

# *Demonstration of a remotely piloted atmospheric measurement and charge release platform for geoengineering*

Article

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1 **Demonstration of a remotely piloted atmospheric measurement and**  
2 **charge release platform for geoengineering**

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16

17 **Abstract**

18 Electric charge is always present in the lower atmosphere. If droplets or aerosols  
19 become charged, their behaviour changes, influencing collision, evaporation and  
20 deposition. Artificial charge release is an unexplored potential geoengineering  
21 technique for modifying fogs, clouds and rainfall. Central to evaluating these  
22 processes experimentally in the atmosphere is establishing an effective method for  
23 charge delivery. A small charge-delivering Remotely Piloted Aircraft has been  
24 specially developed for this, which is electrically propelled. It carries controllable  
25 bipolar charge emitters (nominal emission current  $\pm 5 \mu\text{A}$ ) beneath each wing, with  
26 optical cloud and meteorological sensors integrated into the airframe. Meteorological  
27 and droplet measurements are demonstrated to 2 km altitude by comparison with a  
28 radiosonde, including within cloud, and successful charge emission aloft verified by  
29 using programmed flight paths above an upwards-facing surface electric field mill.  
30 This technological approach is readily scalable to provide non-polluting fleets of  
31 charge-releasing aircraft, identifying and targeting droplet regions with their own  
32 sensors. Beyond geoengineering, agricultural and biological aerosol applications,  
33 safe ionic propulsion of future electric aircraft also requires detailed investigation of  
34 charge effects on natural atmospheric droplet systems.

35 **Keywords:** aerosol charging; corona emission; meteorology; cloud; Unmanned  
36 Aerial Vehicle (UAV); Unmanned Aircraft System (UAS);

37

## 38 1. Introduction

39 Electricity in the atmosphere has long been supposed to influence clouds of water  
40 droplets. For example, Luke Howard (1772-1864), whose cloud nomenclature  
41 system is still widely used, stated that in nimbus (rain) clouds, water drops “...are by  
42 a change in their electrical state made to coalesce, and descend in drops of Rain.”  
43 (Howard, 1837). This assertion probably arose from the then fashionable interest in  
44 electrostatics rather than observations, but Lord Rayleigh (Rayleigh, 1879)  
45 subsequently reported direct experiments in which “*Instead of rebounding after*  
46 *collision, as the unelectrified drops of water generally or always do, the electrified*  
47 *drops coalesce...*”. More recent experimental and theoretical work (e.g. summarised  
48 in Pruppacher and Klett, 1998) has confirmed that charge does indeed influence  
49 droplet collisions and coalescence, and empirical findings indicate that regional  
50 ionisation release is associated with precipitation changes (Harrison et al, 2020).  
51 Highly charged droplets are also known to disintegrate under intense electric forces  
52 (Rayleigh, 1882; Duft et al, 2003). Here we demonstrate a new enabling technology  
53 to modify droplet electrostatics as a potential geoengineering technique, through  
54 releasing charge from a remotely controlled platform capable of entering clouds or  
55 aerosol regions. We describe a Remotely Piloted Aircraft (also known as an  
56 Unmanned Aircraft System, UAS) from which ions of either polarity can be released  
57 in a regularised manner, also providing an on-board measuring capability with which  
58 the local droplet, thermodynamic and electrical conditions can be monitored.

59 A great advantage of charge release as a possible geoengineering approach using  
60 airborne platforms is that large volumes of modifying substance are not required to  
61 be carried aloft. It is consequently well suited to the capabilities of small Remotely

62 Piloted Aircraft (RPA), equipped with charge emitters and monitoring  
63 instrumentation, as summarised in figure 1. The technology developed is described  
64 here. Section 2 assesses the requirements for an ion release system from which  
65 generated ions ultimately become attached to water droplets, charging them.  
66 Section 3 describes the charge emission and meteorological sensing technology  
67 developed and Section 4 the integration of this technology with an aircraft.  
68 Addressing the practical difficulties of flying beyond visual line of sight into clouds is  
69 a further essential aspect, to obtain good operating duration (tens of minutes) at  
70 significant altitude (to several km). Section 5 describes trials of the system in  
71 specially arranged airspace and section 6 evaluates the charge emission.

72 For such a widespread and fundamental influence as electrostatics on droplet  
73 behaviour there are many other associated applications, including in biology, for  
74 which droplet charging is recognised to enhance insect and foliage deposition  
75 (Gaunt et al 2003; Inculet et al, 1981). Investigating the effect of charge on the  
76 efficiency of airborne aerosol sampling provides a further application. Beyond  
77 aerosol physics, biological systems and geoengineering, additional motivation is  
78 provided by the need to explore atmospheric consequences of future electric  
79 propulsion of aircraft by ion emission (Xu et al, 2018; Ieta and Chirita, 2020). The net  
80 electrostatic effects within natural aerosol systems, and their influence on detailed  
81 microphysical droplet processes leading to rain, remain to be explicitly quantified, for  
82 which the new experimental capabilities described are highly suitable.

83

## 84 **2. Charge release considerations**

85 Charging of water droplets can be achieved by release of air ions into the droplet  
86 region (e.g. Gunn, 1954). The charge modifies the behaviour of the droplets,  
87 especially that concerned with droplet-droplet collisions. This is now discussed  
88 further, together with estimates of the charge required and generated.

89

### 90 *(a) Properties of charged droplets*

91 When a charged water droplet approaches another water droplet, charged or  
92 uncharged, it induces a charge in the second droplet, which induces a further charge  
93 in the original droplet, repeating indefinitely. Charged, colliding water droplets  
94 therefore experience an infinite system of electrostatic image charges between them,  
95 with associated electric forces (Thomson, 1853; Russell, 1922; Davis, 1964).  
96 Formally, the net droplet-droplet force is always attractive at small separations  
97 regardless of the droplets' relative polarities, unless the exact ratios of their charges  
98 would make them an equipotential on contact (Lekner, 2012; Banerjee and Levy,  
99 2015). With natural variability, this unique equipotential condition is unlikely to occur,  
100 hence two colliding charged cloud droplets can be generally considered as being  
101 more likely to coalesce than two neutral droplets. Therefore, if cloud droplets can be  
102 charged artificially, the electrical influence on coalescence may, in turn, hasten the  
103 generation of rain (Harrison et al, 2015). Another application for artificial charge  
104 dispersal might arise from the practical need to remove droplet or aerosol charge,  
105 such as in the case of release of radioactive aerosol, which can become sufficiently  
106 highly charged to be preferentially washed to the surface by water droplets (Tripathi  
107 and Harrison, 2001).

108 Release of corona ions into fogs and clouds has been contemplated previously and  
109 considered for possible hydrological and electrical benefits. After observing a fog  
110 near a high voltage tower, the inventor and electrical engineer, Nikola Tesla (1856-  
111 1943), said *“I am positive...that we can draw unlimited amounts of water for*  
112 *irrigation”* (Cheney, 2001). The most well-known artificial charge release work is  
113 probably that of Vonnegut and Moore, in which corona ions were released from near-  
114 surface high voltage horizontal wires 14 km long (Vonnegut et al 1962a,b). With this  
115 apparatus, it was demonstrated that the charge released modified the initial  
116 electrification of small cumulus clouds. Later work (Phelps and Vonnegut ,1970),  
117 estimated the charging needed to influence the droplet growth.

118

#### 119 *(b) Requirements for charge release*

120 Introducing charge into an aerosol or cloud can be achieved through surface or  
121 airborne release of air ions. Surface emission systems require extensive  
122 installations, and depend on natural updrafts and entrainment processes to allow the  
123 generated ions to reach and enter aerosols or clouds. As substantial quantities of  
124 ions can be generated relatively easily, the inefficiency of the vertical transport  
125 process may not matter in allowing some additional ions to ultimately reach and  
126 enter clouds, through following natural updraft routes. The disadvantage is that, even  
127 with large quantities of charge generation at the surface, assessment of any  
128 consequent effects will be complicated by the wide spatial dispersion of ions likely to  
129 be encountered. Using aircraft to provide targeted charge release controlled from the  
130 surface provides a promising alternative, allowing cloud regions to be located where  
131 small droplets, which are those most likely to be influenced electrically, are more



132 abundant. In addition, because charge can be generated easily electrically, there are  
133 no substantial payload requirements and hence small aircraft are particularly  
134 suitable.

135 Although more detailed work at local scales is needed to fully evaluate the charge  
136 required to influence natural aerosols and clouds, some bounding estimates can be  
137 made. The regional scale cloud and precipitation changes reported by Harrison et al  
138 (2020) were associated with an approximate doubling of the natural ion  
139 concentration. Over land surfaces, the typical volumetric ion production rate  $q_0$ , is  
140 about  $10^7$  ion pairs  $\text{m}^{-3} \text{s}^{-1}$  (Chalmers, 1967). This reduces with height, before  
141 increasing from cosmic ray ionisation above about 3 km. If clear air is considered  
142 (i.e. neglecting ion removal to aerosol or droplets), the steady-state mean ion  
143 number concentration  $n_0$  is given by

$$144 \quad n_0 = \sqrt{\frac{q_0}{\alpha}} \quad (1)$$

145 where  $\alpha$  is the ion-ion recombination rate ( $1.6 \times 10^{-12} \text{ m}^3 \text{ s}^{-1}$ ). For  $q_0 = 10^7 \text{ m}^{-3} \text{ s}^{-1}$ , this  
146 gives  $n_0 = 2500 \times 10^6 \text{ m}^{-3}$  (Harrison and Carslaw, 2003).

