A computer-controlled Gerdien atmospheric ion counter

K. L. Aplin and R. G. Harrison
Department of Meteorology, University of Reading, P.O. Box 243, Earley Gate, Reading RG6 6BB, United Kingdom

(Received 8 February 2000; accepted for publication 8 May 2000)

Accurate measurements of atmospheric ions are desirable in order to investigate atmospheric aerosol processes. A cylindrical capacitor ion counter is described which has a flexible computerized control system, to allow selection of ion mobility by changing the bias voltage across the capacitor. Ion measurements obtained correlate well with the ionization rate measured with an adjacent Geiger counter in clean air. Measurements of air ions using the device in current and voltage decay modes show consistent results. The collecting electrode is exposed directly in the air stream to be sampled, eliminating diffusive losses in intake tubes. The system can measure ion concentrations from 20 ions cm$^{-3}$ (including typical atmospheric concentrations) and can sample ions rapidly. These characteristics enable comprehensive air conductivity measurements to be made. © 2000 American Institute of Physics.

I. INTRODUCTION

Atmospheric small ions are continually created from ionization by natural sources, primarily natural radioactivity and cosmic rays. Small ions are cluster ions of 4–10 molecules and typically exist in concentrations of a few hundred per cm$^{-3}$. Ion concentration measurements are indirectly related to aerosol concentration, and therefore offer an indirect method for measuring aerosol pollution. The ability to resolve ion mobility spectra is also useful in understanding particle formation processes. Recent predictions suggest that the established relationship between air conductivity and aerosol concentration may be invalidated under certain conditions, when large ions contribute to the air conductivity. A Gerdien ion counter operating at sequential bias voltages is necessary to also establish the contributions of different sizes of ions to the total air conductivity.

The utility of a ventilated cylindrical capacitor (or Gerdien condenser) to measure atmospheric small ion concentrations and air conductivity has long been established in atmospheric electricity. Varying the field strength within the capacitor, to control the minimum mobility of ions contributing to the current measured, is an effective approach to analyzing the behavior of atmospheric small ions. The instrument described here offers several advantages over previous implementations: it is exposed directly in the air stream to be sampled, eliminating inlet tube losses, and it is sufficiently small for an array to be constructed to make a set of measurements close to the surface. A programmable control system permits flexible investigations of ion concentrations and mobilities, and our original modernized device has been substantially improved here with flexible control of the bias voltage. This also allows calibration to be achieved by using the device alternately in voltage decay and current measurement modes.

II. SYSTEM DESCRIPTION

A. Overview

The different components comprising the spectrometer system are shown in Fig. 1(a). The Gerdien condenser is an aluminum cylinder of length 25.8 cm, radius 1.25 cm, with a central coaxial electrode (radius 0.8 cm) connected to a current amplifier. The central electrode is rigidly mounted using high quality polytetrafluoroethylene-insulated connections at each end. The tube is ventilated with a fan, and ions are transported through the tube by a combination of mean flow and electrical migration, determined by a controllable bias voltage of up to ±30 V applied to the outer electrode. Some of the ions reach the central electrode and cause a current to flow, which is registered by a sensitive current amplifier. The output from the i-to-V converter is in the range ±2.5 V, and is sent to a unipolar analog to digital converter (ADC). The digital ADC signal is processed by a 16C56 microcontroller and sent to a personal computer (PC) via the serial port. The microcontroller runs a basic program, controlling the bias voltage selection, ADC operation, and data formatting. It also controls a protective reed relay, which shorts out the feedback resistor in the current amplifier during bias voltage transitions.

B. ADC

IC$_1$ is a 12-bit ADC, running in single-ended mode, controlled by two serial lines from the microcontroller. A series level shift using a stable 2.5 V voltage reference (measured at 2.51995±0.00005 V) is added to the current amplifier output voltage before the ADC input, to ensure that bipolar ion currents can be recorded.

