Exploring a new ammeter traceability route for ionisation chamber measurements

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We compared the performance of a commercial ammeter and a home-made integrating electrometer in reading ionisation chamber currents less than 100 pA. The noise performance of both systems was very similar for averaging times less than 1000 seconds. Both systems were calibrated using a reference current source with 1 ppm accuracy, revealing an error of 460 parts per million in the electrometer indicated current. This is well within the uncertainty budget for radionuclide calibrations, but much larger than the individual uncertainties in the traceable calibrations of capacitance, voltage and time. The noise in the ion chamber current was much larger than the noise floor of both instruments, with tests providing strong indication that the excess noise originated in the high voltage source used for energising the chamber.

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I. INTRODUCTION

Ionisation chambers are of great utility for measuring radionuclide activities and half-lives. The chamber outputs a current proportional to the activity of the source inside the chamber, with the constant of proportionality determined by primary calibration methods involving absolute counting of decay events from a diluted source. The linearity and stability of the ion chamber current measurement is ensured by traceable calibration of the current measuring instrument. Historically, these instruments have usually been capacitor-ramp electrometers which integrate the ion chamber current and allow the current to be calculated according to $I = C \frac{dV}{dt}$. For ion chamber currents in the picoamp to nanoamp range, voltage ramp rates of $\frac{dV}{dt} \sim 1$ V/s require capacitances $C$ in the picofarad to nanofarad range. Such capacitors are available commercially as low-loss air or sealed-gas units possessing long-term stability at the part-per-million level, and low sensitivity to temperature and humidity changes. The relevant calibrations of voltage, capacitance and time are available as standard services from national metrology institutes (NMIs), and accredited laboratories, with relative uncertainties less than 10 parts per million (ppm), and in the absence of complicating factors these low uncertainties are transferred directly to the measured current.

In the last 15-20 years, a number of developments have occurred in the field of small current metrology which encourage a fresh look at ion chamber current readout methods. In response to industry demand, a number of NMIs have inaugurated calibration services for nanoamp-level ammeters with uncertainties as low as $\sim 10$ ppm. Reference currents are usually sourced by applying a linear voltage ramp to a low-loss capacitor (essentially the reverse process of a capacitor-ramp electrometer). To validate these new services, the first international inter-comparison of reference current sources was undertaken. While broadly validating NMI capability, the comparison could not provide information at uncertainty levels much below $\sim 100$ ppm due to transport instability and environmental effects in the commercial ammeters used as transfer standards. In parallel, research into prototype current sources, known as electron pumps, which generate small currents by moving electrons one at a time, focused attention on small-current metrology at the lowest possible uncertainty level. In this research setting, currents of order 100 pA have been measured with combined uncertainties of $\sim 0.2$ ppm. A practical spin-off from the electron pump research has been the ultrastable low-noise current amplifier, or ULCA, which can either source or measure small currents with uncertainties as low as 0.1 ppm, and has demonstrated stability under international transportation at the 1 ppm level. Recently, different versions of the ULCA have been tested, including ones with high gain and small, stable, offset suitable for the measurement of the very low background currents from ion chambers.

Inspired by these developments, in this paper we test an alternative traceability route for ion chamber currents: an ammeter calibrated directly using a primary reference small-current source. We compare this ammeter method with an established capacitor-ramp method, and discuss the advantages and limitations of each. We also address an important and neglected question in ion-chamber metrology: how does the random uncertainty in the measured current depend on the measurement time, and what is the optimum interval between chamber background measurements.

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II. TRACEABILITY ROUTES

In figure I (a), three complete traceability routes for small electrical currents are summarized, starting with primary standards at the top. The electron pump is included for completeness; although they currently have the status of research devices, electron pumps offer a very direct traceability route and are likely to play a role in primary current metrology in the future. In this paper, we will be concerned mainly with the first two - the capacitor ramp method and the resistor/voltage method.