147 For an air ion generator operating by corona emission, the associated unipolar ion  
148 production rate, neglecting recombination, is directly proportional to the current  
149 flowing to the emitter tip. If the corona current is  $I_c$ , the corona ion production rate  $R_c$   
150 will be

$$151 \quad R_c = \frac{I_c}{e} \quad (2),$$

152 where  $e$  is the elementary charge ( $1.6 \times 10^{-19} \text{ C}$ ). If the aircraft is in level flight at a  
153 speed  $v$ , and air ions are emitted in a cylindrical beam of cross section area  $S$ , the

154 instantaneous number of unipolar ions,  $n_c$ , generated per unit volume due to corona  
155 is

$$156 \quad n_c = \frac{R_c}{Sv} = \frac{I_c}{Sve} \quad (3).$$

157 The current required to generate an instantaneous corona ion concentration which is  
158 a multiple  $f$  of the steady-state background ion concentration  $n_0$  (i.e.  $f = n_c/n_0$ ), is  
159 therefore

$$160 \quad I_c = fSve \sqrt{\frac{q_0}{\alpha}} \quad (4).$$

161 For a small aircraft (1 m wingspan) flying at  $v = 30 \text{ ms}^{-1}$ , emitting an ion plume into  
162 an area defined by the wingspan (i.e.  $S = 1 \text{ m}^2$ ),  $I_c$  is found from eqn (4) for  $f = 1$  as  
163  $\sim 10^{-8}$  A. If, as observing smoke plume releases from small aircraft suggests, the  
164 emitted ion plume spreads vertically by up an order of magnitude more,  $S \sim 100 \text{ m}^2$   
165 and the associated  $I_c$  required is  $\sim 10^{-6}$  A. Emission currents of at least  $10^{-6}$  A (i.e.  
166  $1 \mu\text{A}$ ) are realisable, hence  $f \gg 1$  from a practical emission system is readily  
167 obtained. The total cloud volume into which ions are released is determined by the  
168 flight path and duration.

169 An alternative perspective was provided by Phelps and Vonnegut (1970), who  
170 estimated that, to increase the coalescence efficiency of droplets to near 100%, an  
171 oppositely charged droplet carrying an order of magnitude more charge than the  
172 surrounding droplets would be needed. Takahashi (1973) showed that the average  
173 charge on a droplet in a warm cloud was approximately  $1 \times 10^{-17} \text{ C}$  ( $\sim 60|e|$ ) Thus, for  
174 enhanced coalescence, a charge of  $1 \times 10^{-16} \text{ C}$  would be needed on half of the cloud  
175 droplets. Assuming a cloud droplet concentration of  $100 \text{ cm}^{-3}$  this would require a

176 charge delivery rate of  $10 \text{ nC m}^{-3}$ . With the typical RPA air speed assumed of  
177  $v = 30 \text{ ms}^{-1}$ , a charge delivery system would therefore need to provide  $0.3 \text{ } \mu\text{A m}^{-2}$   
178 which is similar to that estimated above.

179 Releasing unipolar charge will also affect the electric potential of the aircraft  
180 compared with the local environmental potential, as the aircraft will develop an  
181 opposite charge equal in magnitude to the charge released. The charging rate of the  
182 aircraft can be estimated as

183 
$$\frac{dV}{dt} = \frac{I_c}{C} \quad (5),$$

184 where  $\frac{dV}{dt}$  is the rate of change of the potential of the aircraft and  $C$  is the aircraft's  
185 capacitance. If the aircraft is considered as an isolated spherical capacitor of radius  
186  $1 \text{ m}$ ,  $C \sim 100 \text{ pF}$ , and the associated  $\frac{dV}{dt}$  for  $I_c = 10 \text{ nA}$  will be  $90 \text{ V s}^{-1}$ . This is likely to  
187 overestimate the charging rate, as any loss of charge from the aircraft is neglected.  
188 This could occur by collision or attraction of atmospheric space charge, which would  
189 act to reduce the charging rate.

190 The limitations on unipolar charge release implied by eqn (5) are important, as if the  
191 charge emission continues indefinitely, the electric field at the surface of the aircraft  
192 will ultimately become dangerously large, leading to systems failure through  
193 electrostatic discharge damage, and possible loss of the aircraft. (In the case of ion  
194 thrusters for spacecraft, neutralisers are specifically included to avoid this e.g. Kent  
195 et al, (2005) ). This risk can be reduced by approximately balanced emission of  
196 positive and negative charge, as then the aircraft charging will be less rapid,  
197 determined by the difference in the emission currents which is likely to be smaller  
198 than their absolute magnitude. A discharge wick, widely used on traditional aircraft,

199 provides another possibility. A consequence of bipolar emission is, however, that the  
200 loss of corona ions by recombination will be increased.

201 A controllable RPA charge emission system developed is now described (section 3)  
202 able to provide up to  $\pm 5 \mu\text{A}$  of corona current, followed by considerations associated  
203 with its integration into the aircraft (section 4). Flight tests evaluating the  
204 meteorological and electrical aspects are described in section 5.

205

### 206 **3. Aircraft charge emitters**

207 The charge emitters emit corona ions from a carbon fibre brush, raised to a high  
208 voltage. Two separate unipolar emitters are used, controllable to release positive  
209 and negative charge independently. These were designed to have a physical form  
210 (130 mm x 40 mm x 40 mm) and mass (100 g) suitable for small aircraft, and to  
211 operate from a 12 V power supply. Each emitter's current varies with the operating  
212 voltage chosen, which is remotely controllable through the aircraft telemetry  
213 (figure 2). The currents supplied to the emitting tips can be monitored, which allows  
214 the positive and negative currents to be balanced, to minimise the aircraft charging  
215 hazard. Because the current measurement has to be obtained at the emission (high  
216 voltage) part of the corona emitter circuit, an isolated system is required to provide  
217 the measurement at safe voltages for the aircraft's data telemetry. Communication  
218 between the aircraft system and the emitters is therefore required in two directions,  
219 from the aircraft to the emitter to set the high tension operating voltage (which is also  
220 confirmed back), and from the emitter to the aircraft to report the corona current. This  
221 information is recorded by the aircraft data system.

222 In each charge emitter, the operating high voltage is requested by the aircraft's data  
223 logger, over a USB-UART serial link, and the resulting output current monitored.  
224 Within each emitter, a microcontroller acts as the main control and communication  
225 link between the aircraft and the device, providing control of the high-voltage module  
226 and monitoring of the output voltage, while another internal UART serial link  
227 communicates over an optical isolator with the current sensing section.

228 The amount of ion production is determined by the current flowing from the high-  
229 voltage module through the discharge brush into the surrounding environment. This  
230 current is monitored by measuring the voltage drop across a series resistor, between  
231 the module output and emitting tip. Since the current sense circuit is elevated to the  
232 potential of the high-voltage output of the module, the measurements are returned  
233 through an optical link (e.g. Harrison 2002; Aplin et al 2008), with its supply  
234 galvanically isolated from the low voltage section of the board. A chain of three  
235 transformers (type PT6) with their secondaries in series is used to provide a total  
236 isolation of 9 kV, using a square wave oscillator drive, as shown in Harrison (1997).

237 The actual output currents from the charge emitters were characterised using the  
238 experimental arrangement summarised in Figure 3. For this, the emitting tip (a  
239 carbon fibre discharge brush) of the charge emitter was mounted on a PTFE stand-  
240 off, within a large grounded diecast box. The discharge tip was pointed at a brass  
241 detector plate connected to a trans-resistance converter (using a 1 M $\Omega$  feedback  
242 resistance) circuit, to measure the corona ion current flowing to the brass plate at the  
243 local ground potential. The detector plate was mounted centrally within the box, to  
244 allow operation of the two emitters either side of the detector plate symmetrically.  
245 Through this arrangement, balancing of the output currents from both emitters was

246 achieved by independently adjusting their operating high tension (HT) voltages, until  
247 the opposite currents were sufficiently similar that no net plate current was  
248 measured.

249 Figure 4(a) shows the current measured by the detection plate as the operating  
250 voltage of the corona emitters was varied. The onset threshold for corona emission  
251 is also related to the precise emitter tip shape, but was found to be around 1200 V  
252 for the negative emitter and 2300 V for the positive emitter. The absolute current  
253 measured by the detector plate depended on the geometry, as varying the distance  
254 between the discharge wick and the plate changed the effectiveness of ion capture  
255 and the associated detector plate current. Figure 4(b) shows the operation of the  
256 onboard isolated corona current measurement circuit when the corona current was  
257 varied, by changing the HT voltage. The linear relationship found between the  
258 corona current and HT voltage demonstrates that, through adjusting the HT voltage,  
259 the emission current can be altered in flight.

260

#### 261 **4. Aircraft science equipment integration**

262 The RPA platform chosen for this work is the commercially available Skywalker X8  
263 fixed wing aircraft. Use of a standard platform allows for possible scaling up to a fleet  
264 of aircraft. The X8 is capable of the long-range operations required to fly into clouds,  
265 including an ability to climb to altitudes of 3 km. It is a flying wing design made of  
266 expanded polyolefin foam, with a single folding propeller in a pusher configuration. It  
267 has a wingspan of 2.1 m and maximum take-off mass of 5 kg, with capacity to carry  
268 scientific equipment in a small payload bay at the front of the aircraft. The “pusher”  
269 configuration allows the science instrumentation to be located far from the propellers

270 and noise generating components, reducing electrical interference on the  
271 measurements. In use, the RPA is flown autonomously using a Pixhawk 2.1 Cube  
272 autopilot with Arduplane software (V3.9.6), propelled by a Cobra 3520 550Kv motor  
273 with Aeronaut 13" x 8 propellers and a FrSky Neuron 60 Electronic Speed Controller.  
274 UHF control links are made at 868 MHz. Separate 3000 mA h and 4000 mA h LiPo  
275 batteries are used to power the systems and propulsion motor respectively.

