J4.1 A LOW-POWER ELECTRIC-FIELD METER WITH RECIPROCATING SHUTTER

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1. INTRODUCTION

There is a trend toward improving the quality of hazard-warning decisions in order to reduce danger and interruption of work or leisure caused by electrified clouds and thunderstorms. Lightning warning devices fall into two classes: lightning detectors and electric-field monitors (Chalmers, 1967). Some lightning warning systems employ both lightning detectors and electric-field monitors. Stand-alone lightning detectors provide warnings of nearby discharges. Lightning detection networks provide maps of the ground-strike points of lightning flashes, which are used to track the movement of electrical storms. New types of stand-alone lightning detectors and the National Lightning Detection Network, (Cummins, 1998) developed over the last two decades, have greatly improved lightning hazard-warning capabilities for many applications. Where human casualties or catastrophic explosions are of great concern, there is often a need for as much information as possible about the lightning hazard. The magnitude, sign and time rate of change of the atmospheric electric field near the ground is necessary information in these high-risk situations. For many decades, the instruments of choice to measure atmospheric electric field have been field mills. Field mills have been deployed singly, in small numbers, and in a few large networks, as required to meet the need for coverage of areas of concern (Jacobson and Krider, 1976; Krider and Koshak, 2001).

Traditional field mills employ a spinning metal rotor connected to ground potential, placed between the external field and stationary metal sense electrodes. The spinning rotor alternately shields and exposes the sense electrodes to the electric field to be measured, resulting in a modulation of the charge induced on the sense electrodes. Typically a pair of charge amplifiers convert the modulated charge into AC voltages that are synchronously rectified and filtered to form a DC voltage proportional to the electric field.

A variety of methods have been employed to make electrical contact with a spinning motor shaft, all of which suffer incremental degradation with use. Chubb (1990) developed an elaborate scheme which eliminates the need to ground the shutter of a field mill albeit at an increase in cost and complexity. Traditional field mills have no convenient way to compensate for measurement errors due to electronic drift in the charge amplifier and synchronous rectifier circuitry. Leakage currents also develop across the sense-electrode insulators, introducing additional measurement errors. Frequent scheduled cleaning of insulators is often necessary in critical field-mill applications, especially in coastal environments, to keep measurement errors due to leakage currents across insulators to a minimum (Stewart and Barnum, 1993; Slaton, 1993).

Under a license agreement with the University of Oklahoma, Campbell Scientific Inc. has developed an electric-field meter that employs a reciprocating shutter, in a manner evocative of the apparatus of Wilson (1916). The resulting instrument offers several performance improvements over instruments that use a continuously spinning rotor. First, the reciprocating shutter accommodates a direct bond to the motor shaft for the ground connection, eliminating the problematic rotating contacts. In addition, DC measurement errors are automatically and continuously compensated for by means of the zero electric-field reference available when the shutter is closed.

2. A MODERN IMPLEMENTATION OF WILSON'S ELECTRIC FIELD METER

The reciprocating-shutter electric-field meter developed by Campbell Scientific Inc. is illustrated in Fig. 1.

