (a) the pressure transmitter (hysteresis, terminal-based linearity, repeatability, pressure calibration laboratory), (b) stability of the pressure transmitter, (c) radio-frequency interference (RFI) effects, (d) temperature effects, (e) atmospheric pressure, (f) vibration effects, (g) power supply effects, and (h) miscellaneous effects (mounting, etc.). With exception for (c) and (e), information on these input uncertainties may be provided by the instrument manufacturer or calibration laboratory, cf. e.g. [20].

3.2 Temperature element / transmitter uncertainty

The relative combined standard uncertainty of the temperature measurement is given as $E_T \equiv u_c(\hat{T})/\hat{T}$, where [1,10]

$$u_c^2(\hat{T}) = u^2(\hat{T}_{elem,transm}) + u^2(\hat{T}_{stab,transm}) + u^2(\hat{T}_{RFI}) + u^2(\hat{T}_{temp}) + u^2(\hat{T}_{stab,elem}) + u^2(\hat{T}_{vibration}) + u^2(\hat{T}_{power}) + u^2(\hat{T}_{cable}) + u^2(\hat{T}_{misc}) \quad (6)$$

gives the combined standard uncertainty of the temperature measurement. The nine terms at the right hand side of Eq. (6) account, respectively, for uncertainties related to (a) the temperature element and transmitter calibrated as a unit, (b) stability of the temperature transmitter, (c) RFI effects, (d) temperature effects, (e) stability of the Pt100 element, (f) vibration effects, (g) power supply effects, (h) lead resistance effects, and (i) miscellaneous effects. With exception for (c), information on these input uncertainties may be provided by the instrument manufacturer or calibration laboratory, cf. e.g. [21].

3.3 Densitometer uncertainty

The relative combined standard uncertainty of the density measurement is given as $E_\rho \equiv u_c(\hat{\rho})/\hat{\rho}$, where [1,10]

$$u_c^2(\hat{\rho}) = s_{\rho_u}^2 u^2(\hat{\rho}_u) + u^2(\hat{\rho}_{stab}) + u^2(\hat{\rho}_{rept}) + s_{\rho,T_d}^2 u_c^2(\hat{T}_d) + s_{\rho,P_d}^2 u_c^2(\hat{P}_d) + u^2(\hat{\rho}_{temp}) + + u^2(\hat{\rho}_{pres}) + u_c^2(\hat{\rho}_{inst}) + u^2(\hat{\rho}_{misc}) \quad (7)$$

gives the combined standard uncertainty of the density measurement. In addition to the usual frequency relationship regression curve, the functional relationship of the vibrating-element liquid densitometer used here accounts for temperature correction and pressure correction [1,10].

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[3] With respect to symbol notation, the *Handbook* deviates in a few cases from the recommendations given in [2], mainly for practical reasons. E.g., for relative standard uncertainties and rel. sensitivity coefficients, the symbols "E_x" and "s_x^*" are used in [1], whereas the recommended symbols in [2] are "$u(x)/x$" and "c_x^*", respectively.

[4] To distinguish between a quantity and an estimated value of the quantity, the symbol "$\hat{x}$" (the "hat notation") is used here to denote the estimated value of the quantity "x".

The nine terms at the right hand side of Eq. (7) account, respectively, for uncertainties related to (a) the indicated (uncorrected) density (calibration laboratory instruments, reading error during calibration, hysteresis, etc.) (also referred to as the "densitometer accuracy" [22]), (b) stability, (c) repeatability, (d) temperature measurement in the densitometer, T_d, (e) pressure measurement in the densitometer, P_d, (f) the temperature correction model, (g) the pressure correction model, (h) temperature and pressure effect of an on-line installation (by-pass) of the densitometer, and (i) miscellaneous effects (reading error, deposits, corrosion, vibrations, power supply variations, self-induced heat, flow in by-pass line, etc.). The various $s_{x,y}$ terms are sensitivity coefficients given in [1].

Figures for the input uncertainties $u(\hat{\rho}_u)$, $u(\hat{\rho}_{stab})$, $u(\hat{\rho}_{rept})$, $u(\hat{\rho}_{temp})$, $u(\hat{\rho}_{pres})$ and $u_c(\hat{\rho}_{inst})$ and contributions to $u(\hat{\rho}_{misc})$ should normally be provided by the instrument manufacturer or the calibration laboratory, cf. e.g. [22]. $u_c(\hat{P})$ and $u_c(\hat{T})$ are given by Eqs. (5)-(6).

3.4 Proving uncertainty

In Eq. (4a), the relative combined standard uncertainty related to proving of the USM is given by [1]

$$E_{proving}^2 \equiv E_{C_{dev,j}}^2 + E_{Q_{prover,j}}^2 + \left(E_{rept,j}^{proving}\right)^2 . \qquad (8)$$

The three terms at the right hand side of Eq. (8) account, respectively, for uncertainties related to (a) the deviation factor, (b) the prover measurement at proving flow rate no. *j, j = 1,…,M* (representing the uncertainty of the prover), and (c) the repeatability at proving flow rate no. *j*, *j* = 1, …, *M*. In practice $E_{rept,j}^{proving}$ represents the relative standard deviation of the spread of measured flow rates, at proving flow rate no. *j* (due to random effects related to the USM and the prover).

The deviation factor $C_{dev,j}$ represents the uncorrected deviation between the USM measurement and the "deviation curve" resulting from proving the USM at the *M* proving points, after correction of the USM measurement by the correction factor C_{prov} has been made. It can be shown [1] that the relative standard uncertainty of the deviation factor may be expressed as

$$E_{C_{dev,j}} = \frac{1}{\sqrt{3}}\left|\frac{Dev_{C,j}}{\hat{C}_{dev,j}}\right| \approx \frac{Dev_{C,j}}{\sqrt{3}} , \qquad Dev_{C,j} = \frac{C_{prov} \cdot Q_{USM,j}^{proving} - Q_{prover,j}}{Q_{prover,j}} , \qquad j = 1, \ldots, M, \qquad (9)$$

where $Q_{USM,j}^{proving}$ is the standard volumetric flow rate measured by the USM under proving, at proving flow rate no. *j*, $Q_{prover,j}$ is the standard volumetric flow rate as measured by the prover, $Dev_{C,j}$ is the corrected relative deviation at this test flow rate (i.e. the relative deviation after multiplication with the proving correction factor, C_{prov}), and $C_{dev,j} = 1 + Dev_{C,j}$ is the deviation factor. The deviation data $Dev_{C,j}$, *j = 1, …, M*, are available from proving at the *M* proving flow rates. Details are given in [1].