276 The locations of the various science sensors installed on the aircraft are shown in  
277 Figure 5. As the RPA is designed to fly within, and sample, cloud properties, it has  
278 been instrumented with temperature (RSPRO 2.4mm diameter bead thermistor) and  
279 RH sensors (Honeywell HIH-4000), and an optical cloud sensor (OCS) (Harrison and  
280 Nicoll, 2014) located in the front of the aircraft, pointing downwards to minimise  
281 water ingress and to provide shielding from solar radiation. Atmospheric space  
282 charge density sensors (with both linear (Nicoll, 2013) and logarithmic (Harrison et  
283 al, 2017) responses) are also located in the front of each wing to monitor the charge  
284 environment surrounding the aircraft. Data from all the science sensors are logged  
285 at 1 Hz through a custom-made data logging board based on a TinyDuino (an  
286 ATMEGA328-based device) as the main processor, carrying its own GPS and data  
287 storage.

288 Mounting positions for the corona emitters are also shown in Figure 4, on the  
289 underside of the wings, approximately 20 cm from the propeller, facing backwards.  
290 The positive corona emitter is located on the left wing, the negative emitter on the  
291 right wing. This positioning ensures that the corona ions are emitted into the  
292 turbulent flow behind the aircraft, helping to disperse the ions and ensuring they do  
293 not return to the aircraft, which would modify its charge. The corona emitters can be

294 switched independently to provide positive, negative or bipolar ion emission, using  
295 optically isolated switches activated by the pilot through the remote control (RC).

296

## 297 **5. Flight tests of aircraft instrumentation**

298 Separate series of flight tests were undertaken to evaluate the flight endurance and  
299 payload capability, meteorological measurements and charge emission. Calibration  
300 information on the sensors is provided in the Appendices.

301

### 302 *(a) Aircraft aspects*

303 To examine the flight capabilities of the extensively instrumented Skywalker  
304 airframe, test flights were conducted at the Pallas Atmosphere-Ecosystem Supersite,  
305 in sub-Arctic Finland during the Pallas Cloud Experiment (PaCE 2019) (Latitude  
306 68.01°N, Longitude 24.14°E) during September 2019. This site had a designated  
307 Temporary Dangerous Area (EFD527), permitting flights to a ceiling of 2 km Above  
308 Mean Sea Level (AMSL). Table 1 summarises all the RPA flights undertaken,  
309 including details of the eleven flights conducted at Pallas. The longest endurance  
310 flight path is shown in figure 6.

311 The maximum altitude reached in this flight was 2000 m AMSL in a flight duration of  
312 20 min 45 s. This consisted of a 11 min climb at a 10° angle to 2000 m, followed by a  
313 9 min glide to landing. The principal battery usage occurred during the climb,  
314 requiring a mean current of 16 A compared with 0.2 A during the descent. Over the



315 entire flight, the total charge drawn from the propulsion battery was 3850 mA h, of  
316 the 4000 mA h nominally available.

317

318 *(b) Meteorological sensors*

319 The meteorological measurements made by the X8 RPA during flight were  
320 compared with nearby meteorological measurements made using a balloon-carried  
321 instrument package, employing an RS41 radiosonde augmented with additional  
322 science sensors.

323 The balloon payload consisted of a standard Vaisala RS41 radiosonde with an  
324 optical cloud sensor (OCS) (Harrison and Nicoll, 2014) and charge sensor (Nicoll,  
325 2013) attached, of identical design to those on the aircraft. The add-on sensors were  
326 housed in a 3D printed enclosure. This enclosure had fixing spikes printed to grip  
327 into the RS41's polystyrene shell, firmly securing the add-on sensors with a  
328 tensioned cable tie. Data from the sensors was relayed through the RS41's telemetry  
329 system using the ozone sensor (OIF411) port, following Harrison et al (2012). The  
330 sensor data was interleaved with the RS41's data-stream and recorded by the  
331 ground station. The additional data packets were synchronised with the standard  
332 meteorological data after the ascent. The RS41 carried standard temperature and  
333 humidity sensors, having a quoted accuracy of  $\pm 0.01$  °C and  $\pm 0.1$  % respectively  
334 (Vaisala 2018):

335 An Intense Observation Period was undertaken at the Pallas site on 27th September  
336 2019 to compare the balloon and aircraft systems. For this, a fully instrumented RPA  
337 flight into a thin stratiform cloud was made, followed by a RS41-special sensor

338 balloon launch to provide reference data. The radiosonde and aircraft data obtained  
339 are now compared.

340 Figure 7a and b show the standard thermodynamic meteorological quantities from  
341 the RS41 radiosonde in black, and the X8 aircraft in red. From the temperature and  
342 RH data a cloud layer 100m thick at approximately 1700m is apparent. The cloud top  
343 is capped with a 5 °C inversion at 1800m. Figure 7a demonstrates a -2 °C cold bias of  
344 the temperature sensor on the X8 when compared to the RS41 temperature sensor,  
345 which can be corrected in future flights. The X8's RH sensor tracked the RS41  
346 sensor closely, except in the cloud top region at 1800 m where it lagged the RS41,  
347 taking longer to adjust to the cloud features. As the radiosonde and the X8 each  
348 encountered the cloud layer at different speeds, displaced in time, their lag times  
349 cannot be uniquely identified. The response time of the RS41's humidity sensor is  
350 given by the manufacturer (Vaisala, 2018) as less than 0.3s at 20°C and less than  
351 10s at -40°C.

352 Figure 7c shows the charge density from the port wing-mounted charge sensor,  
353 plotted alongside the charge density inferred from the charge sensor data from the  
354 radiosonde. The charge was calculated following Nicoll and Harrison (2016). In the  
355 cloud at 1700 m the wing mounted charge sensor detected a maximum positive  
356 charge density of approximately 50 pC m<sup>-3</sup>; the radiosonde detected a similar  
357 maximum positive charge density of 60 pC m<sup>-3</sup>. Such extensive layer clouds often  
358 show charging associated with the upper and lower cloud boundaries (Nicoll and  
359 Harrison, 2016). The two traces demonstrate similar charge profiles from two  
360 different measurement platforms which encountered the same cloud environment.

361 The greater variability apparent in the X8 profiles may be due to additional electrical  
362 noise from the aircraft systems, or naturally generated lateral charge variations.

363 Finally, cloud droplet number concentrations derived from the OCS on the two  
364 measurement platforms are compared in Figure 7d. Both OCSs on the radiosonde  
365 and X8 aircraft recorded peak droplet concentrations of  $150 \text{ cm}^{-3}$  within the cloud  
366 layer. (The method of calculation of the droplet concentration from the raw sensor  
367 output is described in Supplementary Information S1).

368 In summary, the instrumented X8 airframe can provide thermodynamic, electrical  
369 and optical measurements in cloud, at up to 2000 m above the surface.

370

### 371 *(c) Charge emission aspects*

372 Further trials were undertaken to test the operation of the corona emitters in flight  
373 and quantify the emitted charge during low level flying over a surface electric field  
374 instrument. Positive charge emission from the aircraft would result in a positive  
375 electric field perturbation beneath and a negative field perturbation for negative  
376 charge emission. Flights were performed at the University of Bristol's Fenwood  
377 Farm, Long Ashton, UK (51.423°N, -2.671°W). The site is a large flat agricultural  
378 pasture without obstacles. Two flights were conducted on the 29th November 2019,  
379 under fair weather conditions with clear skies and no appreciable local charge  
380 generation from meteorological processes. (Details of these further flights are also  
381 provided in Table 1). Detection of the aircraft's charge emission was made using a  
382 Chubb JCI131 electric field mill (EFM), to measure the vertical electric field at the  
383 surface. The EFM was mounted on a 3m high vertical mast, separately calibrated to

384 correct for the electric field distortion due to the presence of the earthed mast. The  
385 measurement range of the EFM was  $\pm 2 \text{ kV m}^{-1}$  with a resolution of  $0.1 \text{ V m}^{-1}$ , and  
386 values logged at 1 Hz.

387 To detect charge emission from the aircraft, a stable and reliable pattern of corona  
388 emission was required, which was achieved through conducting flight operations  
389 automatically to maintain consistent flight paths. Each mission was divided into three  
390 separate operational stages. Initially, a rectangular flight path conducted at 50 m  
391 altitude was used to ensure that the aircraft was operating correctly. This was  
392 followed by level flight operations above the EFM. Finally, a circular, unlimited loiter  
393 pattern was made above the EFM. The mean loiter speed of the aircraft was  $19 \text{ m s}^{-1}$   
394 and the total flight time was 17 mins.

395 Figure 8a shows details of the flight path, demonstrating the level flight operation  
396 legs, and the indefinite circular loiter pattern. The circular loiters were conducted at  
397 15 m and 20 m above ground level, with a 50 m radius. Each loiter was planned to  
398 position the edge of the flying circle above the EFM.

399 Figure 9 shows the surface electric field,  $E$ , time series during the X8's second flight.  
400 Markers show when either corona emitter was switched on and off. Whenever one  
401 emitter was activated on the aircraft, a transient change in  $E$  was detected beneath.  
402 For positive corona,  $E$  increased and for negative corona events  $E$  decreased.  
403 When, however, both emitters were activated there was a negligible change in  $E$ ,  
404 which indicates that the opposite polarities act to cancel the point charge, as  
405 perceived by the EFM.