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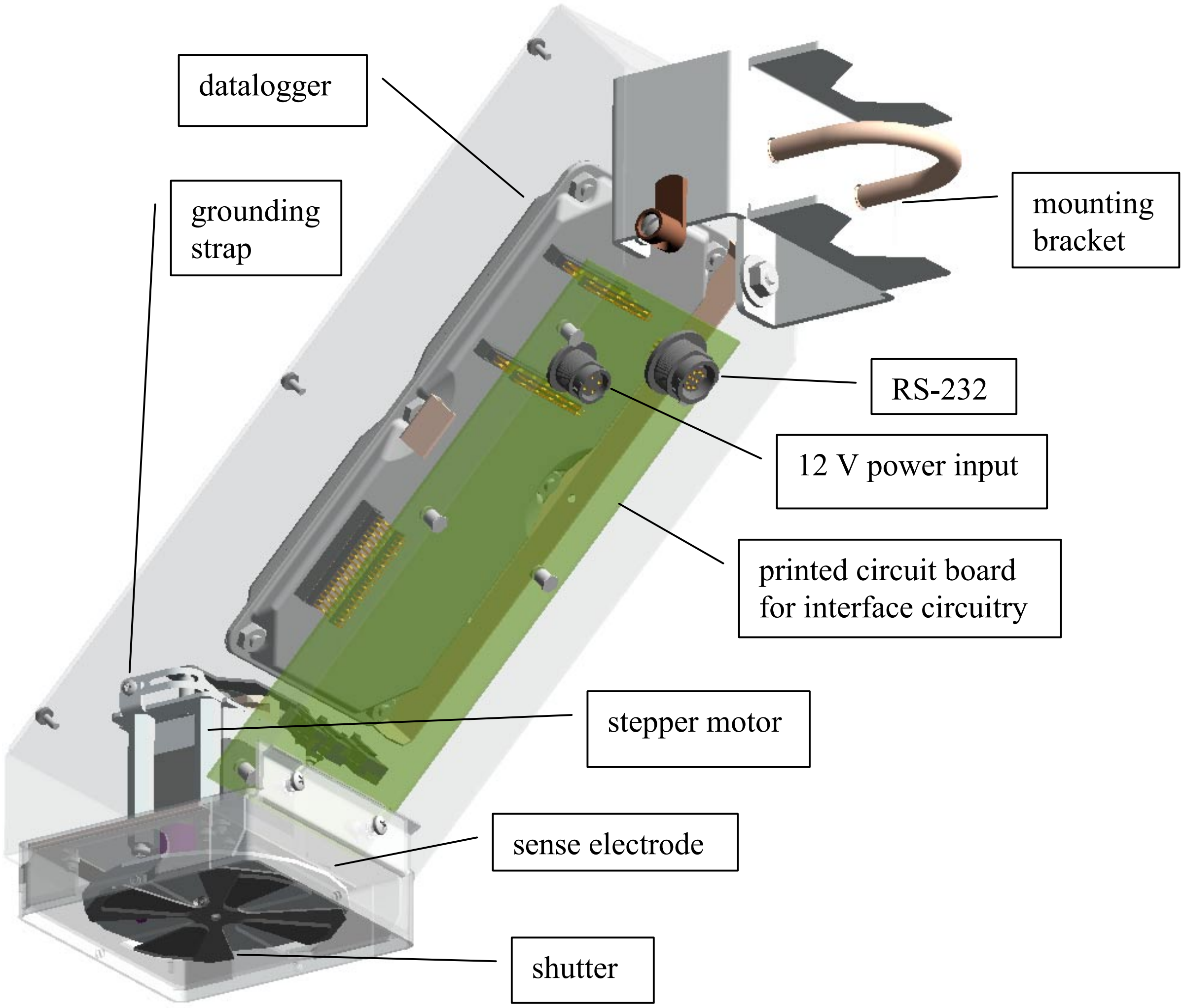

Fig. 1. Illustration of reciprocating electric-field meter.