The relative combined standard uncertainty of the prover volumetric flow rate measurement at proving flow rate no. *j* is given by [1]

$$E_{Q_{prover,j}}^2 \equiv E_{BV}^2 + E_{\Delta t_p}^2 + E_{C_{tsp}}^2 + E_{C_{psp}}^2 + E_{C_{tlp}}^2 + E_{C_{plp}}^2 + correlation\ terms\ C \ . \qquad (10)$$

In Eq. (10), "correlation terms C" refer to correlations between the volume correction factors, such as (a) temperature correlations between C_{tsp} and C_{tlp}, C_{tsp} and C_{plp}, C_{tlp} and C_{plp}, (b) pressure correlations between C_{psp} and C_{plp}, and (c) density correlation between C_{tlp} and

C_{plp} [1]. Such correlations are neglected in the simplified calculation example given here, cf. Section 5.

3.5 USM duty operation uncertainty

In Eq. (4a), the relative combined standard uncertainty of the USM in duty operation is given by [1]

$$E_{USM}^2 \equiv E_{rept}^2 + E_{USM,\Delta}^2 + E_{misc}^2 . \tag{11}$$

The three terms at the right hand side of Eq. (11) account, respectively, for uncertainties related to (a) repeatability of the USM measurement in duty operation, at the flow rate in question (due to random transit time effects), (b) systematic effects in duty operation of the USM, due to change of conditions from proving to duty operation, and (c) miscellaneous systematic effects on the USM duty measurement which are not eliminated by proving, and which are not covered by other uncertainty terms accounted for here (e.g. inaccuracy of the USM functional relationship (the underlying mathematical model), etc.).

In Eq. (11), the "USM duty repeatability" term is given by

$$E_{rept}^2 \equiv 2\sum_{i=1}^{N} (s_{t1i}^* E_{t1i,U})^2 . \tag{12}$$

The relative sensitivity coefficient s_{t1i}^* is given in [1]. $E_{t1i,U}$ is the relative standard uncertainty of those contributions to the transit times of path no. *i* which are uncorrelated with respect to upstream and downstream propagation. It is given as

$$E_{t1i,U} = u(\hat{t}_{1i}^{random}) / \hat{t}_{1i} , \tag{13}$$

where $\hat{t}_{1i}$ is the upstream transit time of path no. *i*, and and $u(\hat{t}_{1i}^{random})$ is the standard uncertainty due to in-duty random effects on transit times (after possible signal averaging), such as (a) turbulence, (b) incoherent noise (due to pressure reduction valves, RFI, vibrations, etc.), (c) coherent noise (acoustical and electrical cross-talk, acoustic reverberation, other signal interference), (d) finite clock resolution, (e) electronics stability (possible random effects), (f) possible random effects in signal detection/processing (e.g. erroneous signal period identification), and (g) power supply variations. In practice, at a given flow rate, $u(\hat{t}_{1i}^{random})$ represents the standard deviation of the spread of measured transit times in path no. *i*. Similarly, E_{rept} represents the standard deviation of the spread of measured flow rates, at the actual flow rate.

In Eq. (11), the "systematic USM duty effects" term can be expressed by[5]

$$E_{USM,\Delta}^2 \equiv E_{body,\Delta}^2 + E_{time,\Delta}^2 + E_{I,\Delta}^2 , \tag{14}$$

where the three terms at the right hand side of Eq. (14) account, respectively, for uncertainties related to (a) possible uncorrected change of the USM meter body dimensions (radius, lateral chord positions, inclination angles) from proving to duty operation, caused by possible deviation in *P*, *T* between proving and duty operation, (b) possible uncorrected systematic effects on the transit times caused e.g. by deviation in conditions from proving to duty operation (*P*, *T*, transducer deposits, transducer ageing, etc), and (c) possible change of installation conditions from proving to duty operation (related to the USM integration method).

[5] The subscript "Δ" denotes that *only deviations relative to the conditions at proving* are to be accounted for in the expressions involving this subscript. That means, uncertainty contributions which are practically eliminated by proving, are *not* to be included in these expressions.

In Eq. (14), the "meter body uncertainty" term can be shown [1] to be given as

$$E_{body,\Delta} \equiv E_{rad,\Delta} + E_{chord,\Delta} + E_{angle,\Delta} \ , \tag{15a}$$

where

$$E_{rad,\Delta} \equiv s_R^* E_{R,\Delta} \ , \qquad E_{chord,\Delta} \equiv \sum_{i=1}^{N} sign(\hat{y}_i) s_{yi}^* E_{yi,\Delta} \ , \qquad E_{angle,\Delta} \equiv \sum_{i=1}^{N} sign(\hat{\phi}_i) s_{\phi i}^* E_{\phi i,\Delta} \ , \tag{15b}$$

$$E_{R,\Delta}^2 = E_{yi,\Delta}^2 = E_{KP}^2 + E_{KT}^2 \ , \qquad E_{\phi i,\Delta} = \frac{B \sin 2\hat{\phi}_{i0}}{2\hat{\phi}_{i0}} E_{KP} \ . \tag{15c}$$

Here, s_R^*, s_{yi}^* and $s_{\phi i}^*$ are relative sensitivity coefficients given in [1], ϕ_{i0} is the inclination angle of path no. *i* at "dry calibration" conditions, *N* is the number of acoustic paths in the USM, and *B* is a constant defined in [1]. E_{KP} and E_{KT} are the relative standard uncertainties of the radial pressure and temperature correction factors for the USM meter body, K_P and K_T, respectively, given as

$$E_{KP} \equiv u_c(\hat{K}_P)/\hat{K}_P \ , \qquad u_c(\hat{K}_P) = \sqrt{(\Delta\hat{P}_{cal})^2 u^2(\hat{\beta}) + \hat{\beta}^2 u_c^2(\Delta\hat{P}_{cal})} \ , \tag{16a}$$

$$E_{KT} \equiv u_c(\hat{K}_T)/\hat{K}_T \ , \qquad u_c(\hat{K}_T) = \sqrt{(\Delta\hat{T}_{cal})^2 u^2(\hat{\alpha}) + \hat{\alpha}^2 u_c^2(\Delta\hat{T}_{cal})} \ , \tag{16b}$$

where $u(\hat{\alpha})$ and $u(\hat{\beta})$ are the standard uncertainties of the coefficients of linear temperature and pressure expansion of the meter body material (usually steel), α and β, respectively. ΔP_{cal} and ΔT_{cal} are the difference in pressure and temperature between line and proving conditions, respectively. For calculation of the combined standard uncertainties of ΔP_{cal} and ΔT_{cal}, two cases are addressed here. In cases for which *P* and *T* corrections of the meter body are *not* used, these uncertainties are determined by the *span* of ΔP_{cal} and ΔT_{cal}, so that

$$u_c(\Delta\hat{P}_{cal}) = \Delta\hat{P}_{cal}/\sqrt{3} \ , \qquad u_c(\Delta\hat{T}_{cal}) = \Delta\hat{T}_{cal}/\sqrt{3} \ . \tag{17}$$