406 The densest region of charge emitted by the aircraft can be considered quantitatively  
407 to be represented by an equivalent point charge above the EFM. For a point charge  
408  $Q$ , the electric field  $E$  induced by the point charge at distance  $r$  is given by

$$409 \quad E = \frac{Q}{4\pi\epsilon_0 r^2} \quad (6),$$

410 where  $\epsilon_0$  is the permittivity of free space and  $r$  becomes the height of the aircraft  
411 above the EFM. By using a smoothing spline (with a unit smoothing parameter for a  
412 piecewise cubic spline interpolation), to detrend the electric field time series to retain  
413 only the transient changes (as shown in figure 10), the emitted charge from the  
414 aircraft can be calculated from eqn (6). Using this methodology, the mean of the  
415 inferred point charges for the five positive and five negative transients observed in  
416 Figure 10 was found to be 0.43  $\mu\text{C}$  when the positive emitter was activated, and -  
417 0.35  $\mu\text{C}$  when the negative emitter was activated. The small magnitude difference is  
418 likely to be associated with the different magnitudes of operating currents from the  
419 two emitters (calculated to be 5.3  $\mu\text{A}$  and -2.8  $\mu\text{A}$  for the positive and negative  
420 emitters respectively). The detected charge was evidently much less (90%) than the  
421 instantaneous charge emitted. For an emitter current of  $\sim 5 \mu\text{A}$ , a charge of  $\sim 5 \mu\text{C}$   
422 would be expected to be observed when the RPA passed directly over the electric  
423 field mill. These measurements, when combined with the findings in figures 3 and 4,  
424 indicate that most of the released ionic charge is rapidly dispersed in the  
425 atmosphere, to be removed through ion recombination or attachment to boundary  
426 layer aerosol (Harrison and Carslaw, 2003). The charge removal to droplets in a  
427 cloud situation can be expected to be similar, with the mixing processes associated  
428 with the turbulent air behind the aircraft acting to spread the air ions released.

429

430 (d) Summary

431 Taken together, the evaluations undertaken in sections 5a, b and c show that the  
432 objectives stated in the opening paragraph have been addressed and specifically  
433 that the instrumented aircraft is able to:

434 (1) carry scientific payload to cloud-level altitudes, with an endurance  
435 of ten minutes

436 (2) provide thermodynamic meteorological profile information

437 (3) locate cloud regions through the combination of a rapid time  
438 response relative humidity sensor and an optical cloud sensor using  
439 backscattered light from the water droplets

440 (4) deliver charge in a controllable and monitored manner, of either, or  
441 both polarities.

442 Further, the commercial airframe employed and the standard devices and  
443 components used in construction of the instrumentation make the production of  
444 multiple aircraft readily achievable, to increase the volume of cloud which can be  
445 intermittently sampled or continuously interacted with.

446

447 **6. Conclusions**

448 The instrumented RPA platform described here generates a new capability for cloud  
449 and aerosol investigations, and for assessing effects on their electrical behaviour  
450 following charge release. It successfully provided thermodynamic, optical and

451 electrical properties of clouds at heights up to 2 km, allowing most boundary layer  
452 clouds to be accessed and studied, as well as mists, fogs and aerosol plumes. The  
453 novel combination of a controllable bipolar charge delivery system with integrated  
454 optical sensors allows cloudy regions to be identified and targeted remotely or  
455 autonomously. Future use of electric aircraft by ionic propulsion, or the neutralisation  
456 of highly charged particle clouds presenting electrostatic hazards, illustrate further  
457 environmental applications which may benefit from targeted charge release  
458 capability.

459 Atmospheric charge release has established biological and agricultural applications  
460 and may ultimately have a new use in geoengineering through providing cloud  
461 droplet charging. This work shows that charge delivery into large atmospheric  
462 volumes can be effectively achieved by small electrically powered aircraft. As the  
463 charge is only emitted from a single point, further work is needed to establish the  
464 active area over which the charge is distributed. To achieve a greater effective  
465 release area, some alternative approaches could be considered. Fitting a set of  
466 emitters on a larger airframe provides one possibility; another, with greater volume  
467 coverage, would be through implementing an aircraft “swarm”, with multiple aircraft  
468 following the same flight pattern and simultaneously releasing charge across a range  
469 of altitudes.

470 Investigating geoengineering applications, whatever their ultimate societal value, is  
471 an increasingly urgent priority which is directly addressed by this technology. For this  
472 new application, electrically powered robotic aircraft provide adaptable delivery  
473 platforms without combustion products, and the charge released itself leaves no  
474 environmentally damaging residues.

475

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480 Natural Environment Research Council, NERC (NE/L011514/1) and (NE/L011514/2).  
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483 building and flying the aircraft. The meteorological sensor characterisation was  
484 undertaken by NERC SCENARIO summer students Heather Jones and Charlie Bell.  
485 Test flights in Finland were made during the 2019 Aerosol, Clouds and Trace Gases  
486 Research InfraStructure (ACTRIS) project in Pallas co-ordinated by the Finnish  
487 Meteorological Institute, a co-funded Institute of UAEREP. (ACTRIS-2 received  
488 funding from the European Union's Horizon 2020 research and innovation  
489 programme under grant agreement 654109; ACTRIS PPP is supported by the  
490 European Commission under the Horizon 2020 – Research and Innovation  
491 Framework Programme, H2020-INFRADEV-2016-2017, Grant Agreement: 739530).  
492 The University of Bristol provided access to Fenwood farm for flight tests.

493

494 **Data availability**

495 Data from the instrument tests are available from the corresponding author.



## 496 **Appendix A - Meteorological sensor calibration**

497 This section discusses the meteorological sensor package carried on the aircraft,  
498 and their calibration. The sensors consisted of a bead thermistor and an integrated  
499 relative humidity sensor (Honeywell HIH4000).

500 The RSPRO 10k $\Omega$  bead thermistor (type RS 151-237, 2.4mm diameter) was  
501 connected to a 10k $\Omega$  precision resistor to form a half-bridge, i.e. a potential divider  
502 from a regulated supply, giving a voltage output  $V_{THS}$ . The thermistor was calibrated  
503 against a standard Platinum Resistance Thermometer (PRT),  $T_{PRT}$  over a  
504 temperature range of -20 °C to 40 °C in an environmental chamber. Through this, the  
505 thermistor-bridge was found to have a first order linear response of

$$506 \quad T_{PRT} = 20.397V_{THS} - 25.960 \quad (A.1),$$

507 for  $T_{PRT}$  in Celsius and  $V_{THS}$  in volts.

508 The HIH4000 humidity sensor was calibrated by placing it in an environmental  
509 chamber at 20 °C. The HIH4000's voltage output,  $V_{RH}$  was calibrated against a  
510 Michell dewpoint sensor in the chamber. The Relative Humidity (RH) within the  
511 chamber was increased from 30% to 100% in 5% steps. A first order response was  
512 found between the HIH4000's voltage output,  $V_{RH}$  and the RH measured from the  
513 dewpoint hygrometer  $RH_D$  of

$$514 \quad RH_D = 30.547V_{RH} - 24.607 \quad (A.2),$$

515 for RH measured in % and  $V_{RH}$  in volts.

516

## 517 **Appendix B – Cloud droplet sensor calibration**

518 The calibration of the optical cloud sensor (OCS) is presented here. Its operation is  
519 described in Harrison and Nicoll (2014), but for this application it was extended to  
520 provide four channels. It consists of four high power light emitting diodes (LEDs) in  
521 an open path arrangement, with their backscattered light sensed by a photodiode  
522 mounted behind the LEDs. Two of the four LEDs are infra-red devices (peak emitting  
523 wavelength 850 nm), one cyan (505 nm) and one orange (590 nm), each of which is  
524 driven by a square wave at a unique frequency in the range between 1.1 kHz and  
525 1.5 kHz. Any cloud droplets in the optical path from the LEDs will backscatter the  
526 modulated light, some of which is received by the photodiode. The photodiode signal  
527 is bandpass filtered to eliminate fluctuating daylight, so that only the modulated  
528 backscattered signal from the cloud droplets is retained. The independent square  
529 wave signals driving the LEDs are also used for phase-sensitive detection of the  
530 individual channels, to allow the photodiode signal to be decomposed into separate  
531 responses associated with each LED. Each of the four recovered signals is  
532 separately low pass filtered and amplified to yield a DC voltage output which is  
533 proportional to the backscatter, from which the size and concentration of water  
534 droplets are found by calibration.

535 The OCS was calibrated against a Light Optical Aerosol Counter (LOAC), described  
536 in Renard et al. (2015). The LOAC measures the concentrations of aerosol, dust and  
537 water droplets in the size range 0.1  $\mu\text{m}$  to 50  $\mu\text{m}$  range. It operates by pumping air  
538 through a laser chamber, with photodiodes mounted at 12° and 60° from the laser  
539 path to receive light scattered by droplets and particles. The number of forward  
540 scattered pulses received at each photodiode gives the concentration. By comparing  
541 the nature of the scattered light at each photodiode, information about the size and

542 type of particle, e.g. carbon, mineral, ice or water can also be recovered. The LOAC  
543 returns concentrations in 17 size bins at 1 min resolution.

544 In a calibration experiment, two OCS devices were mounted alongside the LOAC  
545 above the surface on a 2.5 m mast, approximately 500 m from the River Thames in a  
546 large flat arable field on the University of Reading's Sonning farm (51.47°N, 0.89°W).  
547 This site experiences fog and river mists. The OCS devices were logged by an  
548 Arduino microcontroller operating in a similar manner to that used on the aircraft  
549 logging system. This arrangement was deployed in January 2019 for two months.  
550 During the 14th, 15th and 17th February 2019, fog events lasting several hours  
551 occurred at the site.

552 Figure B1 shows data from a fog event on the 15th February 2019. The fog formed  
553 at approximately 0700UTC and dissipated at 1200UTC. Only the infra-red channels  
554 of the OCS are considered here. The voltage outputs from the OCS' two infra-red  
555 channels are plotted in red and black, with LOAC droplet count (integrating across  
556 the several size bins that span the 10µm - 30µm range) in blue. The time series from  
557 the two instruments track well, showing the OCS response to fog droplets.