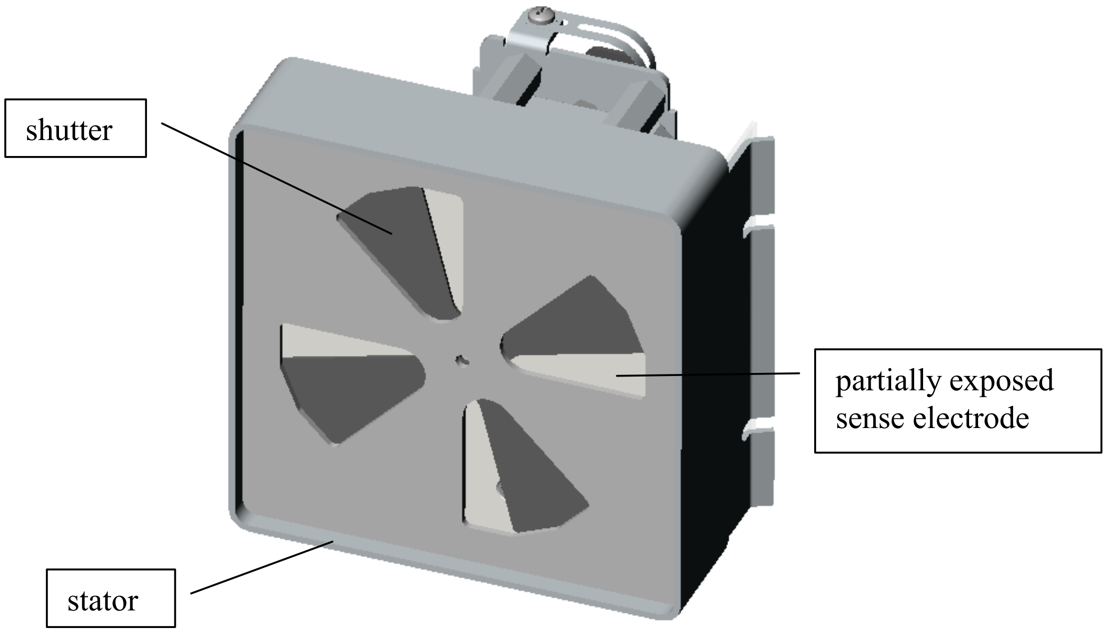

Fig. 2. Partially opened shutter on reciprocating-shutter electric-field meter.

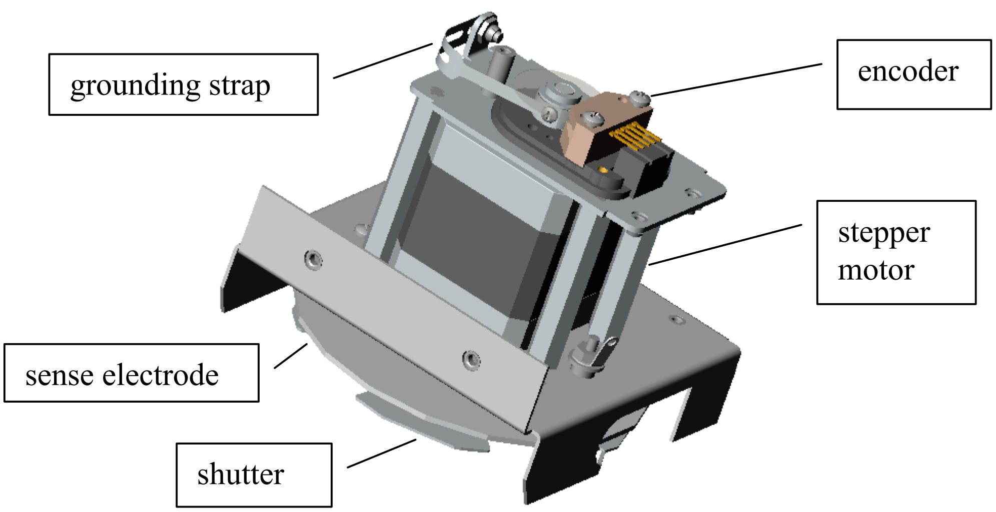

Fig. 3. Grounding strap design in reciprocating-shutter electric-field meter.

A high-reliability stepper motor is used to rotate the shutter back and forth, while position is determined by a rotary encoder. Measurement, control and communications functions are performed by a microprocessor-based datalogger, which includes a user-programming language that provides extensive flexibility in choosing measurement rates, averaging techniques and alarm threshold settings.

The stainless-steel stator, shutter and sense electrode are illustrated in Fig. 2. The shutter and stator are connected to ground potential during operation. As a result, the sense electrode is completely shielded from external electric field with the shutter closed.

The reciprocating shutter is connected to ground potential by means of a flexible stainless-steel strap as illustrated in Fig. 3, improving significantly upon traditional rotating contacts.

