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Evaluation of a modern point discharge sensor as an atmospheric electricity instrument

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Abstract. Point discharge sensors have been used for a long period of time, but are still not fully understood. The data collected by one of these sensors has been investigated along with electric field data in an attempt to parameterise the sensor. It was found that the sensor was best described by an equation with terms dependent on the atmospheric electric field and the first derivative of this electric field, with respect to time. This behaviour implies that both electrostatic and electrodynamic processes are important to the operation of the sensor. The inclusion of the electrodynamic term means that although this sensor is able to detect electrical disturbances, it is more difficult to recover the precise nature of the electric field using this sensor.

1. Introduction

Point discharge is an interesting electrical phenomenon with far reaching impacts. It occurs when the atmospheric electric field is enhanced at the tip of a sharp point, allowing the air to become ionised, and conduct a point discharge current (PDC) between the point and the atmosphere [1]. During times of disturbed weather, the local atmospheric electric field can become sufficiently large that point discharge currents flow from the tips of sharp objects, such as the leaves of plants [2]. These PDCs are important to the flow of charge within the Earth's global atmospheric electric circuit, however they also have important impacts on other systems [1]; The process of point discharge can provide enough energy to enable the production of species such as ozone and nitrogen oxides in the atmosphere [3, 4]. Additionally, it is possible for the atmospheric ions produced from the point discharge process to reduce the concentration of particulate matter in the atmosphere [5].

Point discharge is able to be used as a measure of atmospheric electricity, via PDC sensors [6]. A PDC sensor operates by measuring the current that flows from a sharp point in the Earth's atmospheric electric field. A schematic diagram detailing a PDC sensor, and the atmospheric parameters which drive the discharge current, is shown in figure 1.

PDC sensors have been used to study atmospheric electricity for many years[6]. These sensors are cheap and robust compared to other atmospheric electricity instruments, such as electric field mills. Because of this, an understanding of the operation of these sensors is desired, since it would allow atmospheric electricity measurements to be taken in environments where delicate sensors are unsuitable (such as remote sites on mountain tops) [7].

Despite PDC sensors having been used for such a long time, their operation has still not been fully understood. Previous empirical and theoretical studies have attempted to parameterise

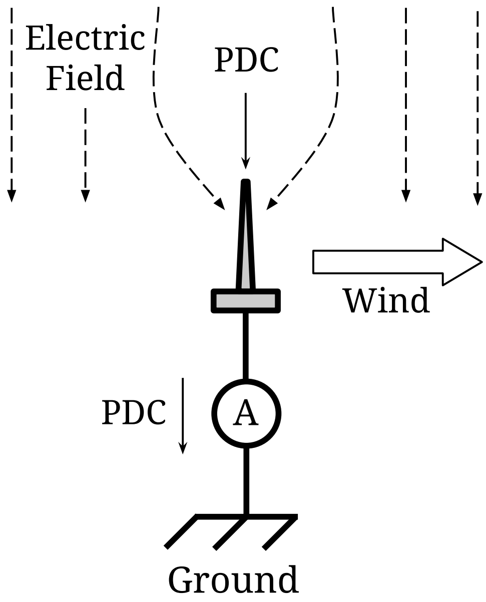

Figure 1: Conceptual diagram of a point discharge sensor. The point discharge current (PDC), atmospheric electric field, and horizontal wind speed have been shown. The pointed tip of the sensor causes electric field lines to curve towards the sensor, creating a high electric field near the sensor tip. This allows a discharge current to flow into the sensor, towards ground. The electrometer inside the sensor records the polarity and magnitude of this discharge current.

the operation of these sensors. The parameterisations found typically involve an electrostatic dependence, where the discharge current measured is proportional to some power of the electric field. Such examples are shown in equation 1 from Kirkman and Chalmers [2] and equation 2 from Whipple and Scrase [8].

$$I = K(W + c)(F - M) \tag{1}$$

$$I = a(F^2 - M^2) \tag{2}$$

where I is the discharge current, F is the potential gradient (the negative of the electric field), W is the wind speed, and K, c, M, and a are constants.