The capacitor ramp method realizes current via the rate of change of voltage across a capacitor, and the concept can be applied to either the generation or measurement of a current. The traceability route for capacitance is either to the dc quantum Hall resistance (QHR) via a quadrature bridge and ac/dc transfer resistor, or via the calculable capacitor, which realizes a small (< 1 pF) capacitance based on a length measurement. Both these routes are moderately complex to implement, but the end result is that standard capacitors of 1 nF or less can be calibrated routinely at audio frequencies with uncertainties of order 1 ppm. Voltage is traceable to the ac Josephson effect, and digital voltmeters (DVM's) can be calibrated directly against a Josephson voltage standard (JVS), or indirectly using a calibrator. High-specification DVMs may drift by at most a few ppm in a 1-year calibration interval and have non-linearity errors less than 1 ppm. The third traceable quantity, time, can be realized with ppm accuracy in a number of ways - for example using a commercial off-air frequency standard. The quantity $C \times \frac{dV}{dt}$ can consequently be realized with an uncertainty of a few parts per million, and precision reference current sources have mostly used this route.

Generation of sub-nA reference currents using a resistor and voltage source is less common. This may be because high-value standard resistors, in contrast to sub-nA air-gap capacitors, can have temperature co-efficients as large as few tens of ppm per degree, and therefore require additional environmental control to reach ppm-level accuracy. Calibration uncertainties of high-value resistors have also been generally higher than low-value capacitors, although ppm-level calibration uncertainties of resistors up to 1 GΩ are now attainable using CCCs. The ULCA also generates and measures current with respect to an internal 1 MΩ resistor and an external DVM, and as already noted, has demonstrated 1-year stability at the ppm level. The resistor and voltage source method has the obvious advantage that current can be generated continuously without being constrained by a capacitor charge-discharge cycle.

A problem with the capacitor ramp method is that the low calibration uncertainties of the standard capacitors are achieved using voltage-transformer bridge techniques, which work at audio frequencies. Calibrations are typically performed at 1 kHz, and the techniques can be extended down in frequency to a practical lower limit of ~ 25 Hz. In contrast, capacitor ramp methods for generating or measuring small currents operate at frequencies many orders of magnitude lower, in the millihertz range. One study found that some samples of standard capacitor exhibited unexpectedly large frequency dependence in the range ~ 10 mHz - 1 kHz, up to several hundred ppm, which is certainly far in excess of the 1 kHz calibration uncertainty and begins to impact the uncertainty budgets of NMI-level ion chamber readout systems. Either the capacitance needs to be measured at the ramp frequency, which is a laborious and non-standard procedure, or the capacitance uncertainty must be expanded to allow a worst-case scenario. This issue reduces somewhat the apparent advantages of the capacitor ramp method, and prompts fresh consideration of the resistor and voltage method.

III. CURRENT MEASUREMENT SYSTEMS

The two types of current readout system investigated in this paper, the capacitor ramp electrometer and the feedback ammeter, are illustrated schematically in figure I (b,c). We will refer to them subsequently as the electrometer and the ammeter respectively. Both types
of instrument use a high-gain amplifier with feedback; the feedback element is a capacitor in the case of the electrometer, and a resistor in the case of the ammeter. The electrometer used in this study employs a home-made amplifier with an external integrating capacitor of value \( \sim 500 \text{ pA} \), and an external DVM (Datron model 1061) triggered with calibrated 1 s interval between readings. We denote the current measured by the electrometer \( I_E = \frac{dC}{dt} \). Here, \( C_{\text{corr}} = C_{\text{cal}} + C_{\text{stray}} \) where \( C_{\text{cal}} \) is the calibrated value of the standard capacitor, and \( C_{\text{stray}} \) is the stray capacitance correction. For the bulk of the study, excepting the data of figure 4 (f,g), the ammeter was a Keithely model 6430 set to the 1 nA range. The resistive feedback of the ammeter gives an output voltage \( V_{\text{out}} = I_{\text{in}} R \), which is digitized by an analogue-to-digital converter (ADC) internal to the instrument, and converted to a current reading by the instrument’s firmware. The feedback resistor \((\sim 1 \text{ G\Omega} \text{ on the 1 nA range})\) is internal to the ammeter, and the ammeter was calibrated by supplying it with a reference current.