558 Figure B2 shows the raw ADC counts ( $IR_{ADC}$ ), from the infra-red channel of one of  
559 the cloud sensors plotted against the integrated droplet count  $N_D$  from the LOAC. A  
560 least-squares fit to the data allows  $N_D$  to be calculated from the OCS'  $IR_{ADC}$ , as

$$561 \quad N_D = (0.47 \pm 0.03)IR_{ADC} + (27.05 \pm 3.01) \quad (\text{B.1})$$

562 Uncertainties in the fit are given by 95% confidence intervals, implying that the fitted  
563 line is robust despite the scatter. Mature fogs often have fairly consistent droplet

564 sizes, hence the scatter evident may indicate changes in the droplet size distribution  
565 during the fog evolution.

566 The derived calibration was applied to both the balloon-borne and aircraft OCS, as  
567 described in the main text. To reduce the effects of instrumental drift, the drive signal  
568 to each LED was made steady (*i.e.* without square wave modulation) every 4 mins  
569 for 10 s, to effectively provide a zero for that channel without changing the balance of  
570 currents flowing in the overall device. This reference value was subsequently  
571 subtracted from the observed signal. As noise was also present on the OCS  
572 channels, the calibration was only applied when the mean backscattered signal from  
573 a 10 s moving window was greater than the mean and one standard deviation of the  
574 background noise from the whole flight.

575

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657

658



659 **Tables**

660 Table 1. Summary of instrumented flights conducted.

661

| <b>Date</b> | <b>Local time</b> | <b>Flight duration (minutes)</b> | <b>Max altitude (m)</b> | <b>Location</b> | <b>In-cloud duration (minutes)</b> |
|-------------|-------------------|----------------------------------|-------------------------|-----------------|------------------------------------|
| 24/09/2019  | 11:30             | 15                               | 1000                    | Pallas          | 0                                  |
| 24/09/2019  | 16:30             | 15                               | 1450                    | Pallas          | 0                                  |
| 25/09/2019  | 14:15             | 16                               | 1450                    | Pallas          | 1                                  |
| 25/09/2019  | 15:30             | 17                               | 1450                    | Pallas          | 1                                  |
| 26/09/2019  | 12:10             | 22                               | 1575                    | Pallas          | 5                                  |
| 27/09/2019  | 09:15             | 17                               | 1950                    | Pallas          | 5                                  |
| 27/09/2019  | 10:45             | 21                               | 2050                    | Pallas          | 1                                  |
| 28/09/2019  | 09:20             | 17                               | 1150                    | Pallas          | 0                                  |
| 28/09/2019  | 12:10             | 15                               | 1400                    | Pallas          | 1                                  |
| 28/09/2019  | 12:50             | 20                               | 1315                    | Pallas          | 2                                  |
| 01/10/2019  | 09:25             | 18                               | 815                     | Pallas          | 0                                  |
| 29/11/2019  | 13:45             | 22                               | 100                     | Bristol         | 0                                  |
| 29/11/2019  | 14:55             | 17                               | 100                     | Bristol         | 0                                  |

662

663

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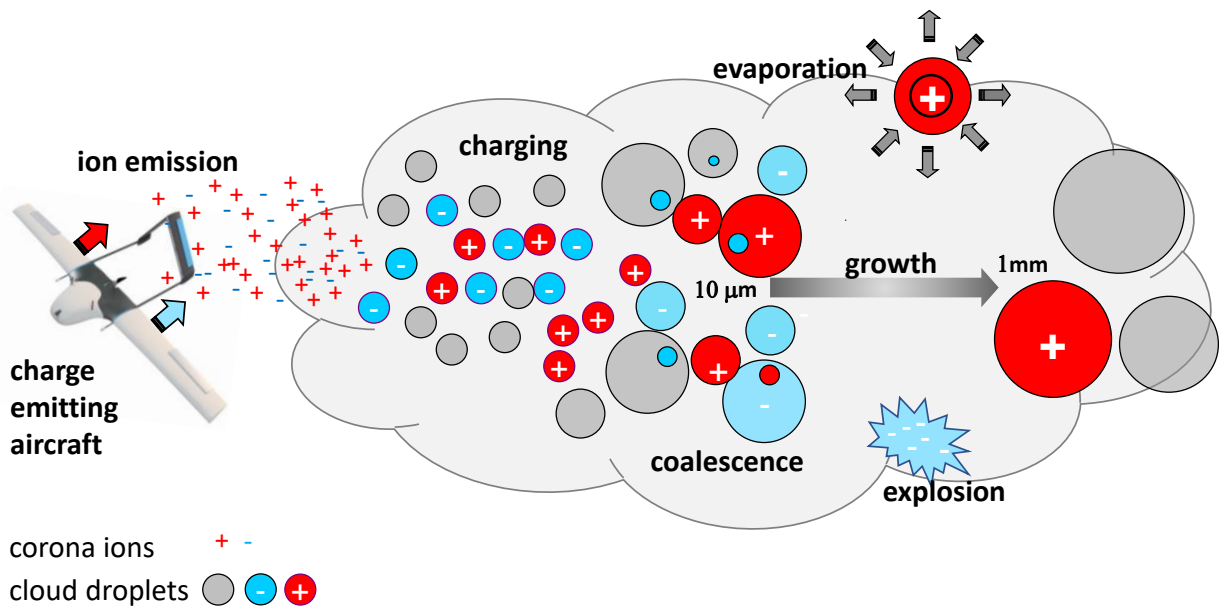
665

666 **Figures and figure captions**

667

668 **Figure 1**

669



670

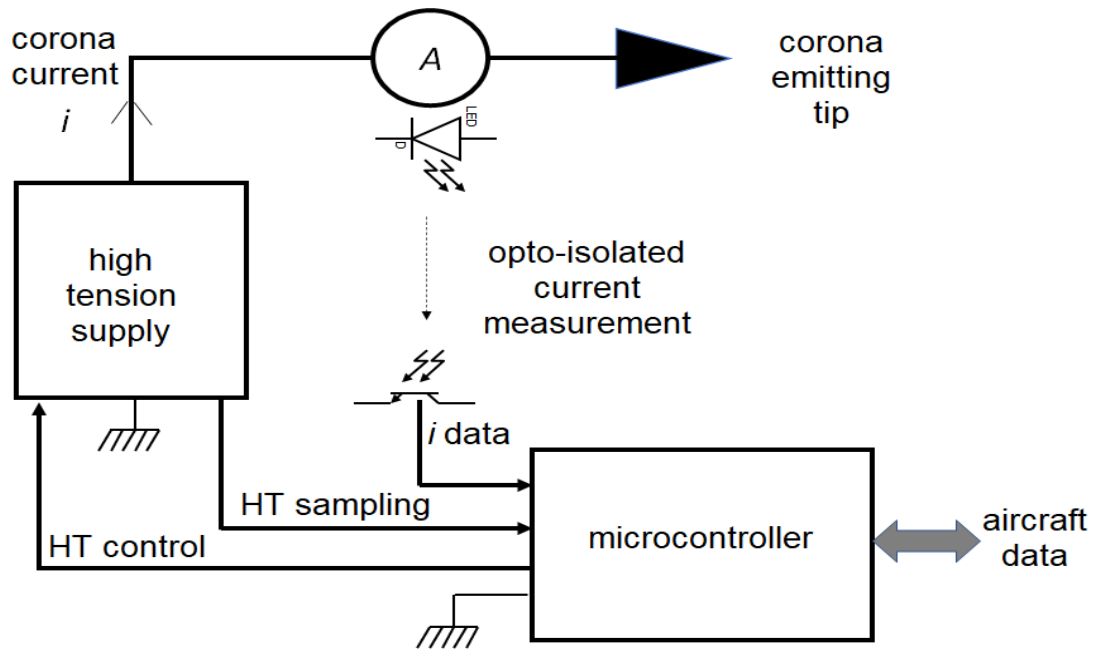
671

672 Figure 1. Conceptual picture of charge emission, droplet charging and droplet growth  
673 in a cloud (drawn to show droplet growth left to right). Corona ions released by an  
674 aircraft become entrained into the cloud, charging the water droplets present by  
675 attachment of the ions. Charging of the droplets modifies the droplet-droplet  
676 coalescence, influencing the growth rate to large drops which ultimately fall out of the  
677 cloud as rain. (Droplets lost by evaporation, or in the case of highly charged drops,  
678 charge-induced explosions which occur through electrical instability, are indicated at  
679 the cloud boundaries).

680

681 Figure 2

682



683

684 Figure 2. Corona emitter block circuit diagram. A miniature high voltage generator

685 (EMCO A-series, A60P-5 for positive, A60N-5 for negative) is used to generate

686 sufficient voltage to generate corona at the emitting tip. The HT voltage is set by the

687 main microcontroller (AT-Tiny 84), using a 12-bit DAC (MCP4725) to control a

688 MOSFET-based op-amp regulator circuit. The HT voltage is sampled by the same

689 microcontroller using a 1000:1 resistive divider potential divider, at 10 bits resolution.