Previous investigations into point discharge sensors have likely been limited by their apparatus. The investigations leading to the parameterisations in equations 1 & 2 used chart recorders to record the point discharge data [2, 8]. The nature of these devices means that it is possible that the detectors used in these studies are not sensitive to high frequency effects. With modern technology, we are able to sample the sensor at a much higher frequency than many previous investigations were able to, allowing investigation into possible high frequency effects. We have used a modern PDC sensor and data logger to investigate how well the PDC process is represented by the parameterisations developed previously.

2. Methods

The PDC sensor used in this investigation featured a bipolar logarithmic amplifier, allowing a wide range of discharge currents to be recorded [9]. It is known that the time response for this type of sensor cannot be described by a simple first order response; The time response is larger for lower magnitude currents [9]. The sensor was deployed at the Reading University Atmospheric Observatory in 2012. This is a well equipped field site, with a number of other meteorological instruments operating. Relevant to this investigation was an electric field mill, which measured the vertical atmospheric electric field, and 3 orthogonal anemometers which allowed the wind speed and direction to be found. For the analysis described here a 15 minute subset of data on 01/03/2020 was selected, as it provided adequate variation in the data. The point discharge data was resampled at a frequency of 0.2 Hz, to remove very high frequency variations in the data.

3. Results

A time series of the PDC and electric field data is shown in figure 2. Since the PDC is varying over several orders of magnitude, a log y axis was desired. However, since both positive and negative currents were being considered, this would require seperate plots for these different polarities. As a compromise, a symmetric log y axis was used, with linear scale between the lowest magnitude current and 0. The electric field data was plotted on the same x axis, also with a symmetric log y axis.

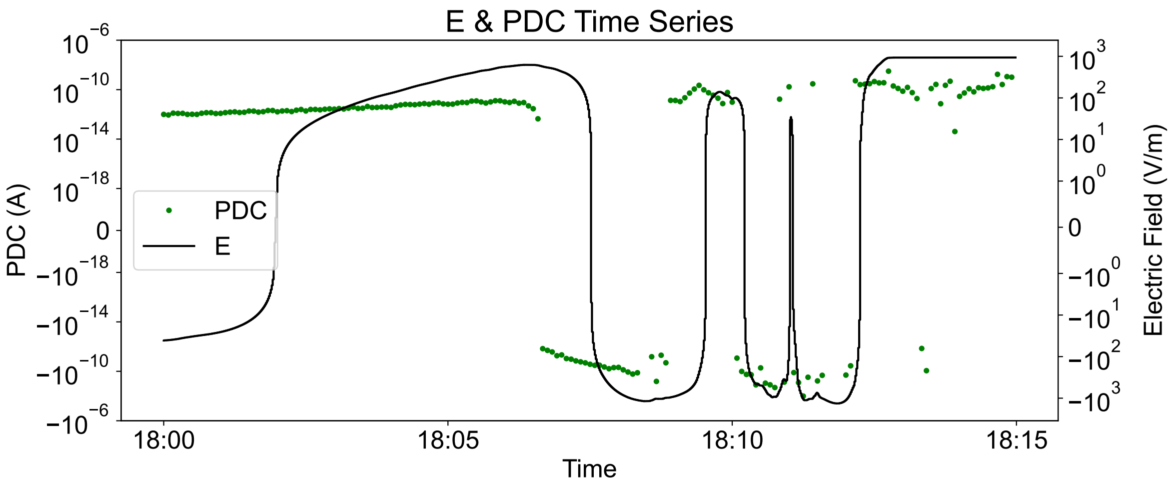

Figure 2: Time series of the PDC (green) and the electric field (black), plotted on the same x axis.