The output voltage from the charge amplifier during a reciprocating measurement cycle is illustrated in Fig. 4.

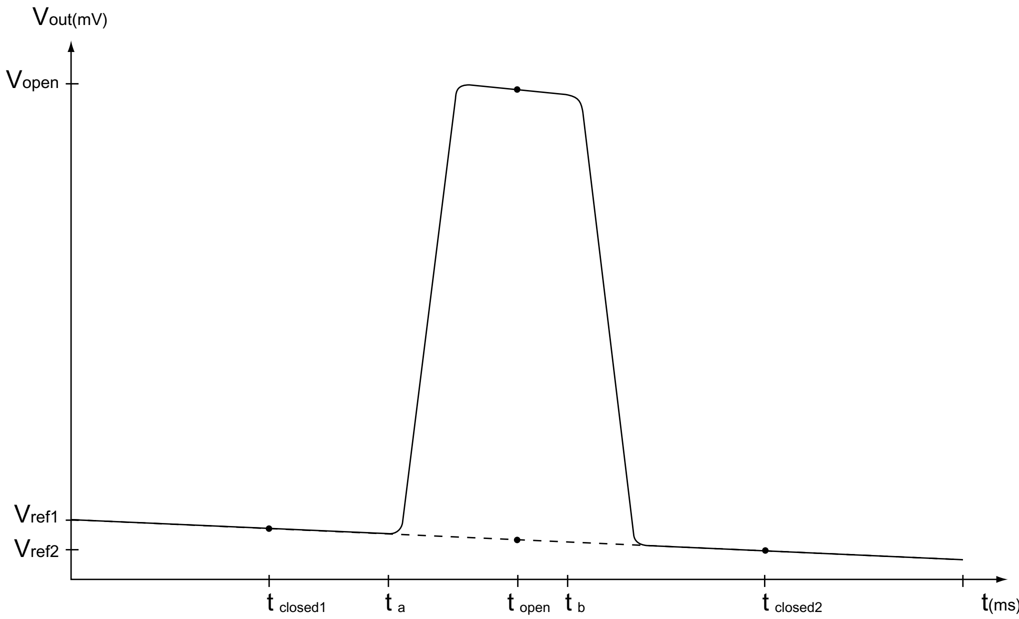

Fig. 4. Charge amplifier output during a measurement cycle.

In Fig. 4, the shutter begins opening at t_a and commences closing at t_b. Three voltage measurements of the charge amplifier output are taken during the measurement cycle; Vref1 = Vout($t_{closed1}$), Vopen = Vout(t_{open}) and Vref2 = Vout($t_{closed2}$).

Voltages Vref1 and Vref2 are the two zero-field reference measurements used for DC error correction. Non-zero values of Vref1 and Vref2 are due to electronic offset voltage, surface potentials between various metallic parts and leakage currents on the charge amplifier input. The DC leakage currents on the charge amplifier input cause a voltage difference between Vref1 and Vref2, the magnitude of which increases with degradation of insulation due to humidity and surface contamination. An electronic reset is utilized prior to each measurement cycle to zero the effects of these leakage currents on the magnitude of the charge amplifier output. Measurement errors due to DC leakage current are eliminated by calculating the zero field reference voltage at time t_{open}. Exploiting symmetry such that $t_{open} - t_{closed1} = t_{closed2} - t_{open}$, the zero field reference voltage at time t_{open} is simply

$$\mathrm{Vref}(t_{open}) = \frac{(\mathrm{Vref1} + \mathrm{Vref2})}{2}. \qquad (1)$$

The measured electric field is then determined as

$$E = k\cdot(\mathrm{Vopen} - \mathrm{Vref}(t_{open})) = \frac{k}{2}[(\mathrm{Vopen} - \mathrm{Vref1}) + (\mathrm{Vopen} - \mathrm{Vref2})] \qquad (2)$$

where k is a constant determined by electrode geometry and electronic gain. The resulting algorithm effectively eliminates measurement error sources that vary slowly with respect to the time between zero-field reference measurements, which is approximately 150 ms. Measurement noise due to 50 or 60 Hz AC power can be suppressed by utilizing the 50 Hz or 60 Hz noise rejection capability of the datalogger.