In cases where *P* and *T* corrections of the meter body *are* used, these uncertainties are determined by the *measurement uncertainties* of ΔP_{cal} and ΔT_{cal}, so that

$$u_c(\Delta\hat{P}_{cal}) = \sqrt{2} u_c(\hat{P}) \ , \qquad u_c(\Delta\hat{T}_{cal}) = \sqrt{2} u_c(\hat{T}) \ , \tag{18}$$

where $u_c(\hat{P})$ and $u_c(\hat{T})$ are given by Eqs. (5)-(6). Details are given in [1].

In Eq. (14), the "systematic transit time effects" term is given as

$$E_{time,\Delta} \equiv \sum_{i=1}^{N} \left(s_{t1i}^* E_{t1i,C}^{\Delta} + s_{t2i}^* E_{t2i,C}^{\Delta} \right) \ . \tag{19}$$

$E_{t1i,C}^{\Delta}$ and $E_{t2i,C}^{\Delta}$ are the relative standard uncertainties of uncorrected systematic transit time effects on upstream and downstream propagation of acoustic path no. *i*, due to possible deviation in pressure and/or temperature from proving to duty operation, defined as

$$E_{t1i,C}^{\Delta} = u(\hat{t}_{1i}^{systematic})/\hat{t}_{1i} \ , \qquad E_{t2i,C}^{\Delta} = u(\hat{t}_{2i}^{systematic})/\hat{t}_{2i} \ . \tag{20}$$

$\hat{t}_{1i}$ and $\hat{t}_{2i}$ are the upstream and downstream transit times of path no. *i*, and $u(\hat{t}_{1i}^{systematic})$ and $u(\hat{t}_{2i}^{systematic})$ are the standard uncertainties of uncorrected systematic effects in these transit times. Information on these input uncertainties should be provided by the USM manufacturer. s_{t1i}^* and s_{t2i}^* are relative sensitivity coefficients defined in [1].

Such systematic transit time effects may be due to (a) cable/electronics/transducer/diffraction time delay (due to line pressure and temperature effects, ambient temperature effects, drift, effects of possible transducer exchange), (b) possible Δt-correction (line pressure and temperature effects, ambient temperature effects, drift, reciprocity effects, effects of possible transducer exchange), (c) possible systematic effects in signal detection/processing, (d) possible cavity time delay correction effects, (e) possible transducer deposits (wax, scaling, etc.), and (f) sound refraction (flow profile effects (“ray bending”)).

In Eq. (14), the “installation effects” term $E_{I,\Delta}$ is related to the USM integration method, and serves as an input uncertainty. Such installation effects on the USM integration uncertainty may be due to (a) change of *axial flow velocity profile* (from proving to duty operation), and (b) change of *transversal flow velocity profiles* (from proving to duty operation). Such changes may be due to e.g. (*i*) line pressure and temperature effects, (*ii*) ambient temperature effects, (*iii*) possible changed wall roughness over time (corrosion, wear, pitting, etc.), in the pipe and meter body, and (i*v*) possible wall deposits / contamination in the pipe and meter body (wax, scaling), etc.

3.6 Signal communication and flow computer uncertainties

In Eqs. (4a), the relative uncertainty term E_{comm} accounts for the uncertainties due to the signal communication between the USM field electronics and the flow computer (e.g. the flow computer calculation of frequency in case of analog frequency output). E_{flocom} accounts for the uncertainty of the flow computer calculations. Both should be specified by the USM manufacturer, and are normally relatively small.

4 MICROSOFT EXCEL PROGRAM “*EMU - USM FISCAL OIL METERING STATION*”

A PC program has been implemented based on the uncertainty model for the metering station described in Section 3. The program *EMU - USM Fiscal Oil Metering Stations* is implemented as a Microsoft Excel 2003 spreadsheet.

The program calculates the expanded and relative expanded uncertainties of an oil metering station which is based on a proved USM, for the three measurands in question, q_v, Q_v and q_m.

In addition to calculation/plotting/reporting of the expanded uncertainty of the oil metering station and the individual instruments of the station, the Excel program can be used to calculate, plot and analyse the relative importance of the various contributions to the uncertainty budget for the various instruments of the metering station (using bar-charts).

For several of the instruments and procedures involved in the metering station, an implementation strategy has been chosen which enables the user to give uncertainty input at two levels: (1) an *“overall level”*, and (2) a more *“detailed level”*, cf. Table 3. This provides a useful flexibility in use of the program.

At the *overall level*, the user specifies the combined standard uncertainty of the instrument in question directly as input to the program. It is left to the user to calculate and document this uncertainty figure. This option is general, and covers any method of obtaining the uncertainty figure[6].

[6] The “overall level” option may be of interest in several cases, such as e.g.: (a) if the user wants a “simple” and quick evaluation of the influence of an instrument uncertainty on the expanded (overall) uncertainty of the oil metering station, (b) in case of a different installation of the oil densitometer (e.g. in-line), (c) in case of a different oil densitometer functional relationship, or (d) in case the input used at the “detailed level” does not fit sufficiently well to the type of input data / uncertainties which are relevant for e.g. the pressure transmitter or temperature element/transmitter at hand.

At the *detailed level*, the combined standard uncertainty of the instrument in question is calculated by the program, from more basic input for the instrument provided e.g. by the instrument manufacturer and calibration laboratory, as outlined in Section 3.

Table 3. Uncertainty model contributions, and optional levels for specification of input uncertainties to the program *EMU - USM Fiscal Oil Metering Stations*.