It was noted that the time series for the PDC and electric field did not seem to line up perfectly, with changes to the PDC appearing to precede changes to the electric field. A number of x-axis crossings were identified for each of the data sets, by finding the times when the electric field/PDC changes polarity. In order to compare the times of the axis crossings from each data set a subset of the crossings was created, where the polarity remains the same for several data points before and after each change in polarity. The root mean squared error (rmse) between each axis crossing in the PDC data set and the nearest crossing in the electric field data set was found. This yielded a rmse of 35.0s for 4 of these x-axis crossings.

Previous parameterisations of PDC sensors have focussed only on electrostatic terms, neglecting any electrodynamical effects on the recorded discharge current. One such electrodynamical effect is the electric displacement current. The displcement current, I_D, crossing a particular surface is given by equation 3:

$$I_D = \iint_S \epsilon \frac{\partial E}{\partial t} \cdot dS \tag{3}$$

where ϵ is the permitivity, S is the area of the surface, and $\partial E/\partial t$ is the rate of change of electric field with respect to time.

In order to explore if these electrodynamical effects may be important, the rate of change of electric field was compared against the PDC, as shown in figure 3. Symmetric log y-axes were once again used, and x-axis crossings were determined in the same way as previous. The rmse between the crossings in the PDC data and the crossings in the rate of change of electric field was found to be 9.3s. This is an improvement from the electric field data, however it was noted that changes to the PDC data were now succeeding changes to the rate of change of electric field for each of the axis crossings studied.

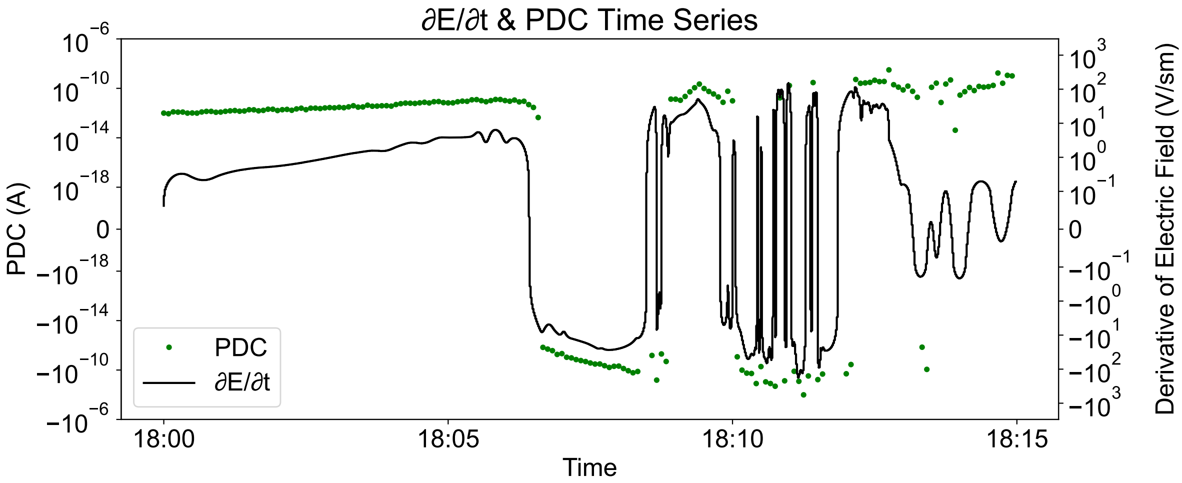

Figure 3: Time series of the PDC (green) and the rate of change of the electric field (black), plotted on the same x axis.

Since the axis crossings from the electric field data were preceding those in the PDC data, and the crossings from the rate of change of electric field were succeeding them, it was proposed that the best description of the PDC data may arise from a combination of electrostatic and electrodynamic terms. In order to investigate this, a fit to the PDC data was considered of the form described in equation 4:

$$I = f(E) + g\left(\frac{\partial E}{\partial t}\right) \tag{4}$$

where I is the point discharge current, E is the electric field, $\partial E/\partial t$ is the rate of change of electric field with respect to time, and f and g are functions describing electrostatic and electrodynamic behaviours respectively.