690 The corona current flowing to the tip is sampled on the high voltage side (using an

691 AD8293G160 instrumentation amplifier with gain of 160) and digitised at 10 bits

692 resolution by a further microcontroller, with the values transmitted serial over an

693 optically-isolated link (OPTEX OPI1264C) to the main microcontroller. Control of the

694 emitters is achieved by data exchange with the aircraft systems, which also provide

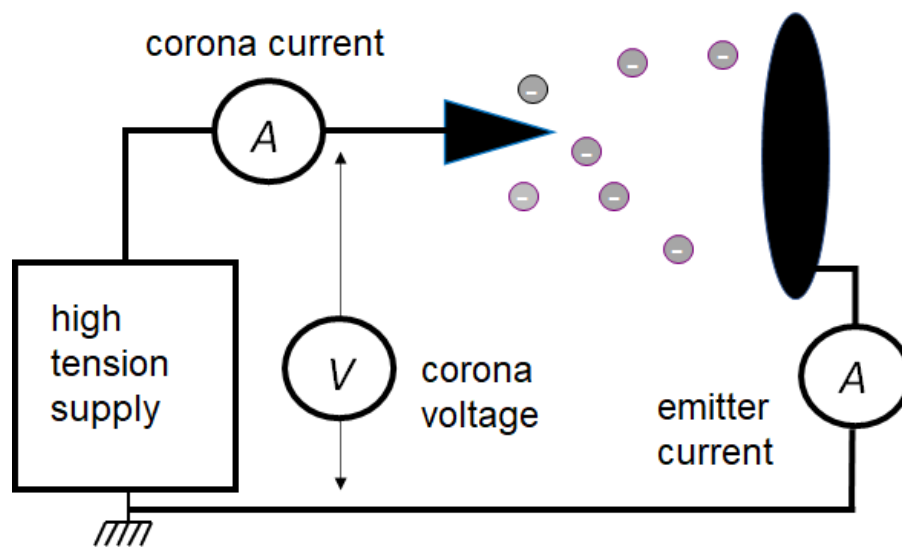
695 data telemetry to the surface.

696

697

698 Figure 3

699



700

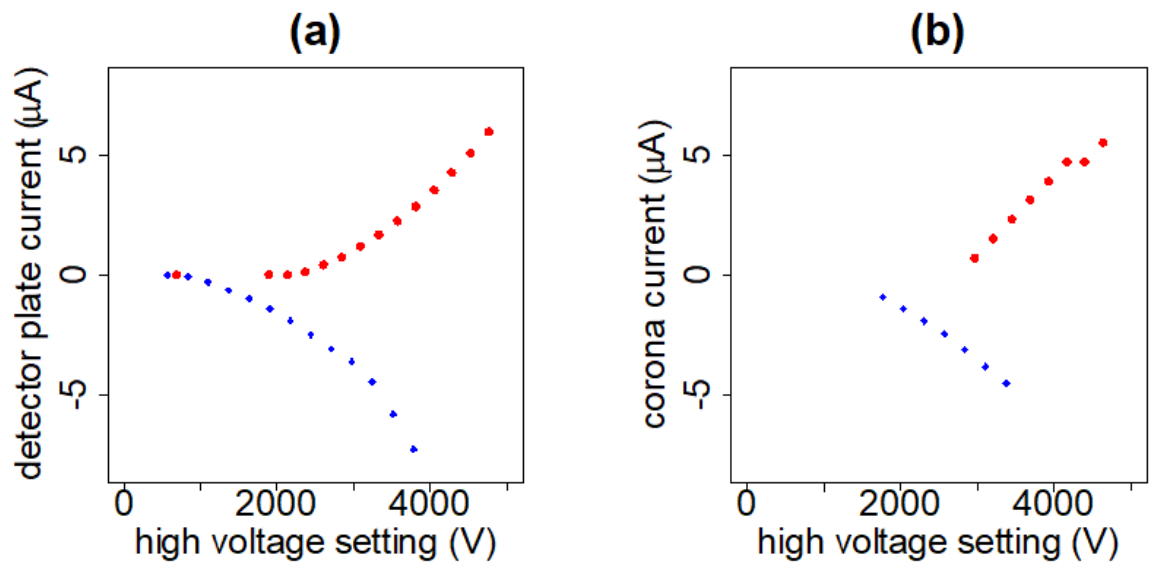
701

702 Figure 3. Conceptual diagram of the test system for a single charge emitter. A  
703 controlled high voltage is applied to an emitting tip (black arrow), and the corona  
704 current determined using the isolated measurement system of figure 2. The current  
705 emitted is also sampled at a nearby detection plate (shown by the black ellipse). For  
706 current balancing, a second opposite polarity emitter can be applied to the other side  
707 of the detection plate.

708

709 Figure 4

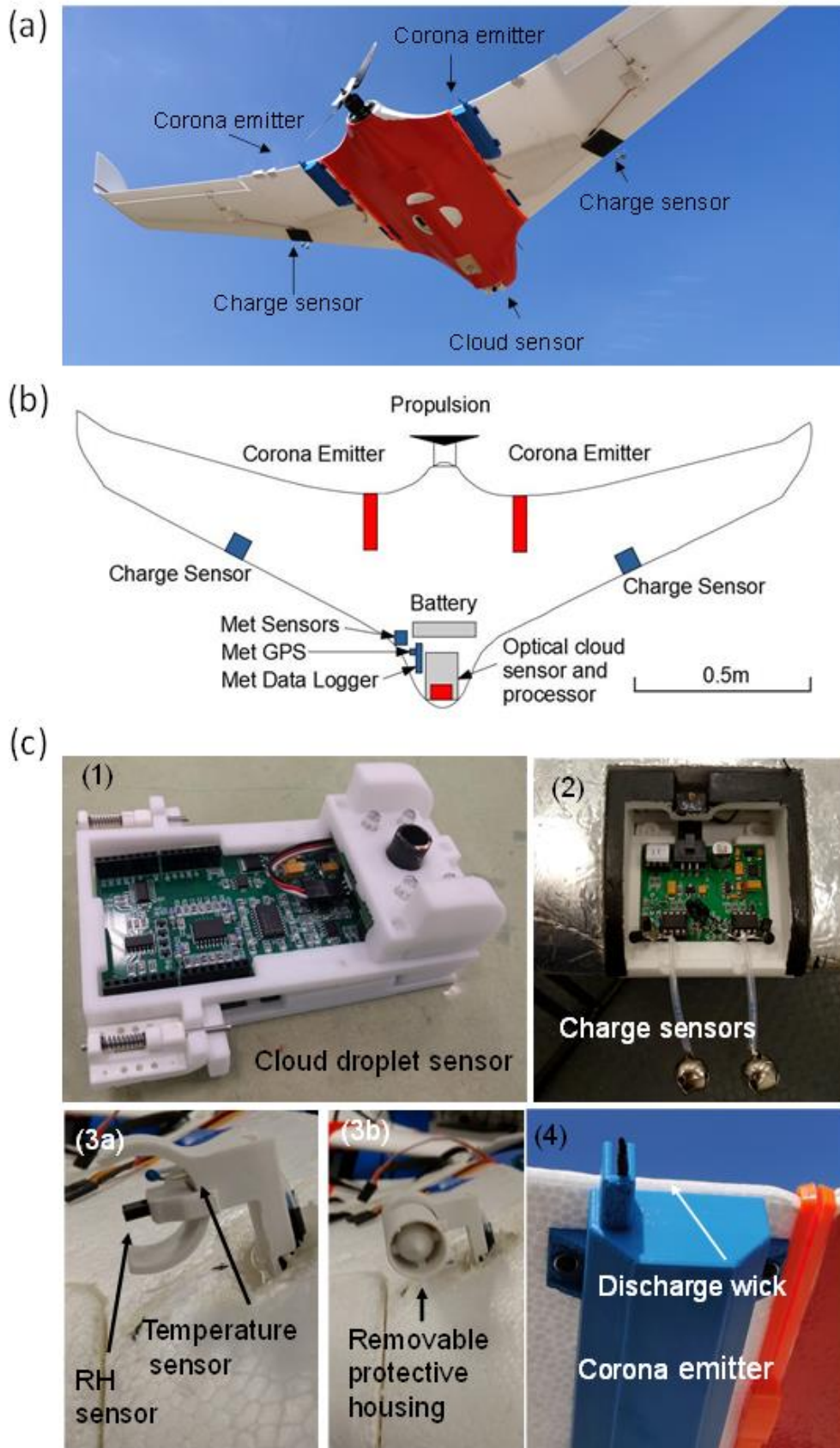
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711

712 Figure 4. Tests on the corona emitters. (a) Ion current measured at the detector plate  
713 of figure 3 as the high voltage setting (HT voltage) on the corona tip was varied, in  
714 separate experiments. (b) Relationship between current measured by the on-board  
715 corona current measurement circuit and HT voltage. (In both cases, red points are  
716 for the positive emitter and blue for the negative emitter).

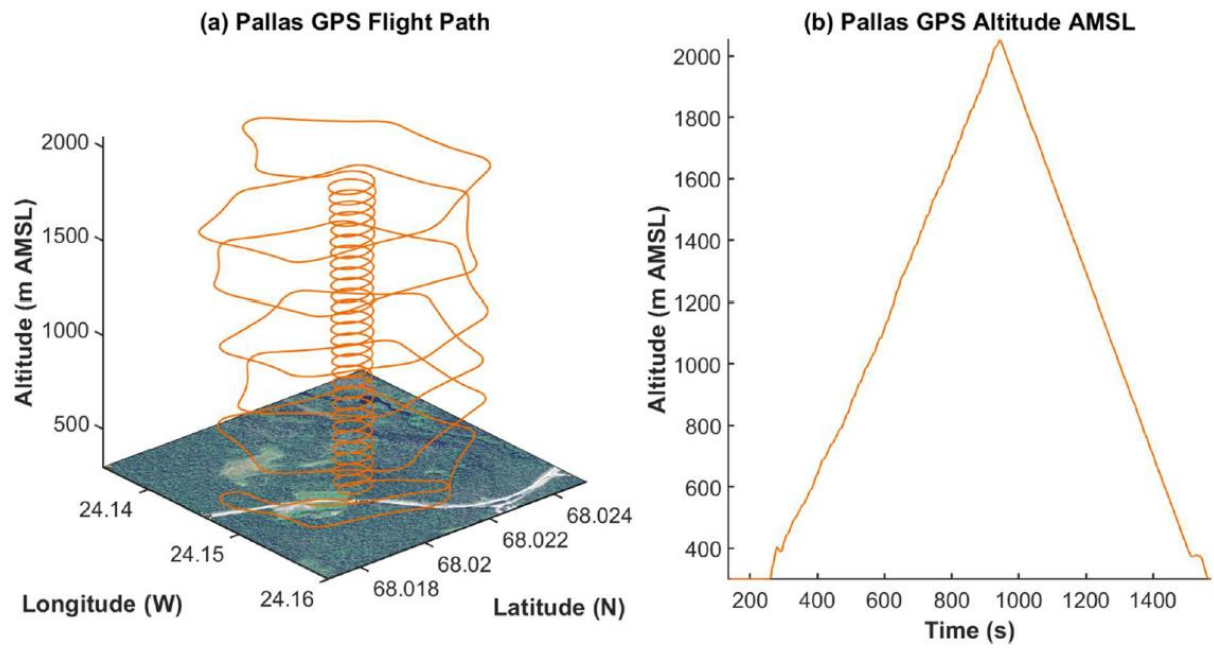
717



720 Figure 5. (a) Instrumented Skywalker X8 aircraft in flight, with instrumentation labelled.  
721 (b) Arrangement of sensors and systems on the X8 airframe (not to scale). (c) Detail of the individual  
722 science instruments: (1) optical cloud sensor, (2) charge sensors, (3a) thermodynamic (temperature  
723 and RH) sensor, (3b) removable protective housing for thermodynamic sensor, and (4) corona emitter  
724 electrode.  
725