Uncertainty contribution	Overall level	Detailed level
Pressure measurement uncertainty (in each of: meter run, densitometer and prover)	✓	✓
Temperature measurement uncertainty (in each of: meter run, densitometer and prover)	✓	✓
Density measurement uncertainty	✓	✓
Reference density calculation	✓	✓
Prover uncertainty	✓	✓
Proving uncertainty		✓
USM duty operation uncertainty	✓	✓
Signal communication and flow computer calculations	✓	

With respect to *USM proving* and *USM duty operation*, the level for specification of input uncertainties at the detailed level is adapted to data available from duty operation, proving and from the USM manufacturer. In particular this concerns:

(1) USM proving:

- **Prover.** The user specifies a number of input uncertainties needed for calculation of the prover uncertainty, $E_{Q_{prover}}$, cf. Eq. (10).
- **Repeatability.** The user specifies the repeatability (relative standard deviation) of the indicated USM flow rate measurement at proving, $E_{rept,j}^{proving}$, cf. Eq. (8). That is, the combined repeatability of the USM and the prover. It can be given in the program to be flow rate dependent.
- **Deviation factor.** The user specifies the corrected relative deviation $Dev_{C,j}$ at each proving flow rate ("proving point"), i.e. the relative deviation from reference after multiplication with the "proving correction factor", C_{prov} , cf. Eq. (9).

(2) USM duty operation:

- **Repeatability.** The user specifies either (a) the repeatability (relative standard deviation) of the indicated USM flow rate measurement in duty operation, E_{rept} , or (b) the repeatability (standard deviation) of the measured transit times, $u(\hat{t}_{1i}^{random})$, cf. Eqs. (12) and (13), respectively. Both can be given in the program to be flow rate dependent.
- **Meter body parameters.** The user specifies whether correction for pressure and temperature effects is used or not for the USM meter body, and the uncertainties of the temperature and pressure expansion coefficients, $u(\hat{\alpha})$ and $u(\hat{\beta})$. Cf. Eqs. (15)-(18).
- **Systematic transit time effects.** The user specifies the uncertainty of uncorrected systematic effects on the measured upstream and downstream transit times, $u(\hat{t}_{1i}^{systematic})$ and $u(\hat{t}_{2i}^{systematic})$, cf. Eqs. (20). Only changes from proving to duty operation are relevant.
- **Integration method (installation effects).** The user specifies the uncertainty related to the integration method / installation effects, $E_{I,\Delta}$, cf. Eq. (14). Only changes from proving to duty operation are relevant here.

With respect to the USM technology, the program can thus be run in two modes:

(A) Completely meter independent, and
(B) Weakly meter dependent.

Mode (A) corresponds to choosing the overall level for the USM duty operation uncertainty (both for the repeatability and the systematic deviation re. proving). Mode (B) corresponds to choosing the "detailed level".

By "weakly meter dependent" is here meant that the inner diameter, number of paths and the number of reflections for each path are to be known. However, actual values for the inclination angles, lateral chord positions and integration weights do not need to be known. Only very approximate values for these quantities are needed (used for calculation of certain sensitivity coefficients).

5 UNCERTAINTY EVALUATION EXAMPLE

As an example of evaluation of the expanded uncertainty of a USM fiscal oil metering station using the EMU program described in Section 4, consider the metering station instrumentation example given in Table 2: 8" pipeline, a 8" USM duty meter with flow computer, a 20" prover, a Rosemount 3051P Reference Class Pressure Transmitter [20], a Pt 100 4-wire RTD element and a Rosemount 3144 Smart Temperature Transmitter [21], and an on-line (by-pass) installed Solartron 7835 Liquid Density Transducer [22]. The type of flow computer and prover are arbitrary (unspecified). The diameter and actual volume of the 20" prover is 0.5 m and 7 m^3, respectively. The 8" USM is a 0.20 m diam. 4-path meter with parallel chords, non-reflecting paths and Gauss-Jacobi integration. A typical North Sea oil is considered [10], with density 776 kg/m^3 at densitometer conditions. Line conditions (in the meter run) are taken to be 18 barg and 65 ^oC. Densitometer conditions are 17.5 barg and 63 ^oC. Proving conditions are taken to be 18 bara and 65 ^oC (for the USM and the prover).

Evaluation of e.g. the relative expanded uncertainty of the axial volumetric flow rate, kE_{q_v}, according to Eq. (4a), involves the USM, the prover, the pressure and temperature measurements, the densitometer, the signal communication / flow computer, and the oil parameters. The "detailed level" of input is used here. 6 proving flow velocities are considered, in the range 0.4 – 10 m/s (corresponds to actual volumetric flow rates of about 45 – 1131 m^3/h).

For the proving of the USM, a number of input uncertainties are in question, cf. Eqs. (8) and (10). The deviation factor uncertainty, $kE_{C_{dev,j}}$, is taken to be 0.02 % (100 % conf. lev., rect. distrib.)[7]. The repeatability (standard uncertainty, i.e. standard deviation) of the proving measurement, $E_{rept,j}^{proving}$, is taken to be 0.02 % at all proving flow rates (which is probably simplified). The relative standard uncertainty of the prover volume, E_{BV}, is taken to be 0.019 %. The standard uncertainty of the proving time period, Δt_p, is taken to be 1 ms. The standard uncertainties of the thermal expansion coefficient and the modulus of elasticity of the prover steel body are both taken to be 11.5 %. The standard uncertainties of the inner diameter and wall thickness of the prover are both taken to be 0.5 %.

With respect to the oil parameters, a relatively large number of input uncertainties are to be specified. The relative standard uncertainties of all oil temperature and pressure measurements (in the meter, densitometer and the prover), E_T and E_P, are taken to be 0.023 % and 0.044 %, respectively. Due to space limitations, it is referred to [1] for details on other oil parameter input uncertainties.

For the USM in duty operation, the input uncertainties in question are given by Eqs. (11)-(20). The USM repeatability in duty operation is tentatively taken to be E_{rept} = 0.02 % (standard deviation), constant over the flow rate range (which is probably simplified). The relative standard uncertainty of the integration method (accounting for possible changes in installation effects from proving to duty operation) is taken to be $E_{I,\Delta}$ = 0.01 %, as a tentative and possibly large example value. The uncertainties of uncorrected systematic effects on the measured upstream and downstream transit times (accounting for possible changes from

7 In the present calculation example given here, all input uncertainties given in the text are taken to correspond to 67 %, 95 % or 100 % confidence levels (depending on type of uncertainty), with normal or rectangular probability distribution, and coverage factor *k* = 1, 2 or $\sqrt{3}$, respectively.

proving to duty operation), $k \cdot u(\hat{t}_{1i}^{systematic})$ and $k \cdot u(\hat{t}_{2i}^{systematic})$, are given as 10 and 9.5 ns (100 % conf. lev., rect. distrib.), respectively, as a tentative example. The case is considered where pressure and temperature correction is used for the meter body. The uncertainties of the temperature and pressure expansion coefficients $k \cdot u(\hat{\alpha})$ and $k \cdot u(\hat{\beta})$ are set to 20 % (100 % conf. lev., rect. distrib.), as example values. Details are given in [1].