Our reference current generator consisted of a calibrated, temperature-controlled 1 G\Omega standard resistor, an uncalibrated voltage source and a calibrated DVM (model Keysight 3458A). The combined type B uncertainty in the reference current was \( \sim 1 \text{ ppm} \). In discussing calibrations, we need first to distinguish the instrument’s gain factor from its offset. We describe the relationship between the true current and current indicated by the instrument as \( I_{\text{true}} = (g \times I_{\text{true}}) + I_{\text{off}} \), where \( g \) is the gain factor. Our calibration determines only the gain factor. The offset current \( I_{\text{off}} \) is automatically removed from the background-corrected measurements of activity discussed in section VI, since it is present in the current with and without the radionuclide source in the ion chamber. We calibrated the gain factor of the ammeter every 2-3 days during the measurement period, and we denote the current measured by the ammeter, after adjusting the indicated current for the gain factor, as \( I_A \). Care was taken not to subject the sensitive ammeter preamp unit to mechanical shock, as previous experience with the EM-S24 small-current inter-comparison showed that even small mechanical shocks, such as plugging a cable into the preamp, could change the gain factor by several tens of ppm. Following these precautions, the ammeter calibration factor changed by less than 5 ppm over 2 – 3 weeks. For part of the study, we also used the same reference current source to calibrate the electrometer, as detailed in section VI.

In figure 2 we present an expanded circuit model for the input stage of an ammeter connected to a non-ideal current source with finite output resistance \( R_{\text{out}} \). In this study, the two instruments are connected to two very different current sources: the reference current source, which has \( R_{\text{out}} = 1 \text{ G\Omega} \), and the ion chamber, which as already noted has \( R_{\text{out}} \) many orders of magnitude higher. Consequently we can expect the noise behavior to be different in the two cases, and this will indeed become apparent in the next sections as we study the behaviour of the two instruments.

**IV. DEPENDENCE OF TYPE A UNCERTAINTY ON AVERAGING TIME**

All the radionuclide measurements were performed using the same ionisation chamber, which was of type Vin-ten 671. To assess the type A (statistical) uncertainty after a given averaging time, we placed a sealed Ra-226 source in the chamber and measured the current for periods of several hours. Raw data from ammeter measurements is shown in figure 3 (a). The ammeter was set to integrate each data point for 10 power line cycles (PLC), with the auto zero function disabled, and consequently