726 Figure 6

727



728

729

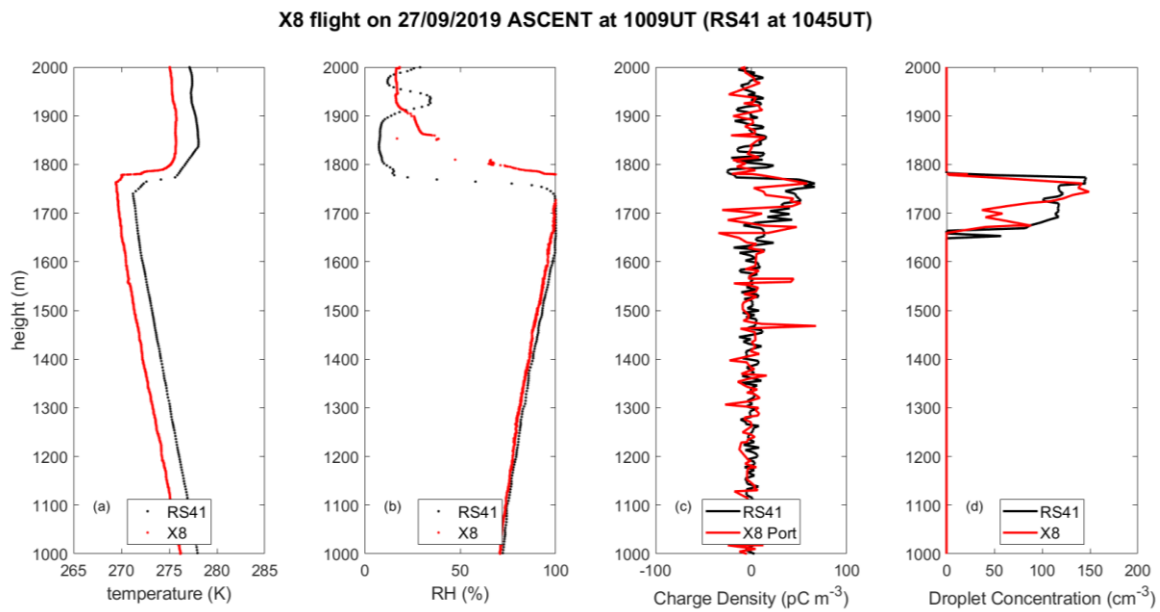
730 Figure 6. (a) Flight path and (b) altitude reached by the X8 during the longest

731 endurance flight undertaken at Pallas at 1045LT on 27<sup>th</sup> September 2019.

732



733 Figure 7

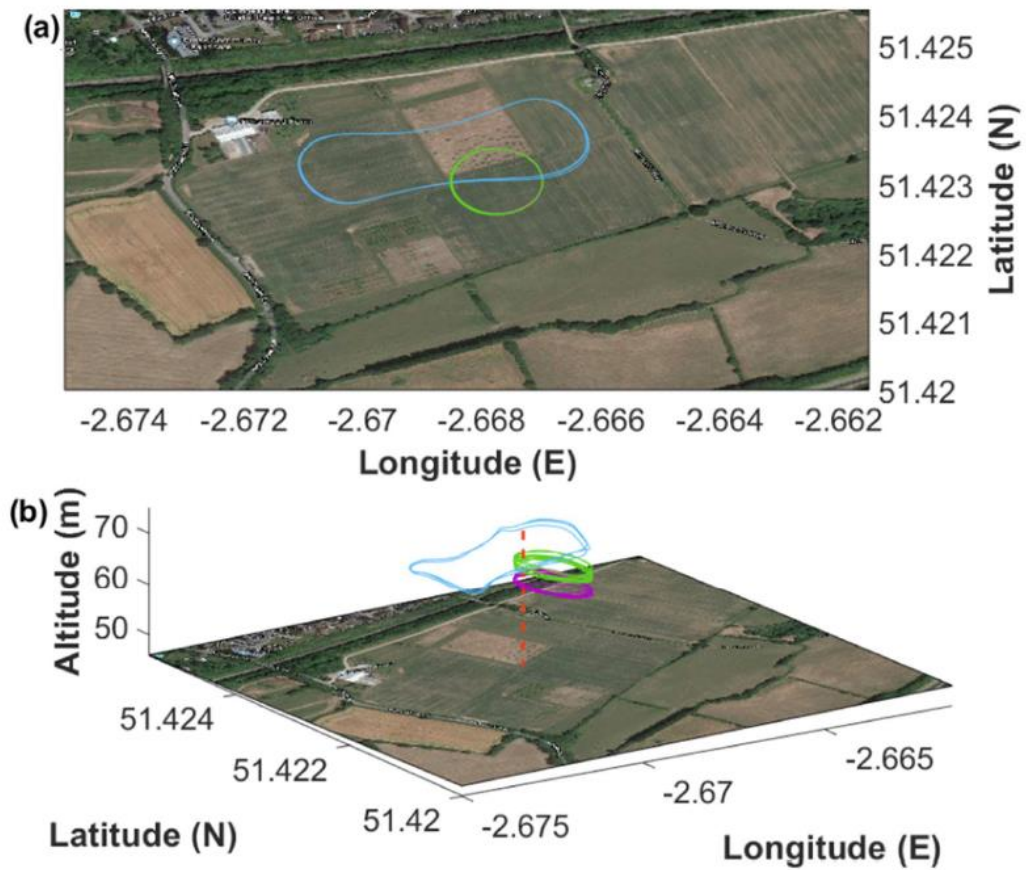


734

735 Figure 7. Comparison of radiosonde (RS41, released at 1045 UTC) and aircraft (X8,  
736 flown at 1009 UTC) profiles on the 27th September 2019. These are for (a)  
737 temperature, (b) relative humidity, (c) charge density, found from the portside charge  
738 sensor on the X8 and (d) droplet concentration, using a nose-mounted optical cloud  
739 sensor on the X8. (X8 data is in red and RS41 data in black).

740

741 Figure 8

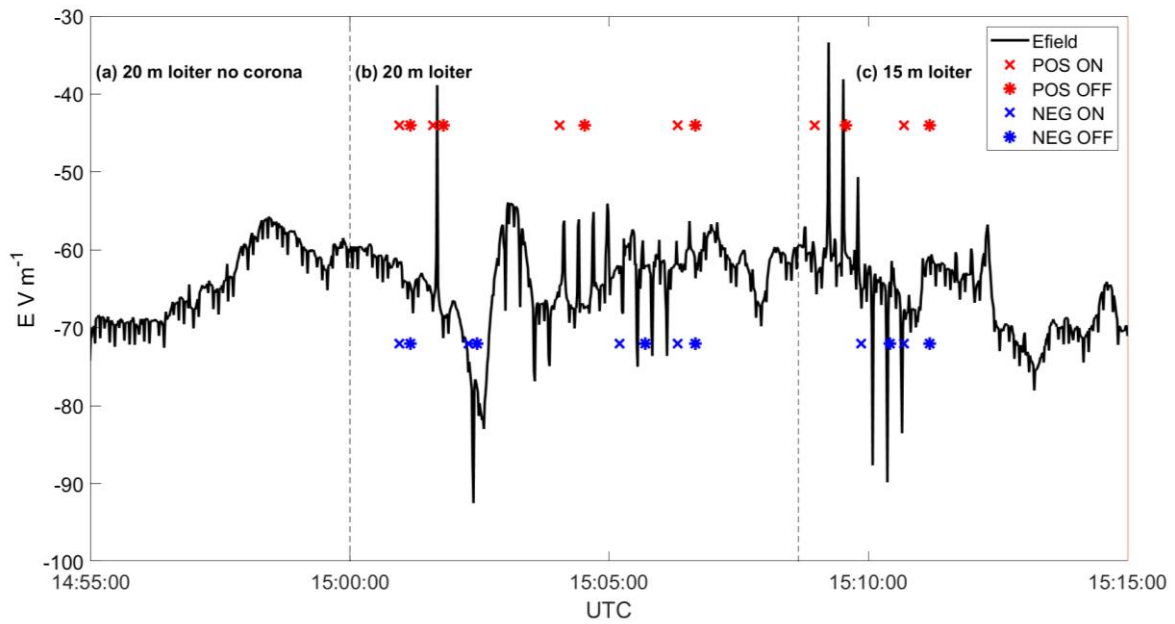


742

743 Figure 8. (a) Bird's eye view of the flight path of the aircraft showing the square path  
744 (light blue) and circular loiter path (green and purple). (b) Three-dimensional view of  
745 the flight path with the square pattern at 20m altitude (light blue), 50m radius loiter at  
746 20m altitude (green) and the 50m radius loiter at 15m altitude (purple), centred on  
747 the surface field mill location (dashed red vertical line).