Field mills typically consume many watts of power because their motors are operated continuously. In the reciprocating approach, the stepper motor is powered off much of the time, resulting in low power consumption. The current required by a 12 V DC powered reciprocating electric-field meter is shown in Fig. 5. As illustrated in the figure, the average electric-field meter current is a function of the desired measurement rate, which is user-controlled by means of the datalogger program, making economical remote solar power feasible. Variable sample rates based on measured results can also be implemented. For example, to minimize power consumption during normal conditions, a user could select a 30-second measurement interval. To better follow rapid changes of electric field during threatening conditions, the user could pre-program the same field meter to automatically shift the measurement interval to one per second when, for example, the electric field exceeded a given value for a specified length of time. Fig. 5 does not include the current required for peripheral devices necessary to communicate with a central site. Like the stepper motor, communication devices that are turned off when not needed offer low average power consumption.

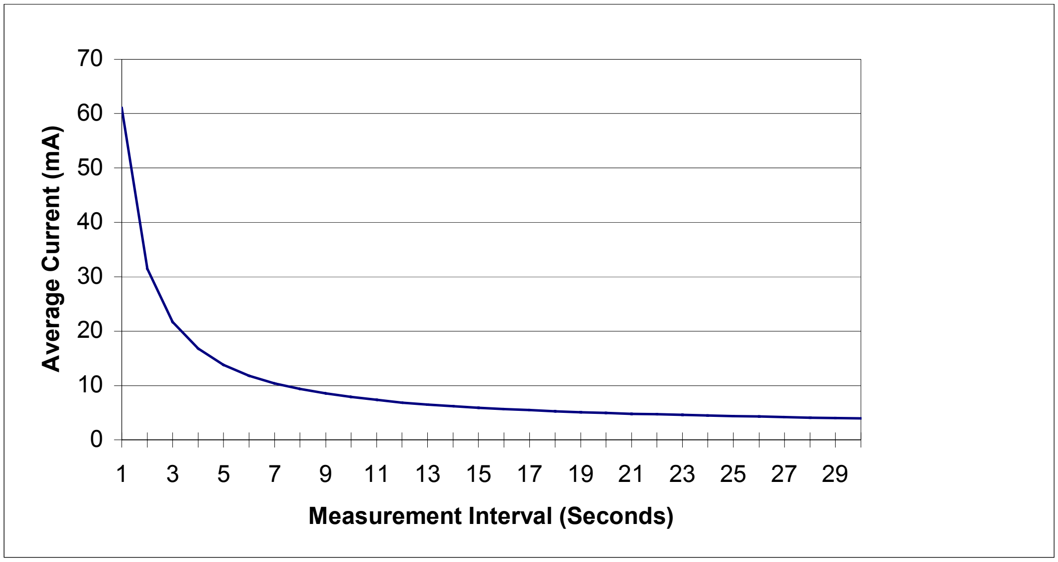

Fig. 5. Reciprocating electric-field meter current consumption versus measurement interval.