The standard uncertainties related to the flow computer and signal communication are set to zero in this example.

Fig. 1 shows the relative expanded uncertainty of the volumetric flow rate measurement for this illustration example (together with the volumetric flow rate itself), plotted over the flow velocity range 0.4 to 10 m/s. The relative expanded uncertainty is calculated at *M* = 6 flow velocities for which proving has been performed, and straight lines are drawn in-between these points.

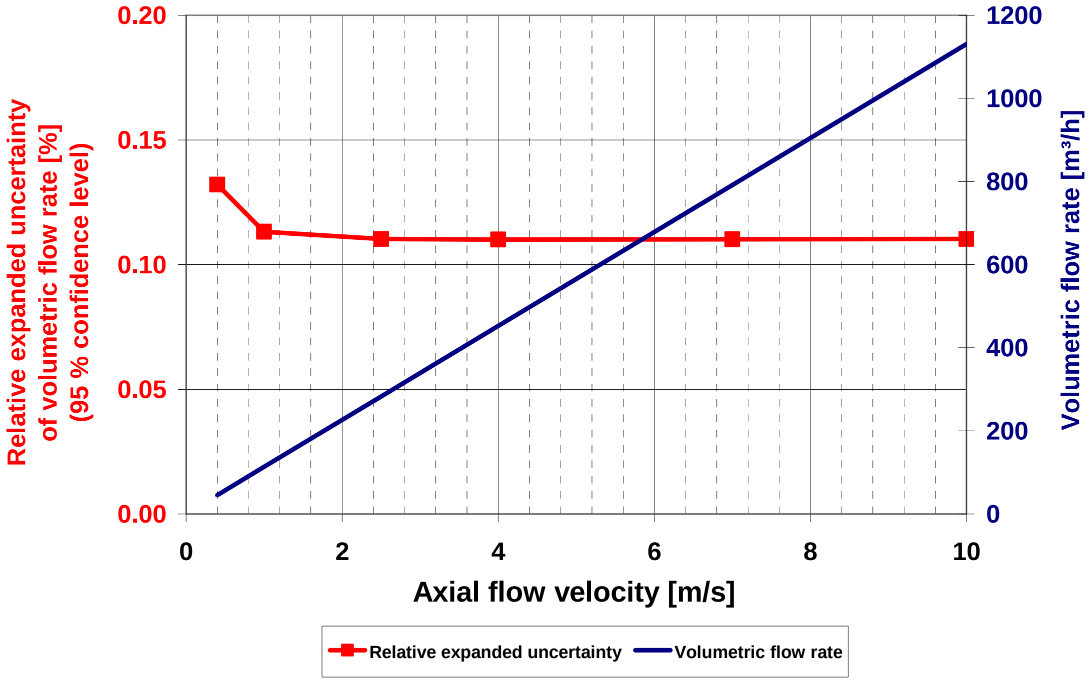

Fig. 1. Illustration example of volumetric flow rate measurement, q_v, and its corresponding relative expanded uncertainty, kE_{q_v}. The markers indicate the 6 flow rates at which proving has been made ("proving points").

The various contributions to the relative expanded uncertainty of the volumetric flow rate measurement may be investigated in further detail at each of the *M* = 6 "proving points" shown by markers in Fig. 1. The bar-chart shown in Fig. 2 gives the relative importance of such contributions at a flow velocity of 1 m/s. At this flow velocity, two uncertainty contributions dominate the uncertainty budget in this illustration and tentative example: the prover uncertainty and the systematic deviation of the USM in duty operation relative to proving, followed by the repeatability contributions at proving and in duty operation.

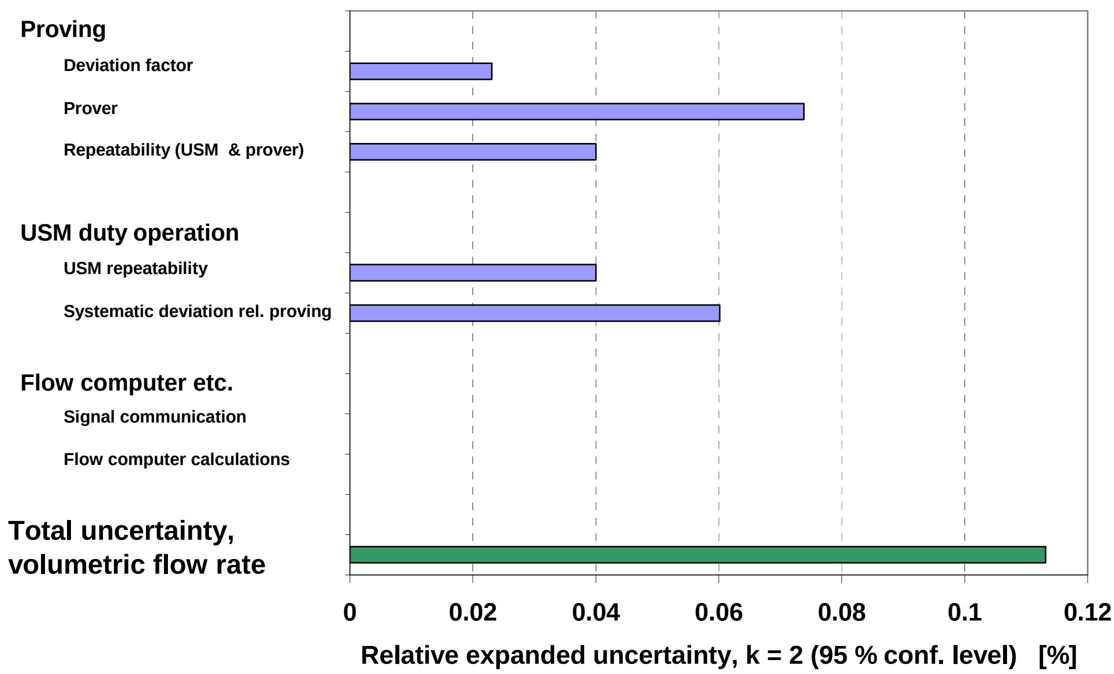

Fig. 2. Bar-chart showing contributions to the calculated relative expanded uncertainty of the volumetric flow rate measurement, at 1 m/s flow velocity.