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I_{\text{off}}, \text{ the thermal noise in the feedback resistor } R, \text{ and the noise in } V_{\text{off}} \text{ driving a noise current in the source resistance } R_{\text{out}}. \text{ The current source itself may also contribute additional noise. Crucially, while the first two contributions are independent of } R_{\text{out}}, \text{ the last one increases in inverse proportion to } R_{\text{out}}. \text{ Amplifier designers face a trade-off: if } I_{\text{off}} \text{ is made very small, it is at the expense of a larger } V_{\text{off}}, \text{ and vice versa. The amplifier for an ion chamber electrometer clearly presents a limit case: the output impedance of the chamber is extremely high } R_{\text{out}} \gg 1 \text{ G\Omega}, \text{ and therefore } V_{\text{off}} \text{ and its associated noise has very little effect and the designer can relax these parameters and focus on minimizing } I_{\text{off}}. \text{ In fact, the electrometer used in this study had } V_{\text{off}} = 5 \text{ mV}, \text{ a fairly large value. The designer of a commercial instrument such as the ammeter used in this study has to make more compromises, as the instrument will be used to measure a wide range of current sources. Our Keithley 6430 unit had } V_{\text{off}} \sim 0.2 \text{ mV on the 1 nA range, more than a factor } 20 \text{ smaller than the electrometer preamp unit. We did not directly measure the noise in } V_{\text{off}} \text{ for the two instruments, but we could reasonably expect the ammeter to have a much smaller voltage noise than the electrometer. In this study, the two instruments are connected to two very different current sources: the reference current source, which has } R_{\text{out}} = 1 \text{ G\Omega}, \text{ and the ion chamber, which as already noted has } R_{\text{out}} \text{ many orders of magnitude higher. Consequently we can expect the noise behavior to be different in the two cases, and this will indeed become apparent in the next sections as we study the behaviour of the two instruments.} \]
The lowest type A uncertainty achievable with the ammeter is no longer a meaningful measure of the type A uncertainty, in which further increases in the averaging time do not gain any further decrease in the type A uncertainty. A plot of the ion chamber current from the same Ra-226 source, measured using the electrometer, is shown in figure 3(c). In this plot, each data point is obtained from one voltage ramp cycle. The ramp cycle lasted 85 s, so the data points in figures 3(b,c) can be directly compared, i.e. each data point corresponds to the instrument integrating the current signal for the same amount of time. The offset of ∼ 0.1 pA between the two instruments is not significant because these measurements are not corrected for the background, and we will investigate the agreement between the two systems in section VI. The significant feature visible in these long data sets is that the average current measured by the ammeter appears to drift with time, decreasing by ∼ 50 fA over the first few hours and continuing a downward drift more slowly for the remainder of the measurement time. The rapid drift visible at the start of this data set was rather atypical of the performance of this instrument, and not the result of mechanical shock. In contrast, the current measured by the electrometer appears to be stationary in time. Next, we employ the Allan deviation to more quantitatively investigate this observation.

The Allan deviation is a statistical tool developed as a way of assigning a meaningful statistical uncertainty to data with a non-stationary mean. It is widely used in time and frequency metrology, and its use in electrical metrology is becoming more widespread, for example to characterize the stability of voltage standards and current comparator bridges. Here, we briefly summarize it. The Allan deviation \( \sigma_A \) is computed from a time-series of data points evenly spaced over a total time \( T \). The computation yields \( \sigma_A \) as a function of averaging time \( \tau \), for \( \tau \lesssim T/4 \). For the case of frequency-independent noise, \( \sigma_A(\tau) = \sigma/\sqrt{\tau} \), where \( \sigma \) is the standard deviation of the data; in other words, the Allan deviation is equal to the standard error of the mean, and decreases as the square root of the measurement time. However, in the presence of frequency-dependent noise, the standard error of the mean is no longer a meaningful measure of the type A uncertainty. Two examples of frequency-dependent noise are 1/f noise, in which the Allan deviation is independent of \( \tau \), and random-walk, or 1/f\(^2\) noise, in which the Allan deviation increases as the square root of \( \tau \).

The Allan deviation of the time-domain data from figure 3(a) and (c) is shown in figure 3(d). Note that the first data point for the electrometer is at \( \tau = 85 \) s, the time for one integration ramp, whereas the ammeter data starts at \( \tau = 0.2 \) s, the time to acquire one reading. It is clear that both instruments have very similar \( \sigma_A \) for \( \tau < 2000 \) s, and that \( \sigma_A(\tau) \propto 1/\sqrt{\tau} \). For \( \tau > 2000 \) s, the behavior of the two instruments diverges. The ammeter enters a regime of approximately 1/f noise, in which further increases in the averaging time do not result in any further decrease in the type A uncertainty. The lowest type A uncertainty achievable with the ammeter, based on this data set, is ∼ 5 fA, or 100 ppm of \( I_A \). The electrometer, on the other hand, continues to follow \( \sigma_A(\tau) \propto 1/\sqrt{\tau} \) out to the longest time-scale probed by this data set, \( \tau \sim 40000 \) s, where \( \sigma_A \sim 1 \) fA, or 20 ppm of \( I_E \).