748

749 Figure 9

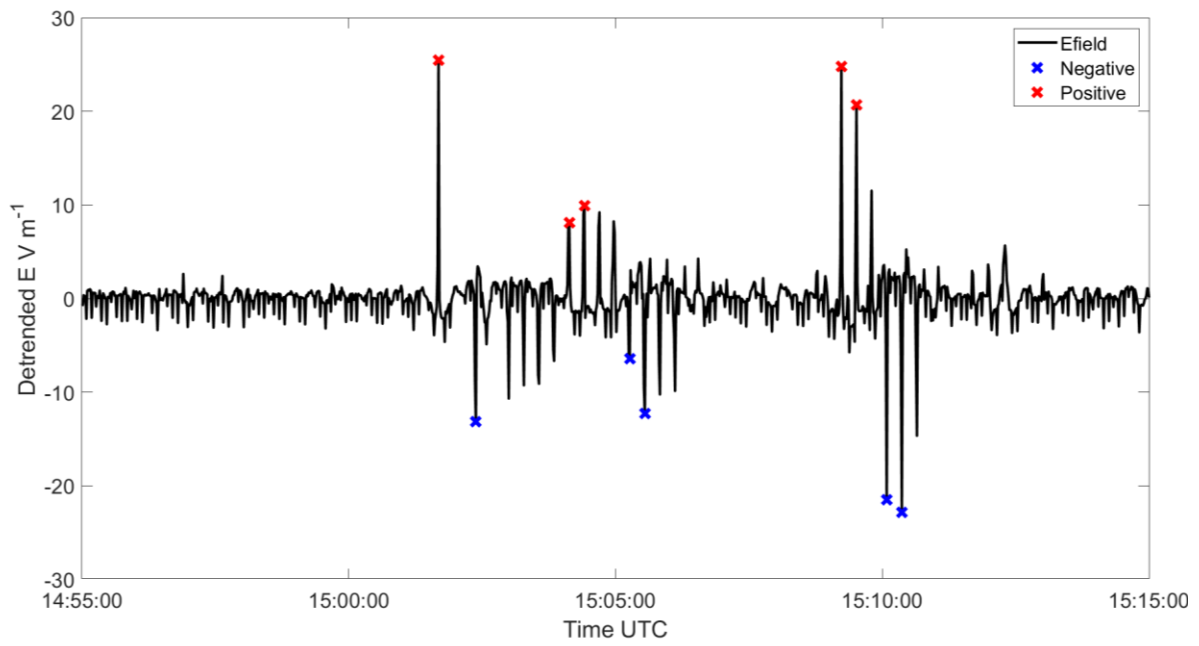


750

751 Figure 9. Time series of electric field ( $E$ ) from the Chubb JCI131 electric field mill at  
752 Fenwood Farm on 29th November 2019, with the instrumented X8 aircraft flying  
753 overhead in different flight patterns. The flight patterns were (a) loiter but no corona  
754 emitters activated, (b) 20 m and (c) 15 m radius loiter with corona emitters cycled.  
755 Crosses and asterisks mark when the charge emission was switched on and off  
756 respectively, with blue and red used to indicate the positive and negative charge  
757 emitter respectively.

758

759 Figure 10

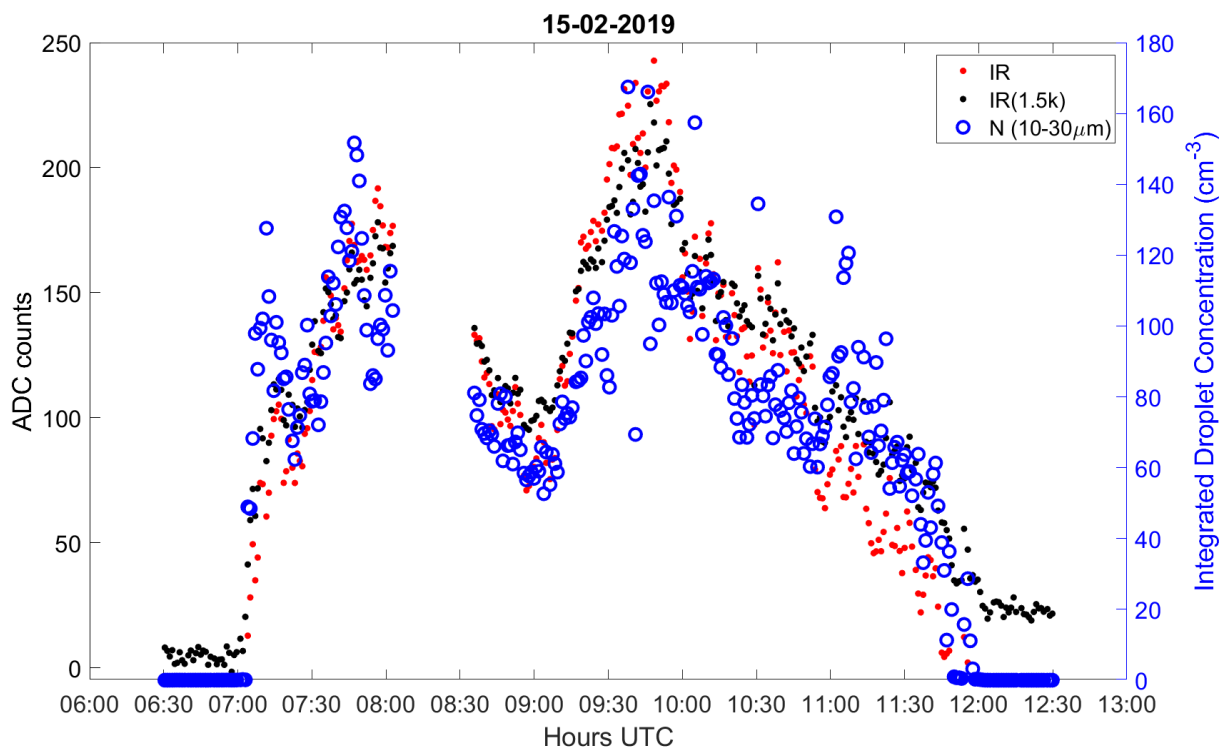


760

761 Figure 10: Detrended electric field ( $E$ ) from the Chubb JCI131 electric field mill at  
762 Fenwood Farm on 29th November 2019, from figure 9. (Red and blue crosses  
763 identify electric field transients from which the charge released was calculated).

764

765 Figure B1



766

767 Figure B1. Comparison of OCS and LOAC devices. Time series showing the

768 Analogue-to-Digital Converter (ADC) voltage counts from the two IR cloud sensor

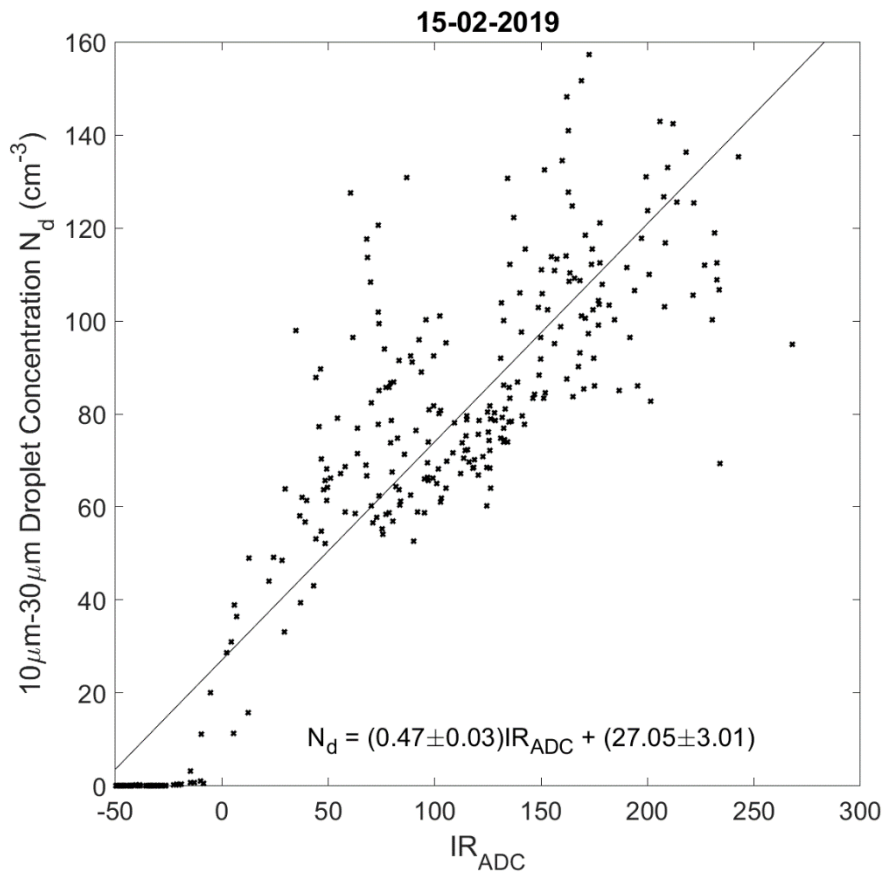
769 channels (black and red) and the integrated droplet count (blue) across the 10μm to

770 30μm diameter bins from the LOAC between 0600UTC and 1300UTC on 15th

771 February 2019.

772

773 Figure B2



774

775 Figure B2. Comparison of OCS and LOAC devices. Infra-red channel ADC counts

776 (IR\_ADC) of the OCS plotted against the LOAC integrated droplet count (10-30 $\mu\text{m}$

777 size range) for all fog events during the 14th, 15th and 17th February 2019.

778