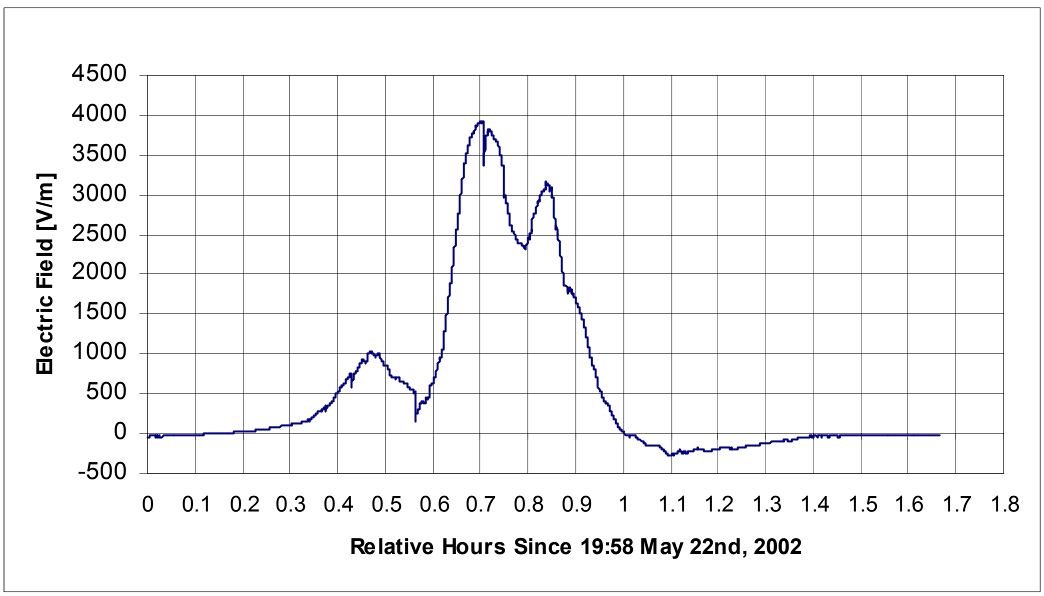

Fig. 6. Electric field during thunderstorm measured at 1 sample per second.

3. PERFORMANCE

The performance of the reciprocating electric field meter was tested in a 1.3 meter by 1.3 meter stainless-steel parallel-plate calibration fixture. A plate spacing of 0.15 meters along with an adjustable high-voltage source were used to establish a uniform electric field at the sensor aperture. An electric-field offset of 10 to 30 V/m existed in the calibration fixture, which we attribute to trapped charges on contaminated or oxidized surfaces. Measured results showed instrument accuracy to be within ±1% of reading with ±30 V/m offset for electric fields ranging from –20 kV/m to +20 kV/m.

Prototype reciprocating electric-field meters implementing the concepts discussed herein have been built and run for extended periods out-of-doors. Figure 6 shows the electric field during a local thunderstorm, as measured by a prototype reciprocating electric-field meter.

Figure 6 illustrates a polarity change in the electric field near 0.1 hours due to an approaching electrified cloud. Rapid field changes indicative of negative cloud-to-ground lightning discharges can be seen at about 0.43, 0.56, and 0.71 relative hours. Following a period of elevated electric field including several electric field changes due to lightning discharges, the electric field is seen to return to normal at the conclusion of the thunderstorm.

4. CONCLUSIONS

An electric-field meter with a reciprocating shutter has been developed that offers important advantages over the conventional field mill. The rotating ground connection has been replaced by a bonded stainless-steel strap that has no inherent wear-out mechanisms. The reciprocating design also allows for continuous automatic compensation of DC measurement errors. Low-power consumption is achieved because the motor is de-energized most of the time. The resulting electric-field meter is suitable for deployment on solar-powered remote automated meteorological stations.

A datalogger is employed for the measurement, control and communications functions of the electric-field meter. The resulting instrument offers a powerful user-programming language that provides extensive flexibility in choosing measurement rates, averaging techniques, alarm conditions, etc. The datalogger also provides several communications options along with networking capability. In an effort to improve reliability and reduce maintenance costs, several self-diagnostic features have been incorporated.

Measurement and reporting of the atmospheric electric field near the ground is an important yet under-utilized meteorological parameter. Unlike the majority of weather variables such as temperature and wind speed, electric field cannot be sensed by humans, except in extreme high-field conditions. While thousands of automated weather stations are presently monitoring other more common meteorological parameters, none are providing electric-field data that could aid in present weather reporting, thunderstorm research and lightning warning. The availability of a low-power, more reliable and less expensive electric-field meter will make it economically possible to include electric field measurements along with other standard meteorological parameters.

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