Some insight into the behaviour of the ammeter can be gained by plotting the Allan deviation of a time-series of data taken with the instrument left open-circuit (open diamonds in figure 3(d)). This exhibits a transition to 1/f noise at \( \tau \sim 10 \) s due to the low frequency behaviour of the input bias current noise. A small additional contribution may be due to the ADC voltage measurement. As discussed in section III, the superior stability of the electrometer at long averaging times is a consequence of its specialised design for one particular function, that of measuring ion chambers with very high output impedance.

The analysis presented in this section is not intended to be a definitive comparison of the two types of current measuring instrument, nor should the ammeter data be interpreted as definitively describing the particular make and model of instrument used in this study. Rather, it

![FIG. 3](image-url)
FIG. 4. (a): Ammeter current as a function of ion chamber voltage, with the ion chamber energised with a low-noise laboratory DC supply. The Ra-226 source in the chamber is the same as in figure 3. (b,c): Ion chamber current with the chamber energised using (b): the low-voltage source and (c): the high-voltage source. In each data trace, the source is initially in the chamber, and is then removed. (d): Allan deviation of sections of data with the chamber empty from plots (b) and (c). Open symbols: LV source, filled symbols: HV source. (e): As (d), but with the Ra-226 source in the chamber. (f): Amplitude spectra of current noise from an empty chamber energised with the LV and HV sources. (g): as (f), but with the Ra-226 source in the chamber.

is intended to demonstrate a methodology for evaluating the type A uncertainty achieved following a given averaging time. For example, referring again to figure 3 (d), if a statistical uncertainty of 50 fA (0.1% of the signal from the Ra-226 source) was desired, it is only necessary to integrate the current for 30 s using either type of instrument. Knowledge of the stability of the current measuring instrument is also important when designing a protocol for measuring the chamber background current. One possible such protocol would be to measure the background current once a day, and subtract the same background from all calibrations performed that day. In this case, the Allan deviation of the readout current for \( \tau = 1 \) day would yield the minimum meaningful statistical uncertainty achievable in any calibration.

Since instruments generally suffer from \( 1/f \) or random walk behavior at long time-scales, a more robust procedure would be to measure a new background signal every time the chamber is empty, i.e. in between calibrations of different sources.

V. INVESTIGATION OF EXCESS NOISE

A remarkable feature of the data in figure 3 (d) is the roughly factor of 100 increase in the short-averaging-time noise when the ammeter is connected to the energised ion chamber. This excess noise is indicated by a vertical double arrow. The excess noise is not due to the cable connecting the ammeter to the ion chamber. Separate measurements showed that the cable on its own, or indeed the cable connected to the chamber, but with the high voltage (HV) source disconnected from the chamber, increased the noise by a negligible amount compared to the situation with the ammeter input left open circuit. The statistical nature of current generation in the ion chamber can be expected to add a shot-noise contribution, but we do not believe it is a significant contributor to the total noise because there was only a small decrease in the total noise (less than a factor of 2) when the source was removed from the chamber.

To investigate the nature of the excess noise, we replaced the HV source with a low-noise laboratory voltage source (Yokogawa GS200), which we will refer to as the low-voltage (LV) source. This source was limited to a maximum of 32 V, but as shown in figure 4 (a), the chamber current almost reached saturation at this voltage using the same Ra-226 source employed in the previous section. In figures 4 (b) and (c) we show data measured using the ammeter, in which the source was initially in the chamber, and was then withdrawn from the chamber. The data of figures 4 (b) and (c) were obtained using the LV and HV voltage sources, set to 32 V and 1455 V, respectively. The lower current noise when using the LV source is immediately apparent. Allan deviation plots of sections of the data from figures 4 (b) and (c) show, however, that the reduction in noise using the LV source is rather more complicated than might appear from the time-domain data plots. With the chamber empty, the reduction in noise using the LV source is indeed dramatic, at least a factor of 20 for averaging times from 0.2 s to 100 s. A single 0.2 s data point using the LV source has a type A uncertainty of less than 10 fA, while to achieve the same type A uncertainty using the HV source requires averaging for at least 100 s. With the Ra-226 source loaded into the chamber (figure 4 (e)), the LV source indeed yields lower noise for averaging times up to a few seconds. For longer averaging times, the Allan deviation plots using the two voltage sources converge, and the LV source yields roughly a factor 2 lower noise than the HV source.