Simple functions for f and g were selected for this investigation, according to equations 5 and 6:

$$f(E) = cE \tag{5}$$

$$g\left(\frac{\partial E}{\partial t}\right) = A\epsilon_0\frac{\partial E}{\partial t} \tag{6}$$

where c and A are some constants, and ϵ_0 is the permitivity of free space. It should be noted that the effects of wind speed have been neglected from the electrostatic term in equation 5. It is likely that including the term could allow a better fit to the data, however, as previous studies have discovered, at low wind speeds processes independent of wind speed become important for determining the magnitude of discharge current [10]. As such, including the effects of wind speed would necessitate the addition of multiple terms in equation 5, adding complexity. It is the hope that further studies will investigate the inclusion of these terms.

Using a least squares approach, the constants c and A were fit for, minimising the rmse between the x-axis crossings of the PDC fit in equation 4 and the PDC data, and minimising the error between the y values for the PDC data and the PDC fit. The values for c and A were found to be 1.2×10^{-13} Sm and 1.1 m^2 respectively. This yielded an rmse between the axis crossings of 5.55s. The PDC fit using these values is compared against the PDC data in figure 4.

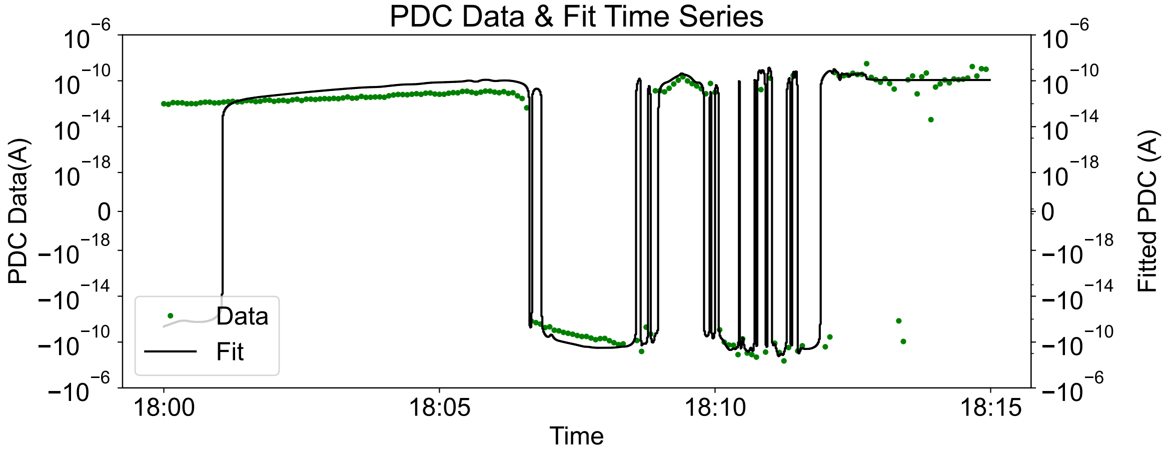

Figure 4: Time series of the recorded PDC data (green) and the fit to this data described in equation 4, using a value of 1.2×10^{-13} Sm for c and a value of 1.1 m^2 for A (black).

4. Discussion

From this investigation, it is clear that including terms based on both the electric field and the rate of change of the electric field provided an improved description of the PDC recorded by the sensor than just considering one of these terms. As discussed before, the dependence on electric field is not unexpected since many previous parameterisations have included electrostatic terms dependent on some power of the electric field. The dependence on the rate of change in electric field was unexpected, however, since it implies that some electrodynamic effect is important, which has been neglected from these previous parameterisations.