In Fig. 2 the relative expanded uncertainty of prover measurement is calculated to about 0.074 %. It may be of interest to investigate the relative importance of the various contributions to this uncertainty figure. Fig. 3 shows the contributions to the expanded uncertainty of the prover, calculated according to Eq. (10). It appears that in this illustration example the prover uncertainty is dominated by the uncertainty of C_{tlp}, followed by the uncertainties of C_{tsp} and the prover "base volume", *BV*. Other uncertainty contributions are relatively smaller.

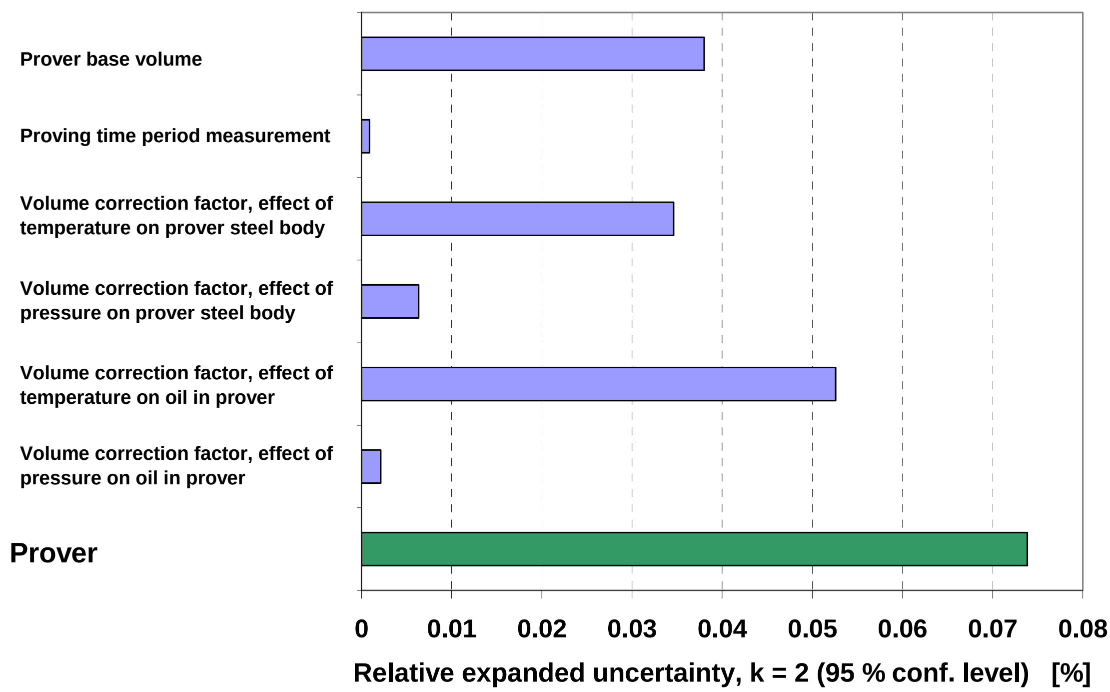

Fig. 3. Bar-chart showing the various contributions to the expanded uncertainty of the prover measurement, at 1 m/s flow velocity, calculated according to Eq. (10).

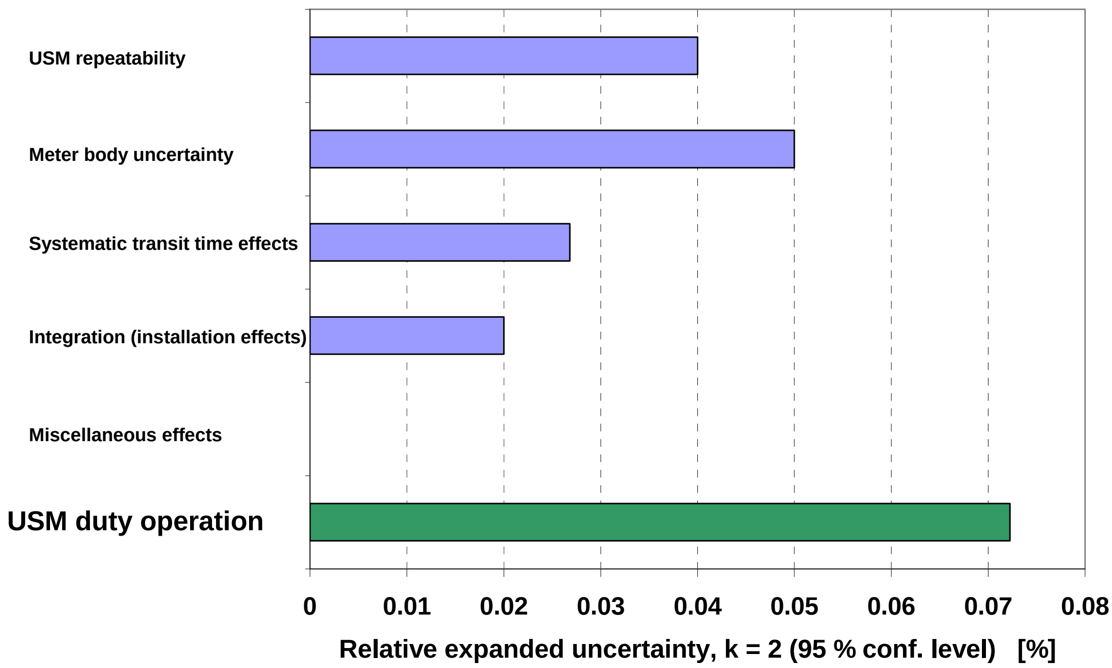

Fig. 4. Bar-chart showing the various contributions to the expanded uncertainty of the USM field measurement, at 1 m/s flow velocity, calculated according to Eqs. (11)-(20).