Next, we measured the amplitude spectra of the cur-
rent noise using both the LV and HV sources, with the chamber empty and containing the Ra-226 check source. For these measurements, the Keithley 6430 ammeter was replaced with an ammeter setup consisting of a Femto DDPCA-300 transimpedance amplifier with gain set to 10^6 V/A followed by a Keysight 34461A integrating volt-

meter sampling 1000 times a second. The bandwidth (3 dB point) of the transimpedance amplifier is 150 Hz. Time-domain data traces were transformed in software to yield the amplitude spectra scaled in units of pA/√Hz (figures 4(f) and (g)). The spectra have peaks at multiples of the 50 Hz power line frequency with both voltage sources, but the striking difference between the sources is at frequencies below about 50 Hz, where the HV source generates a broad background with an amplitude more than ten times that of the LV source. The background due to the HV source persists even if its variable voltage is turned down as low as 10 V, although it disappears if the voltage is set to zero. This data convincingly shows that the HV source is the origin of a large part of the excess noise first seen in figure 3(d). We did not attempt to investigate the origin of the noise further, for example by directly measuring the voltage noise spectral density of the two voltage sources. It is nevertheless clear that elimination of excess noise due to the HV power supply, by filtering or improved design, would result in reductions in the amount of time required to achieve a given resolution in a measurement of ion chamber current, and more dramatic reductions in the time required to measure the background current.

VI. ABSOLUTE AGREEMENT BETWEEN TWO READOUT SYSTEMS

A. Calibration of electrometer using reference current source

We now return to the comparison between the amme-
ter and the electrometer. In this section, we investigate how well the two systems agree in background-corrected measurements of a range of radioactive sources. As already noted in section III, the gain factor of the ammeter was regularly calibrated using a reference current source consisting of a 1 GΩ standard resistor and a calibrated DVM. Here, we also calibrated the gain factor of the electrometer using the same reference current source. For all the calibrations, the reference current was periodically switched between a nominal zero setting, and 50 pA, yielding a difference current ΔI_{cal} = 49.995 pA. The difference currents ΔI_{A} and ΔI_{E} were extracted from the instrument readings. Figure 5(a) shows values of ΔI_{A} (top-left inset) and ΔI_{E} (main plot) extracted from calibrations of the ammeter and electrometer respectively, over times of several hours. The most striking difference between the two instruments is that the values of ΔI_{E} exhibit much more statistical scatter than those for ΔI_{A}. This is a consequence of the specialised design of the electrometer amplifier module: as discussed in section III, it is optimised for measuring high impedance sources, and in section IV we found that it has excellent noise performance when measuring ion chamber currents. However, the resulting large offset voltage and associated voltage noise causes excess noise when connected to the 1 GΩ reference current source.

After averaging the statistical fluctuations in the calibration data of figure 5(a), we find that the mean current difference indicated by the electrometer, ⟨ΔI_{E}⟩, is offset from ΔI_{cal} by a statistically significant amount: (ΔI_{cal} − ⟨ΔI_{E}⟩)/ΔI_{cal} = (460 ± 46) × 10^{-6}. This error, 460 ppm, is much larger than the uncertainty in the capacitance, voltage and time components used to calculate I_E, although still much smaller than the uncertainties in the radionuclide-specific ion chamber calibration factors. As already noted in section III, a possible source of error in capacitor-ramp electrometers is frequency-dependence in the feedback capacitor. We measured the frequency dependence of the capacitor (a sealed-gas unit of ~500 pF) over the range 50 – 20000 Hz, and found that it only changed by a few ppm. However, we did not measure the capacitance at the millihertz frequencies at which the electrometer operates. In a previous study, it was found that capacitors with a large frequency dependence in the millihertz range also showed an anomalously large dependence in the audio range. However, this study was based on a small sample of capacitors, and we cannot rule out capacitor frequency dependence as the cause of the 460 ppm gain error in the ion chamber electrometer. The error may also be due to dielectric storage in C_{stray} leading to non-linearity of the voltage ramp, a type of behaviour already observed in another type of electrometer. In the following, we simply treat the calibration of the electrometer as yielding a correction factor, in the same manner in which we calibrated the ammeter.