The candidate suggested for this electrodynamic effect is the electric displacement current. If this was the case, then it would mean that the sensor is responsive to both “free currents”, caused by the movement of charges in the discharge current, and displacement currents, caused by the changing atmospheric electric field. It is unclear, however, why previous attempts to parameterise these sensors have not encountered effects caused by displacement currents. Among other factors, it is possible that some geometric aspect of this particular sensor is enhancing the currents, or that the high sampling frequency of the sensor makes it particularly sensitive to these variations.

The inclusion of both electrodynamic and electrostatic terms in a parameterisation of the PDC sensor is problematic if this sensor is to be used alone as an atmospheric electrical instrument. Since the output signal is dependant on both the electric field and its derivative, it would be difficult to recover the electric field from just a point discharge measurement. The issues caused by the inclusion of electrodynamic effects would likely be worse for sensors moving vertically in the atmosphere, such as Coronasondes (radiosondes carrying a point discharge sensor) and spacecraft with point discharge instrumentation (e.g. Venera 13 & 14) [11, 12]. The potential difference between the sensor and the atmosphere for these instruments is fundamentally dependent on electrodynamic processes, which would add additional complexity to any attempt to recover the atmospheric electric field signal. The presence of both electrostatic and electrodynamic effects can have an advantage in these deployments however. If it is unclear if there is any electric signal to look for, then the inclusion of both electrostatic and electrodynamic terms means that a detector has a higher chance of detecting the presence of electric effects, even if their precise nature cannot be obtained.

5. Conclusion

The PDC sensor being investigated is likely sensitive to both electrostatic and electrodynamic effects. This complicates the ability for this sensor to operate as an atmospheric electricity instrument, as it means that recovery of the electric field signal is difficult. A good fit to the current data was able to be performed with reasonable accuracy if electric field data was provided, however.

Acknowledgments

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References

[1] Chalmers J A 1967 *Atmospheric Electricity 2nd Edition* ed Haar D T (Pergamon Press) pp 239-62
[2] Kirkman J R and Chalmers J A 1957 Point discharge from an isolated point *Journal of Atmospheric and Terrestrial Physics* **10** 258-65
[3] Bachman C H, Hademenos D G and Underwood L S 1971 Ozone and air ions accompanying biological applications of electric fields *Journal of Atmospheric and Terrestrial Physics* **33** 497-505
[4] Rehbein N and Cooray V 2001 NOx production in spark and corona discharges *Journal of Electrostatics* **51-52** 333-9
[5] Jiang S Y, Ma A and Ramachandran S 2021 Plant-based release system of negative air ions and its application on particulate matter removal *Indoor Air* **31** 574-86
[6] MacGorman D R and Rust W D 1998 *The Electrical Nature of Storms* (Oxford University Press) pp 76-83
[7] Aplin K L and Williams J H 2021 Long-term meteorological measurements in Snowdonia with a resilient solar-powered system *Weather* **76** 78-83
[8] Whipple F J W and Scrase F J 1936 Point discharge in the electric field of the Earth *Meteorological Office Geophysical Memoirs* **68**
[9] Marlton G J, Harrison R G and Nicoll K A 2013 Note: atmospheric point discharge current measurements using a temperature-compensated logarithmic current amplifier *Review of Scientific Instruments* **84** 066103
[10] Chalmers J A 1962 The relation oi point-discharge current to potential difference and wind-speed *Journal of Atmospheric and Terrestrial Physics* **24** 339-44
[11] Byrne G J, Few A A and Stewart M F 1986 The effects of atmospheric parameters on a corona probe used in measuring thunderstorm electric fields *Journal of Geophysical Research: Atmospheres* **91** 9911-20
[12] Ksanfomaliti L V, Vasilchikov N M, Goroshkova N V, Petrova E V, Suvorov A P and Khondyrev V K 1982 The low frequency electromagnetic field in the Venus atmosphere: evidence from venera 13 and venera 14 *Soviet Astronomy Letters* **8** 230-2