C. Bias voltage generator

Bias voltages for the outer electrode are generated by an 8-bit digital-to-analog converter (DAC), IC$_2$, from digital inputs supplied by the microcontroller. Since the full-scale out-
put of the DAC is limited by the voltage reference, which in this circuit is its precision 5V power supply, an additional high voltage op-amp IC3 and power supply are required to provide the ±30 V bias for the Gerdien. The output voltage of the DAC is given by

\[ V = V_{\text{ref}} \left( \frac{n}{256} \right), \]

where \( V_{\text{ref}} \) was measured at 5.061 ± 0.0005 V, and \( n \) is the voltage code supplied serially by the microcontroller. The IC3 stage applies a gain of 6.0 to supply the desired bias range of ±30 V, and an offset is applied to its inverting input to allow the DAC to select bipolar bias voltages. A subminiature glass-encapsulated, reed relay activated by an outer, nontouching coil is used to short out the feedback resistor in the current amplifier and protect it from the transient induced when the outer electrode bias voltage is changed. This is switched by a digital signal from the microcontroller via a VN10KM metal–oxide–semiconductor field effect transistor.

D. Microcontroller system and control program

The microcontroller system used is based on the 16C56 running BASIC Stamp I software in an integral electrically erasable programmable read-only memory (EEPROM).\(^7\) It has eight I/O pins and in this application, six of the eight available pins are used. Once the microcontroller is switched on, and a program downloaded to the EEPROM, it runs until the power is disconnected, and if the power is reconnected, the program will restart. This makes it ideal for remote logging applications. The sequence of operation starts with an initialization routine, sending the number and magnitude of bias voltages serially to the PC. The program then switches the bias voltages, with the ADC sampling the final current data and transmitting it to the PC serial port for logging.

III. CHARACTERIZATION

The instrument characterization was pursued both in the laboratory (Sec. III A), and in atmospheric air (Sec. III B).

A. Instrumentation system

The measurement system was calibrated in the laboratory by generating small currents using a millivolt calibrator and a 1 TΩ resistor. The outputs before and after the level shift stage were measured with a standard DVM, and by logging the final output, respectively. From Fig. 2 it is clear that the direct current response is linear to 99% in the range \(-2.5 < i_{\text{in}} < +3\) pA. The simple level shifting circuit was found to be constant to ±0.05 mV for \(-2 < i_{\text{in}} < +2\) pA. For larger positive voltages the level shift decreases and for

![Fig. 1.](https://example.com/fig1.png)

**Fig. 1.** (a) Block diagram of the computer controlled ion counter. (b) Schematic diagram of the level-shifting and ADC circuitry (IC, LTC1298 12-bit ADC). (c) The bias voltage generator. PSU 1 and 2 are transformer-isolated 30V modules (type NMA12155) supplying noninverting amplifier IC3 (OPA 445). A voltage offset is applied to the output of the 8-bit DAC IC2 (MAX 550A).

![Fig. 2.](https://example.com/fig2.png)

**Fig. 2.** Calibration of the current amplifier system, and the variation in the value of the level shift with the input current. \( V_{\text{shift}} \) was calculated by differencing the voltage measurements before and after the level shift stage. \( V_{\text{out}} \) is the final voltage value, after subtraction of the 2.5 V offset.
smaller negative voltages the level shift increases, such that the ADC input voltage tends to constant values of approximately +5 V or −75 mV, with corresponding over-range output values of 4095 or 0, respectively. A practical implication of this is that for bipolar currents larger than 2 pA magnitude, the output current will be subject to a variable error, however, atmospheric ion currents are considerably less than this. The uncertainty in the current amplifier output is about ±4 fA, which has been studied with an oscilloscope and appears to be largely caused by power line hum, despite screening; the op-amp input bias current also contributes to this uncertainty, and is estimated to be about ±2 fA. Since typical Gerdien output currents are ~100 fA, this represents an error of order 1%.