B. Background-corrected measurements using both readout systems

As a direct comparison, the electrometer and amme-
ter were both used to measure background-corrected ion chamber currents from four different radionuclides. Each measurement consisted of a raw data set similar to that shown in figure 3(c), from which the background corrected currents I_{AC} and I_{EC} were obtained. To ensure that random geometrical factors due to source placement inside the chamber did not affect the comparison, the source was only put into the chamber once for each comparison. So, for example the ammeter would be used to measure first the empty chamber, then the source. Next the electrometer would be used to measure the source followed by the empty chamber. The socket at which the instruments were connected and disconnected from the chamber was mechanically isolated from the chamber via a cable to avoid disturbing the position of the source when the instruments were swapped.
As detailed, $I_{AC}$ already incorporates a correction factor from the ammeter calibration. $I_{EC}$ was optionally corrected, based on the calibration detailed in the previous sub-section. Figure 5(b) shows the normalised difference between the two background corrected currents both with and without the calibration correction applied to the electrometer current. After applying the correction, the weighted mean of the 4 points yields the average $\langle (I_{AC} - I_{EC}) / I_{EC} \rangle = (-0.009 \pm 0.021)^{\%}$, as indicated by the blue horizontal dashed line and error bar; the two systems agree within the random uncertainties. Without applying the correction factor, the weighted mean of the normalised differences is $(0.037 \pm 0.021)^{\%}$, a statistically significant disagreement. Our ability to compare the two measurement systems is hampered by the excess noise, probably due to the HV supply as discussed in section V, but we conclude that once they are both calibrated using a reference current, they agree to within $\sim 0.02\%$. They could be considered as equivalent candidates for an ion chamber readout system, provided a reference current source was available to calibrate them. Significantly however, the electrometer on its own, with traceability to capacitance, voltage and time, is in error by 0.046%.

VII. CONCLUSIONS

We compared examples of a feedback ammeter and an integrating electrometer, and we can conclude that the feedback ammeter, calibrated using a reference current source, can be considered as a viable alternative to the integrating electrometer traditionally used for ion chamber readout. Measuring ion chamber currents of a few tens of picoamps at an uncertainty level of 0.1%, which is sufficient for most radionuclide calibrations, the two current readout systems can be considered equivalent. At an uncertainty level of 0.01%, the two systems can also be considered equivalent with respect to type A uncertainty, reaching a relative type A uncertainty of 0.01% for a current of 50 pA after 1000 seconds of averaging. However, when calibrated using a reference current source, the electrometer was found to be in error by 0.046%. This highlights the importance of calibrating electrometers directly using reference current sources, as non-idealities in these systems can introduce errors orders of magnitude larger than the ppm-level uncertainties in the individual calibrations of capacitance, voltage and time. Reference current sources can be realised at uncertainty levels of around 1 ppm using calibrated standard resistors, voltmeters, and now the ULCA.

Independent of the readout system, the type A uncertainty was increased by a significant amount above the measuring instrument noise floor by a large amount of background noise originating in the high-voltage source. This shows that careful engineering of a low-noise high-voltage source would be a fruitful project, enabling type A uncertainties less than 0.01% to be achieved in just a few seconds of measurement time. We have also presented the Allan deviation as a useful statistical tool for evaluating the stability of current measuring instruments as a function of measuring time. This helps the design of calibration protocols which make most efficient use of the available time to reach a desired uncertainty level.

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