To investigate the relative expanded uncertainty of the USM duty measurement shown in Fig. 2 in some more detail, Fig. 4 shows the contributions to this uncertainty, calculated according to Eqs. (11)-(20). In addition to the miscellaneous effects, these are organized in four groups: USM repeatability in duty operation, meter body uncertainty, uncertainty of systematic transit time effects, and the integration method uncertainty (installation effects). In the present example four groups all contribute to the USM duty uncertainty. In general the latter two groups are the most difficult to specify (only the USM repeatability is normally available from current USM manufacturer data sheets), and only tentative uncertainty figures have been used in the present calculation example, to illustrate use of the program, and demonstrate the sensitivity to these uncertainty contributions.

Table 4 summarizes the calculation results of this example in an overall uncertainty budget. It appears that the proving and USM duty uncertainties contribute almost equally to the relative expanded uncertainty of the volumetric flow rate measurement, at this flow velocity.

Table 4. Illustration example of an overall uncertainty budget for the USM fiscal oil metering station, for the volumetric flow rate, q_v, for a flow velocity of 1 m/s.

Source	**Uncertainty contribution**				**Combined uncertainty**	
	Relative expanded uncertainty	**Confidence level & probab. distribution**	**Cover. factor, *k***	**Relative standard uncertainty**	**Rel. sens. coeff.**	**Relative Variance**
Proving	0.0871 %	95 % (normal)	2	0.0436 %	1	$1.897 \cdot 10^{-7}$
USM duty operation	0.0722 %	95 % (normal)	2	0.0361 %	1	$1.305 \cdot 10^{-7}$
Signal comm. / flow comp.	Neglected	-	-	-	1	0
Sum of relative variances				$E^2_{q_v}$		$3.206 \cdot 10^{-7}$
Relative combined standard uncertainty				E_{q_v}		0.057 %
Relative expanded uncertainty (95 % confidence level, k = 2)				$k \cdot E_{q_v}$		**0.113 %**

The uncertainty evaluation example discussed above for illustration purposes, address the volumetric flow rate, q_v. Similar analyses can be made for the standard volumetric flow rate, Q_v, and the mass flow rate, q_m.

Calculations of this type may be made for the pressure transmitter and the temperature element/transmitters (in the meter run, the densitometer and the prover), the densitometer, the reference density, the prover, and the proving of the USM. For documentation purposes, necessary reporting of input data and calculated results are available, for the three measurands given by Eqs. (1).

6 CONCLUSIONS

The NPD regulations states that "it shall be possible to document the total uncertainty of the measurement system. An uncertainty analysis shall be prepared for the measurement system within a 95 % confidence level" [4]. The *GUM* [2] put requirements to such documentation. To meet such requirements and harmonize procedures and industry practice in the documentation of fiscal measurements, a series of handbooks on uncertainty calculation of fiscal oil and gas metering stations is developed in a cooperation between NFOGM, NPD, Tekna and CMR [8-10,1].

In the present paper, the ongoing development of a handbook of uncertainty calculations of ultrasonic fiscal oil metering stations [1] is described. Three different metering station scenarios are being addressed in [1]:

Scenario A: A USM "duty meter" which is *in-situ* calibrated using a prover, typically every 4th day.
Scenario B: A USM "duty meter" which is operated together with a USM "master meter". The USM "duty meter" is *in-situ* calibrated vs. the USM "master meter". The USM "master meter" is *in-situ* calibrated vs. a prover, typically once a year.
Scenario C: A USM "duty meter" which is operated together with a turbine (TM) "master meter". The USM "duty meter" is *in-situ* calibrated vs. the TM "master meter". The TM "master meter" is *in-situ* calibrated vs. a prover, typically once a year.

The present paper gives a description of Scenario A, including an uncertainty calculation example. The example is meant essentially to illustrate and demonstrate the possibilities of the *Handbook* and the accompanying *EMU* program, and does not serve as an uncertainty analysis of a USM fiscal oil metering station.

The expanded uncertainties calculated by the program *EMU - USM Fiscal Oil Metering Stations* may be used in documentation of the metering station uncertainty. That means, provided the user of the program (on basis of manufacturer information or other sources) can document the numbers used for the input uncertainties to the program, the *Handbook* and the program gives procedures for propagation of these input uncertainties.

For traceability purposes the input data to the program (quantities and uncertainties) must be documented by the user. The user must also document that the calculation procedures and functional relationships implemented in the program are in conformity with the ones actually applied in the fiscal oil metering station[8].

The uncertainty model for USM fiscal oil metering stations presented in the *Handbook* is based on present-day "state of the art of knowledge" for stations of this type, and is not expected to be complete with respect to description of effects influencing on such metering stations. In spite of that, the uncertainty model does account for a large number of the important factors that influence on the expanded uncertainty of metering stations of this type. It is expected that the most important uncertainty contributions have been accounted for. Evaluation of the effects of these factors on the uncertainty of the metering station should be possible with the uncertainty model and the program developed here.

[8] If the "overall level" options of the program are used, the program should cover a wide range of situations met in practice.

It is the intention and hope of the partners presenting this *Handbook* that - after a period of practical use of the *Handbook* and the program - the uncertainty model presented here will be subject to necessary comments and viewpoints from users and developers of USMs, and others with interest in this field, as a basis for a possible later revision of the *Handbook*. The overall objective of such a process would of course be that - in the end - a useful and accepted method for calculation of the uncertainty of USM fiscal oil metering stations can be agreed on, in the Norwegian metering society as well as internationally.

SYMBOL NOTATION

q_v : axial volumetric flow rate at line conditions [m^3/h],

Q_v : axial volumetric flow rate at standard reference conditions (1 atm. and 15 ^oC) [Sm^3/h],

q_m : axial mass flow rate [kg/h],

q_{USM} : axial volumetric flow rate indicated by the USM under duty operation (line conditions), before the "proving correction factor" C_{prov} is applied [m^3/s],

ρ : oil density in the meter run (line conditions) [kg/m^3],

ρ_d : oil density in the densitometer [kg/m^3],

ρ_{ref} : oil density at standard reference conditions (1 atm. and 15 ^oC) [kg/m^3],

C_{prov}: correction factor accounting for proving of the USM (Scenario A) (here referred to as the "proving correction factor") [-],

C_j^{prov} : meter factor determined in proving of the USM (Scenario A), j = 1, …, M [-],

$K_{prov,j}^{USM}$: K-factor of the ultrasonic meter (USM) at proving test flow rate no. j, $j = 1$, …, M, determined in proving of the USM [pulses/m^3],

K_{DFC} : DFC (digital-to-frequency converter) factor [pulses/m^3],

M : number of proving flow rates ("proving points"),

C_{tlm} : Volume correction factor (VCF) for the effect of temperature on the liquid (oil) in the meter, re. standard reference conditions [-],

C_{plm} : Volume correction factor (VCF) for the effect of pressure on the liquid (oil) in the meter, re. standard reference conditions [-],

C_{tld} : Volume correction factor (VCF) for the effect of temperature on the liquid (oil) in the densitometer, re. standard reference conditions [-],

C_{pld} : Volume correction factor (VCF) for the effect of temperature on the liquid (oil) in the densitometer, re. standard reference conditions [-].