The current amplifier was tested with a screened input, to determine the op-amp input bias current $i_b$, and leakage, and with the reed relay cycling at 0.1 Hz. It was found that when the relay opened there was a voltage transient of about 30 mV (corresponding to a negative charge injection of ~6 fC) into the system. This exhibited a RC decay with a settling time of approximately 5 s, so a 10 s recovery time in the microcontroller measurement program was considered adequate.

### B. Ion measurements in atmospheric air

The Gerdien condenser is usually deployed in current measurement mode, but it is also possible to measure ion concentrations by a voltage decay technique for air conductivity. If the central electrode is charged with respect to the outer electrode and allowed to decay, the voltage decay rate is related to the total air ion concentration. This offers two independent measurements of ion concentration in principle, with an instrument of the same geometry in both cases. The measurement itself is straightforward and requires only an electrometer follower circuit. (The current measurement mode is generally preferred because of its faster time response.) The voltage decay can be approximated to an exponential, although in reality the relationship is somewhat more complex because the critical mobility varies with the bias voltage and does not remain constant. Atmospheric air was sampled in the laboratory using adjacent Gerdien tubes by an open window at 1.5 m measuring conductivity by the two methods. In the current measurement mode, where $i$ is the measured conduction current, $V$ the bias voltage on the outer electrode, and $C$ the tube capacitance, unipolar conductivity $\sigma_\pm$ is calculated from

$$\sigma_\pm = \frac{i e_0}{CV_\pm}.$$  

(2)

Determination of the tube capacitance is critical for calibration purposes, and several methods exist for measuring it. It was measured using a further resistive decay method based on a known resistance with a digital storage oscilloscope. $C$ was found to be 8.2±1.6 pF.

In the voltage decay mode, the total conductivity is related to the time constant of the decay $\tau$ by

$$\sigma = \frac{e_0}{\tau}.$$  

(3)

Assuming an ideal exponential decay, $\tau$ can be calculated by measuring the voltage $V$ at a time $t$ from when $V_0$ was applied, such that

$$\tau = \frac{-e_0 \ln \left( \frac{V}{V_0} \right)}{t}.$$  

(4)

The conductivity measurements shown in Fig. 3 were calculated by recording the voltage decay on a chart recorder, and calculating $\sigma$ as an average from $\bar{V}$ and $t$ values every 30 s during the decay, which typically lasts 10 min. The decay rate of the capacitor is influenced by the polar conductivity due to both positive and negative ions, so this method measures total conductivity $\sigma$, where

$$\sigma = \sigma_+ + \sigma_-.$$  

(5)

Equal times every day were spent measuring positive and negative conductivity by the current method, and the daily averages summed to give a total conductivity value for comparison with measurements made by the alternative method. The daily average values of conductivity are shown in Fig. 3, along with the ion asymmetry parameter, $x$ (the ratio of positive to negative ions). $x$ shows an average value of about 1.4 which is a typical value in polluted urban air. 9,10

Results for the air conductivity from the ion current and voltage decay methods are consistent, with a positive correlation of 0.43. Much of the slightly greater discrepancy between 9 and 12 June 1998 is accounted for by variations in flow speeds within the tubes, and the effects of wind direction on the sampling orifice. Average conductivity from the current measurement mode was $0.5 \times 10^{-14}$ S m$^{-1}$, which is in agreement with similar measurements. 11

A further test on the Gerdien system was obtained by monitoring the source rate of ions, which is principally from local radioactivity, and comparing it with measured ion concentrations. The complicating effect of ion removal by aerosol can be reduced if these measurements are made in clean air, for which reason the measurements were made at Mace.

---

**FIG. 3.** A comparison of air conductivity measurements obtained using the time decay and current methods (left-hand axis). All values are daily averages, and total conductivity from the current measurement method is the sum of the positive and negative conductivity measurements. The ratio of positive to negative conductivity is shown on the right-hand axis.

The daily average values of conductivity are shown in Fig. 3, along with the ion asymmetry parameter, $x$ (the ratio of positive to negative ions). $x$ shows an average value of about 1.4 which is a typical value in polluted urban air. 9,10

Results for the air conductivity from the ion current and voltage decay methods are consistent, with a positive correlation of 0.43. Much of the slightly greater discrepancy between 9 and 12 June 1998 is accounted for by variations in flow speeds within the tubes, and the effects of wind direction on the sampling orifice. Average conductivity from the current measurement mode was $0.5 \times 10^{-14}$ S m$^{-1}$, which is in agreement with similar measurements. 11

A further test on the Gerdien system was obtained by monitoring the source rate of ions, which is principally from local radioactivity, and comparing it with measured ion concentrations. The complicating effect of ion removal by aerosol can be reduced if these measurements are made in clean air, for which reason the measurements were made at Mace.
Head, W. Ireland, in summer 1999. A ZP1410 Geiger tube operated at a bias voltage of 550 ± 5 V, in the plateau of its sensitivity curve, was located approximately 5 m away from a microcontrolled ion counter, at the same height. The Gerdien was programmed to make ten samples at 0.66 Hz on a nominally 3 min cycle, which were then averaged. In the recombination limit, when the aerosol concentration is negligible, we expect the ion concentration to depend only on the square root of the ion production rate, $q$. 

$$n \propto \sqrt{\frac{q}{\alpha}}$$

where $\alpha$ is an ionic self-recombination coefficient. Classical work suggests that alpha radiation due to Radon isotopes measurable with a Geiger counter, comprises a significant fraction of $q$ at the surface. Figure 4 shows data from the early morning of a fine day, where the square root of the Geiger count rate shows a good correlation with a correlation coefficient of 0.38 with the ion concentration.

IV. RESULTS

The instrument described was installed to sample at 1.25 m at the Reading University Meteorology Field Site. The tube was mounted externally, i.e., within the air to be sampled, to avoid the diffusion losses associated with inlet pipes. It was powered using a 12 V lead acid battery and data was logged with a mains-powered laptop computer housed in a watertight box at the base of the support mast. Because of its exposure, it was found necessary to clean the insulators with isopropanol daily. Ion currents obtained were logged at 0.66 Hz for 15 s and the raw data files were processed offline using a Turbo Pascal program, Gerdproc, to screen and average the samples, and compute the conductivity from the current measurements, using Eq. (2). The concentration of ions, $n$, with a mobility exceeding the critical mobility $\mu_c$, is approximated by

$$n = \frac{\sigma}{e \mu_c}$$

the ion concentration at a mean critical mobility is then obtained by differencing. If the minimum current resolvable by the current amplifier is 5 fA at a bias voltage of 20 V, and the average critical mobility for atmospheric small ions is $1 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, then the minimum ion concentration measurable is about 20 ions cm$^{-3}$.

Figure 5 shows typical ion concentrations calculated from Eq. (7) measured at bias voltages of $-19.6$ and $-14.0$ V. Mean values are 1820 and 1760 ions cm$^{-3}$ with $\mu > \mu_c$ where $\mu_c = 0.77$ and 1.08 cm$^2 \text{V}^{-1} \text{s}^{-1}$, respectively, and the measurements are seen to track each other well, with a positive correlation of 0.54. The variability is likely to be related to advective transport of radioactive particles, and greater time resolution is desirable to explore this.

Computerization of the Gerdien ion counter system is clearly a substantial improvement on its classical implementation because of the increased flexibility offered in controlling the bias voltage and sampling parameters.

ACKNOWLEDGMENTS

The authors are grateful to A. G. Lomas for technical support and production of circuit diagrams, and to J. R. Knight for his assistance with the DAC control program. One of us (K.L.A.) acknowledges a studentship from the Natural Environment Research Council.
7 Parallax Instruments Inc., 3805 Atherton Road, Suite 102, Rocklin, CA 95765.