C_{tlp} : volume correction factor (VCF) for the effect of temperature on the liquid (oil) in the prover at proving conditions, re. std. reference conditions [-],

C_{plp} : volume correction factor (VCF) for the effect of pressure on the liquid (oil) in the prover at proving conditions, re. standard reference conditions [-],

C_{tsp} : volume correction factor (VCF) for the effect of temperature on the prover steel at proving conditions, re. std. reference conditions [-],

C_{psp} : volume correction factor (VCF) for the effect of pressure on the prover steel at proving conditions, re. std. reference conditions [-],

BV : Prover volume at "base conditions", taken to be standard reference conditions (1 atm., 15 ^oC) [m^3],

Δt_p : proving time period, i.e. time period between signals from the two detector switches 1 and 2 in the prover [s],

k : coverage factor [-],

E_P : relative combined standard uncertainty of the liquid pressure measurement [-],

E_T : relative combined standard uncertainty of the liquid temperature measurement [-],

E_ρ : relative combined standard uncertainty of the liquid density measurement [-],

E_{q_v} relative combined standard uncertainty of the axial volumetric flow rate estimate, $\hat{q}_v$ [-],

E_{Q_v} relative combined standard uncertainty of the standard axial volumetric flow rate estimate, $\hat{Q}_v$ [-],

E_{q_m} relative combined standard uncertainty of the axial mass flow rate estimate, $\hat{q}_m$ [-],

$E_{proving}$: relative combined standard uncertainty of the estimate $\hat{q}_v$, related to proving of the USM [-],

E_{USM} : relative combined standard uncertainty of the estimate $\hat{q}_v$, related to duty operation of the USM [-],

E_{comm} : relative standard uncertainty of of the estimate $\hat{q}_v$, due to signal communication [-],

E_{flocom} : relative standard uncertainty of of the estimate $\hat{q}_v$, due to the flow computer [-],

$E_{C_{dev,j}}$: relative combined standard uncertainty of the deviation factor estimate, $\hat{C}_{dev,j}$, at proving flow rate no. *j*, *j* = 1, …, *M* [-],

$E_{Q_{prover,j}}$: relative combined standard uncertainty of the prover volumetric flow rate measurement, $\hat{Q}_{prover,j}$, at proving flow rate no. *j*, *j* = 1, …, *M* [-],

$E_{rept,j}^{proving}$: repeatability (relative standard uncertainty, i.e. standard deviation) of the proving measurement (volumetric flow rate), at proving flow rate no. *j*, *j* = 1, …, *M* [-],

E_{BV} : relative standard uncertainty of the prover "base volume" *BV* [-],

$E_{\Delta t_{p,j}}$: relative standard uncertainty of the prover time period measurement, Δt_p , at proving flow rate no. *j*, *j = 1, …, M* [-],

$E_{C_{tlm}}$: relative combined standard uncertainty of the volume correction factor estimate $\hat{C}_{tlm}$ [-],

$E_{C_{plm}}$: relative combined standard uncertainty of the volume correction factor estimate $\hat{C}_{plm}$ [-],

$E_{C_{tlp}}$ ≡ relative combined standard uncertainty of the volume correction factor estimate $\hat{C}_{tlp}$ [-],

$E_{C_{plp}}$ ≡ relative combined standard uncertainty of the volume correction factor estimate $\hat{C}_{plp}$ [-],

$E_{C_{tsp}}$: relative combined standard uncertainty of the volume correction factor estimate $\hat{C}_{tsp}$ [-],

$E_{C_{psp}}$ ≡ relative combined standard uncertainty of the volume correction factor estimate $\hat{C}_{psp}$ [-],

E_{rept} : repeatability (relative combined standard uncertainty, i.e. standard deviation) of the USM measurement in duty operation (volumetric flow rate), at the flow rate in question [-],

$E_{USM,\Delta}$: relative standard uncertainty of the estimate $\hat{q}_v$, related to duty operation of the USM [-],

E_{misc} : miscellaneous systematic effects on the USM duty measurement which are not eliminated by proving, and which are not covered by other uncertainty terms accounted for here (e.g. inaccuracy of the USM functional relationship (the underlying mathematical model), etc.) [-],

$E_{body,\Delta}$: relative combined standard uncertainty of the estimate $\hat{q}_v$, due to change of the USM meter body from proving to duty operation. That is, uncertainty of the meter body inner radius, $\hat{R}$, the lateral chord positions of the *N* acoustic paths, $\hat{y}_i$, and the inclination angles of the *N* acoustic paths, $\hat{\phi}_i$, *i* = 1, …, *N*, caused by possible deviation in pressure and/or temperature between proving and duty operation [-],

$E_{time,\Delta}$: relative combined standard uncertainty of the estimate $\hat{q}_v$, due to systematic effects on the transit times of the *N* acoustic paths, $\hat{t}_{1i}$ and $\hat{t}_{2i}$, *i* = 1, …, *N*, caused by possible deviation in pressure and/or temperature between proving and duty operation [-],

$E_{I,\Delta}$: relative standard uncertainty of the USM integration method due to change of installation conditions from proving to duty operation [-],

$E_{rad,\Delta}$: relative combined standard uncertainty of the estimate $\hat{q}_v$, due to uncertainty of the meter body inner radius, $\hat{R}$, caused by possible deviation in pressure and/or temperature between proving and duty operation [-],

$E_{chord,\Delta}$: relative combined standard uncertainty of the estimate $\hat{q}_v$, due to uncertainty of the lateral chord positions of the *N* acoustic paths, $\hat{y}_i$, *i* = 1, …, *N*, caused by possible deviation in pressure and/or temperature between proving and duty operation [-],

$E_{angle,\Delta}$: relative combined standard uncertainty of the estimate $\hat{q}_v$, due to uncertainty of the inclination angles of the N acoustic paths, $\hat{\phi}_i$, i = 1, …, N, caused by possible deviation in pressure and/or temperature between proving and duty operation [-],

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